# Anomaly Detection for Monitoring the Health of Wind Onshore and Offshore Turbine Foundations

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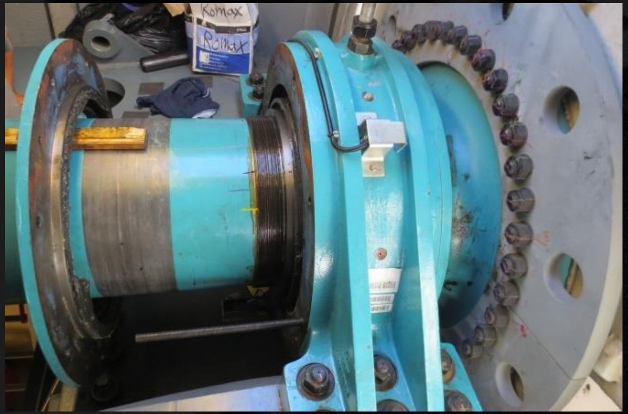
ONYX Insight

# Who are we?

- A **global business** providing **predictive maintenance** technologies
- Focus on **wind turbines** and industrial machinery
- A **trusted and independent** perspective
- A long **heritage of rotating machinery** design, monitoring and lubrication

Romax INSIGHT + bp ventures = ONYX InSight

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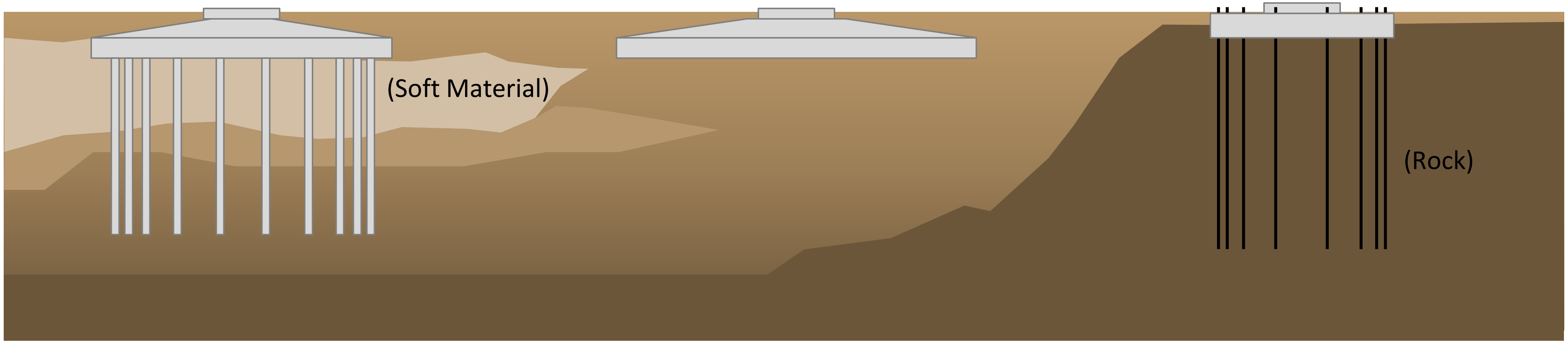
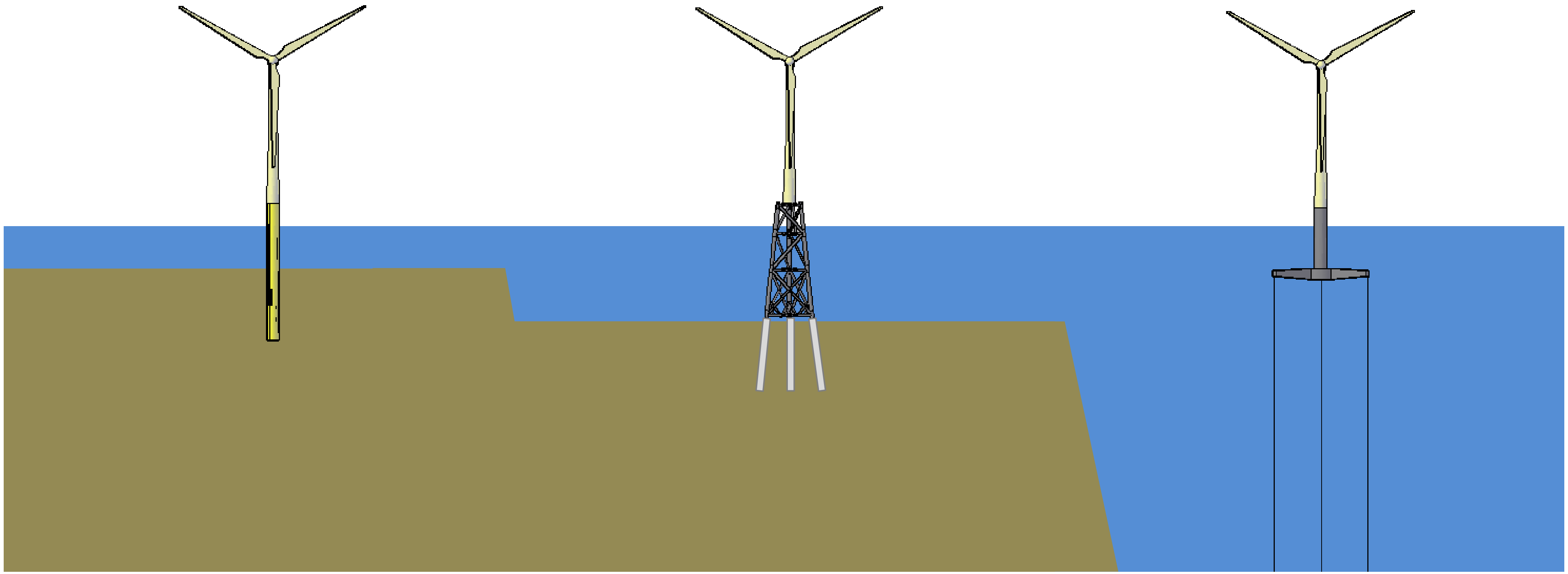
# Common Onshore Foundation Variants

| | Piled / Deep Foundations | Gravity / Spread / Shallow Foundations | Rock Anchored Foundations |
|---|---|---|---|
| **Ground Conditions** | Compressible layers below the foundation | General conditions | Shallow bedrock |



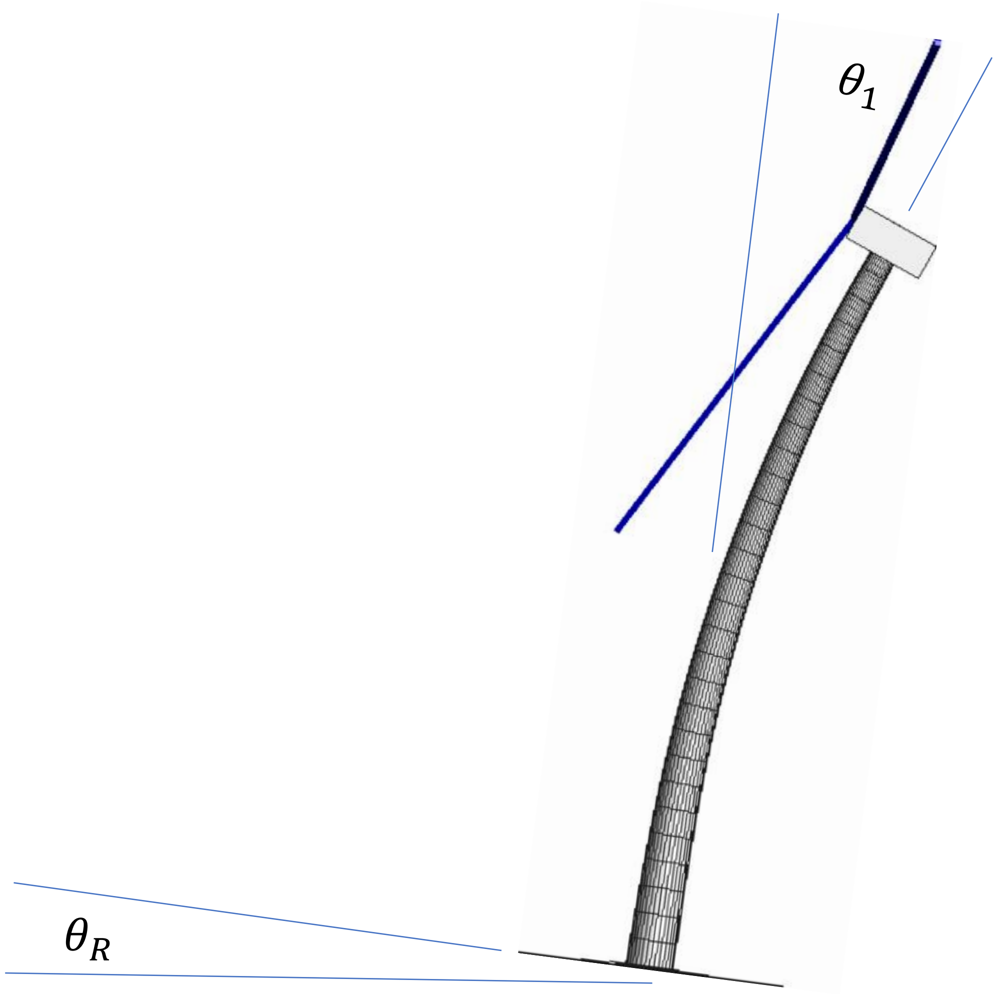
# Common Offshore Foundation Variants

| | Shallow | Transition Depth | Deep Water |
|---|---|---|---|
| **Types of foundations** | Monopiles, gravity base, etc | Jacket or other stiffer substructure | Spar, semisubmersible, TLP |



# The Foundation as Part of the Dynamic System

# Decomposing Observation – Soil-Foundation-Structure Interaction




- Observed rotation, $\tilde{\theta}$, consists of multiple components
- Fixed base component, $\theta_1$, is dominated by the turbine itself
- Rocking component, $\theta_R$, is dominated by the support structure/foundation
- Changes in either will change the observation
- Like rotation, both stiffness and frequency can be decomposed into components





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# Relating Stiffness and Frequency

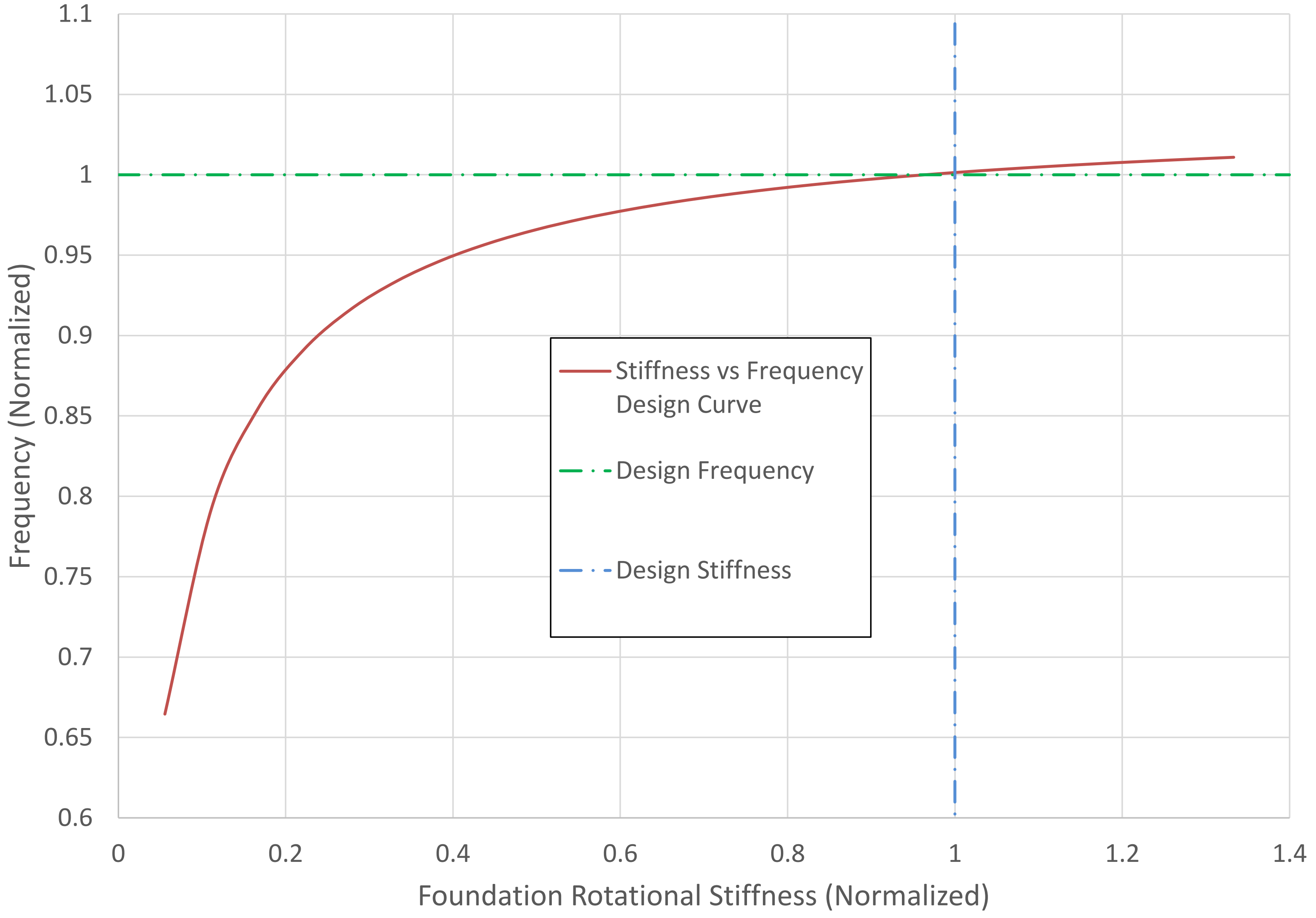
- Essentially a series spring

$$\frac{1}{\tilde{f}^2} = \frac{1}{{f_1}^2} + \frac{1}{{f_R}^2}$$

- Frequency is proportional to mass and stiffness

$$f \propto \sqrt{\frac{K}{M}}$$

- Degradation in either the tower or the foundation will influence the observed frequency



# Damage Mechanisms

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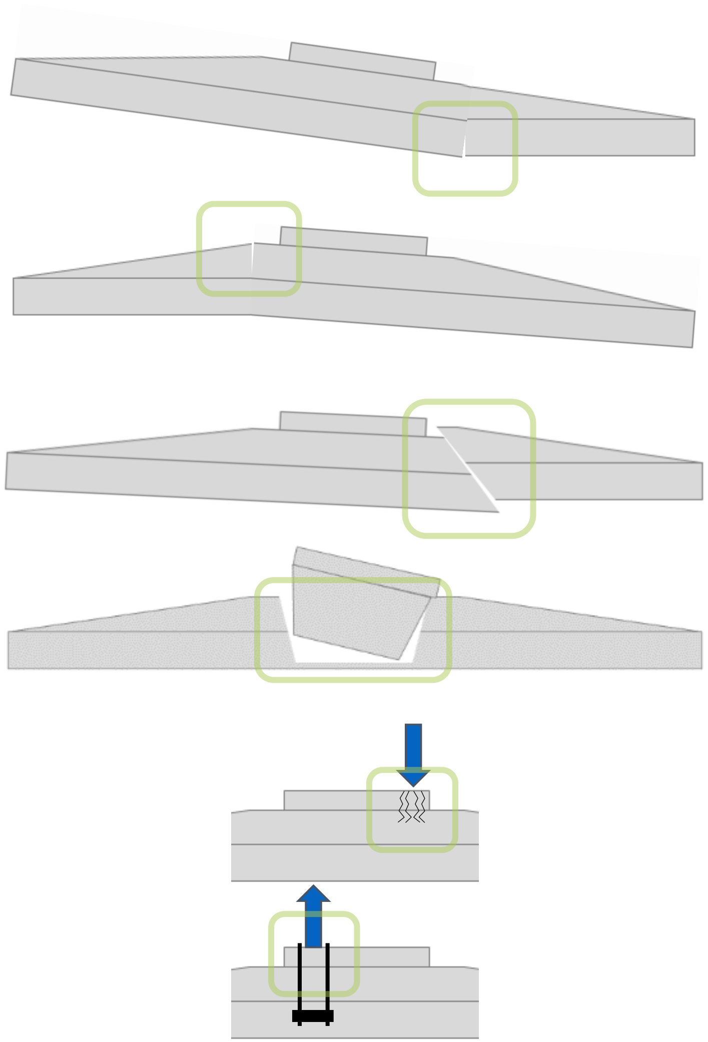
# Onshore foundation damage mechanisms



## Foundation damage

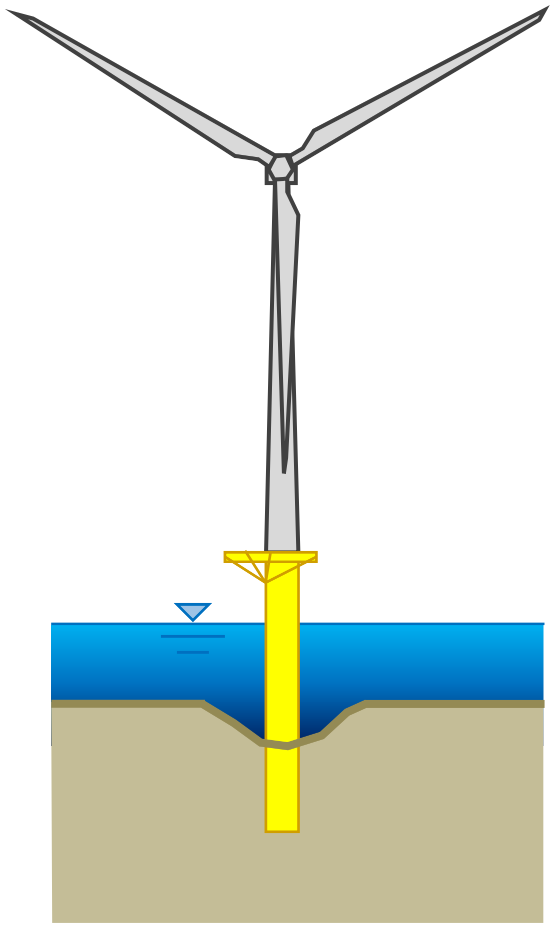
- Crack development
  - Concrete
  - Rebar
- Material crushing
  - Concrete
  - Grout
- Material bursting
  - Concrete
  - Grout
- Loss of anchor tension

## Geotechnical damage

- Soil cracking
- Settlement
- Erosion

# Example offshore damage mechanisms

- Structural damage
  - Cracking
  - Corrosion
- Geotechnical damage
  - Local scour – loss of soil immediately around the foundation
  - Global scour – loss of soil regionally
- Others depending on foundation type



# Some example failure modes

Geotechnical Failure

Concrete Cracking

Grout Failure

Pedestal Pullout

CBC - https://www.cbc.ca/news/canada/new-brunswick/cracks-in-foundation-led-to-wind-turbine-collapse-1.6312668

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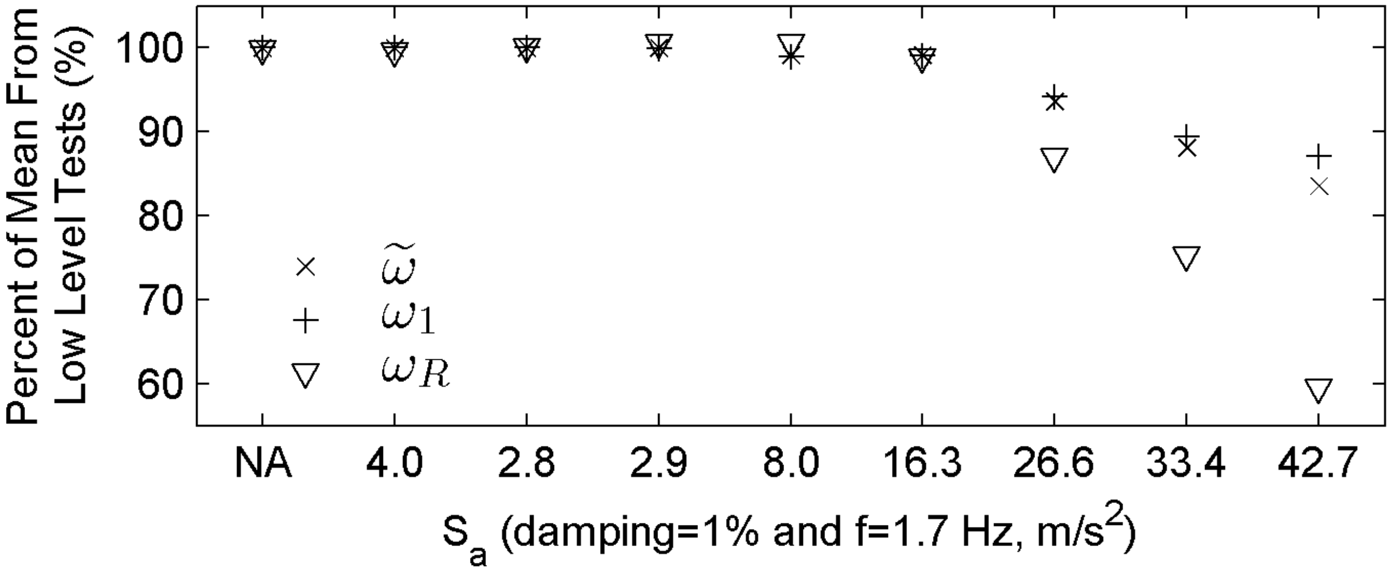
# Experimental Basis and Field Verification

# Observation and attribution of damage

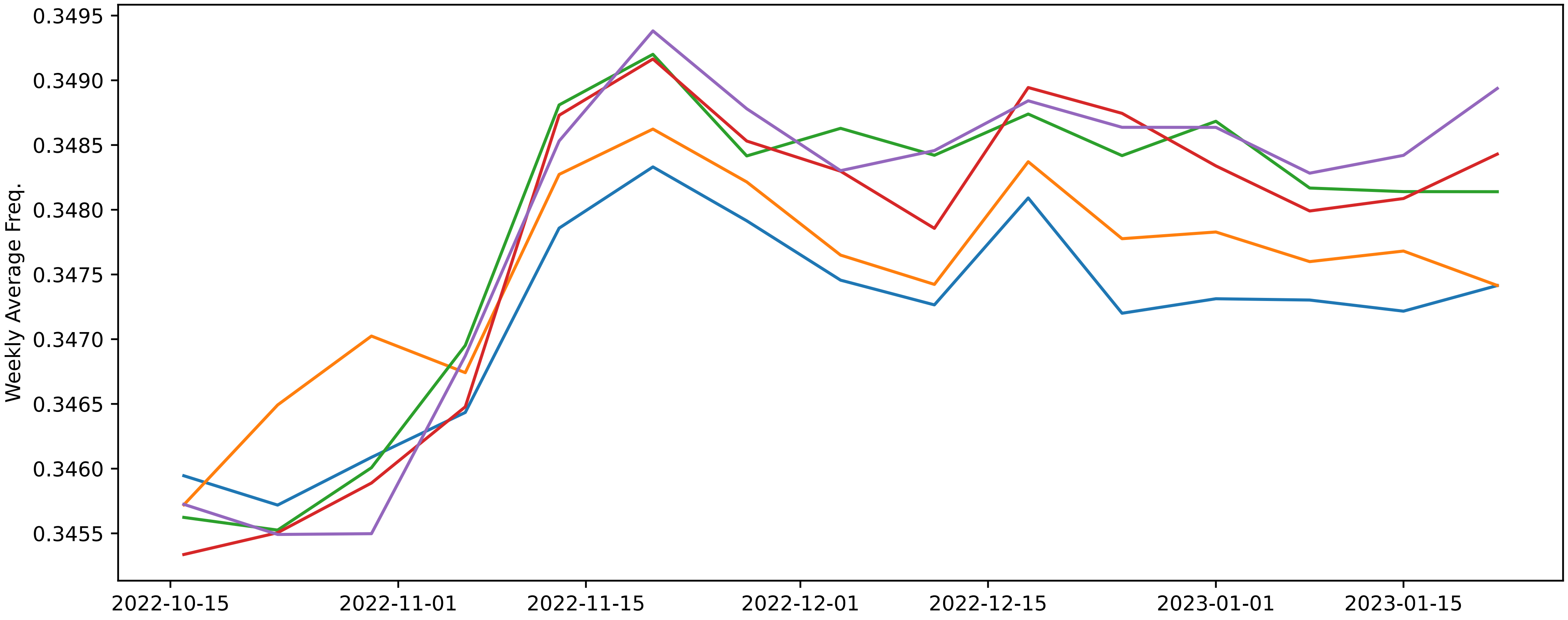

# Observation and attribution of damage

- Measurements showed a global frequency decline as stronger events occurred
- Detailed analysis split decline into
  - Tower damage
  - Reduction in rotational stiffness



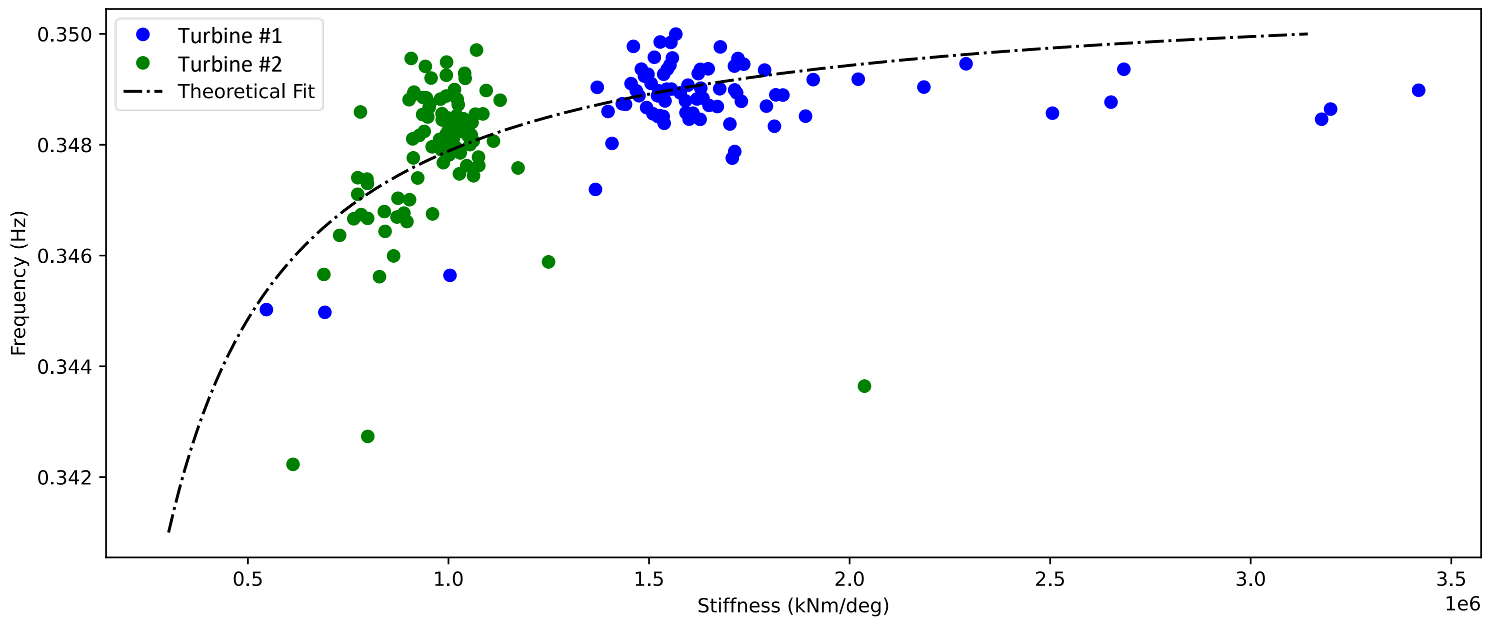
# Repaired Turbine Population

- Repair (anchor re-tensioning) is obvious in the frequency measurement of all the repaired turbines



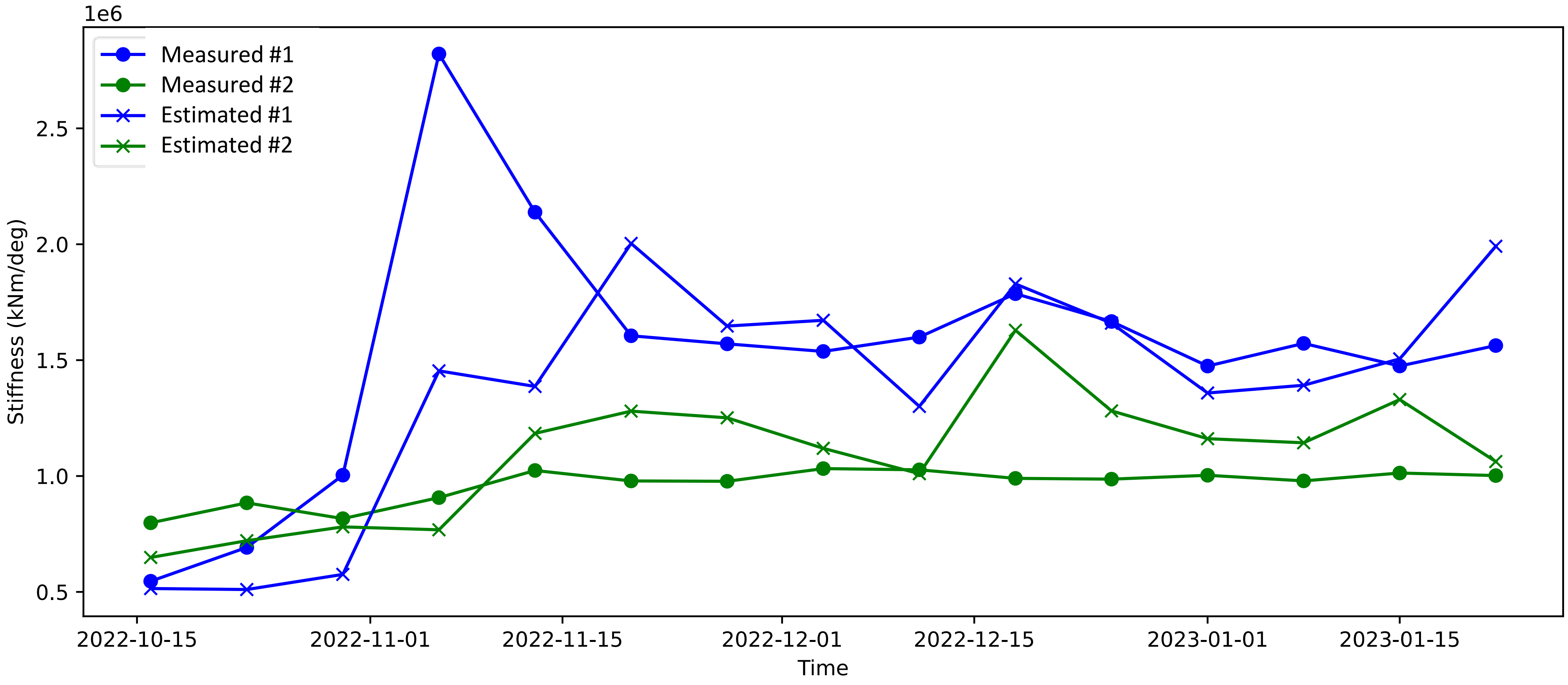
# Observing Stiffness and Frequency Directly

- Daily average stiffness from strain gauges and inclinometers
- Daily average frequency from ONYX ecoCMS units
- Foundation repair conducted during the monitoring period
  - Re-tensioned rock anchors
  - Increase in stiffness and frequency follows expected trends



# Comparison of measure and estimated stiffness

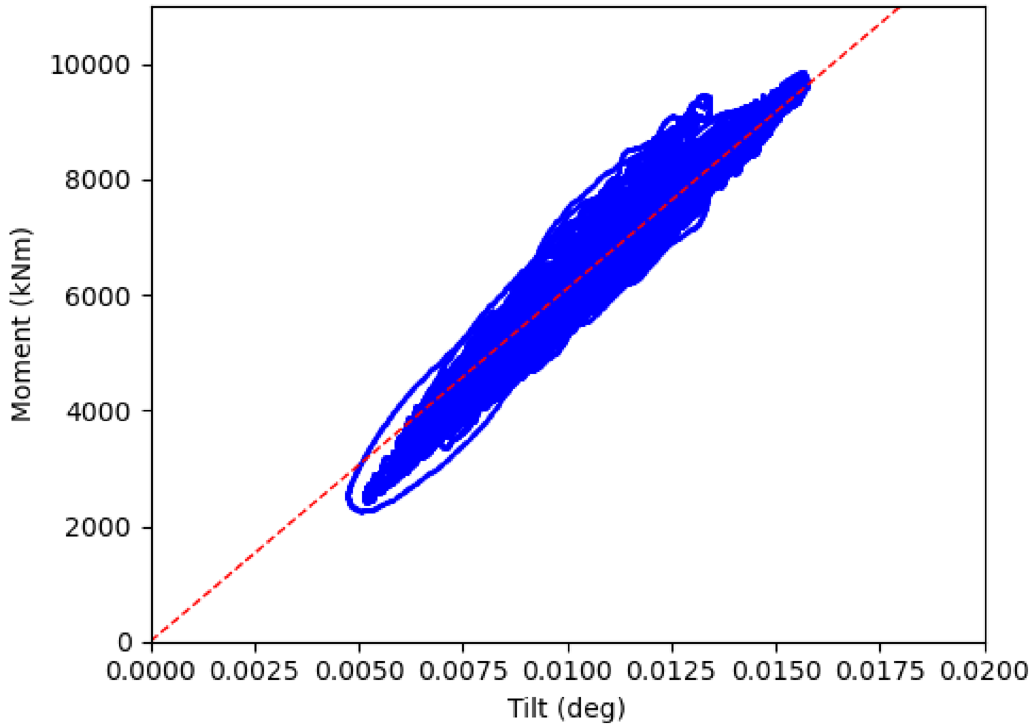
**Some discrepancies, but overall good correlation**



# Putting it Into Practice

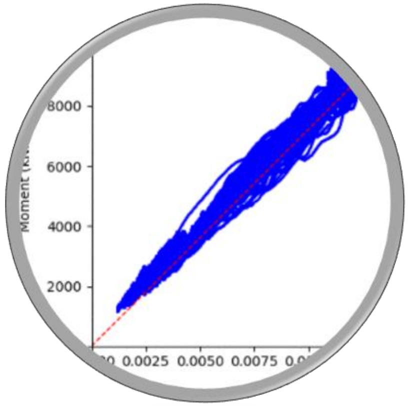
# Foundation Monitoring is Historically Data-poor

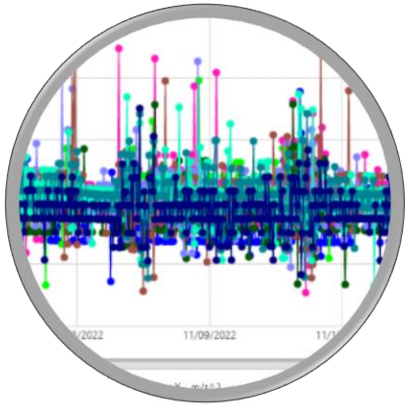
- Rotational stiffness measurement equipment instrumentation is:
  - Relatively expensive
  - Time-consuming to install (i.e., expensive)
- Due to expense:
  - Limited data collection period
  - Limited sample set
  - Unusual to have continuous monitoring
- Comparing theoretical required stiffness values to measured can result in erroneous conclusions
  - A degraded foundation may exhibit a stiffness higher than that required by the aero-elastic loads analysis



# Addressing Data Availability


Simplify the Sensor




Expand the Dataset





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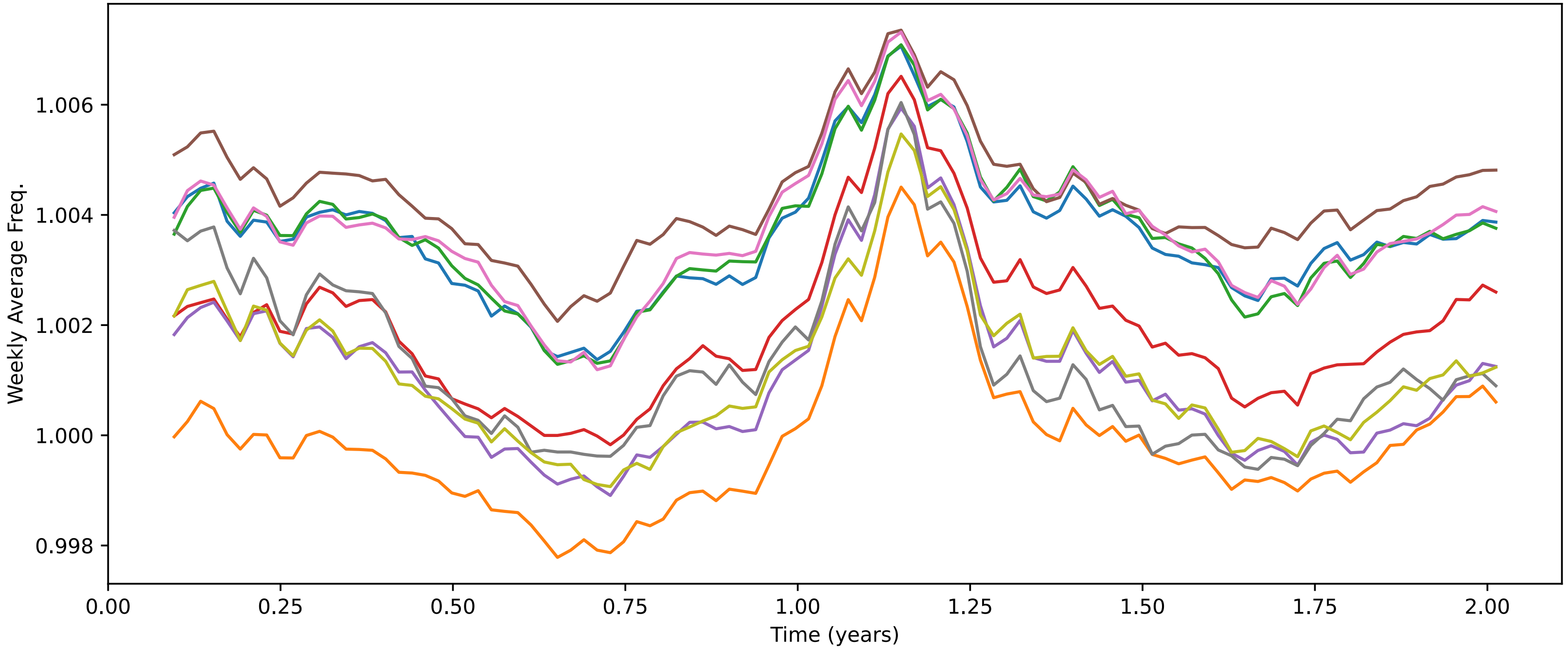
# Seasonality Confounds Interpretation

- Onshore seasonality tends to be periodic on an annual basis and dominated by temperature fluctuation
- Tidal variation (water depth) drive offshore seasonality for fixed-base turbines
- Seasonal variation can overwhelm variation due to damage



# Leverage the Situation

Unique

Similar Population





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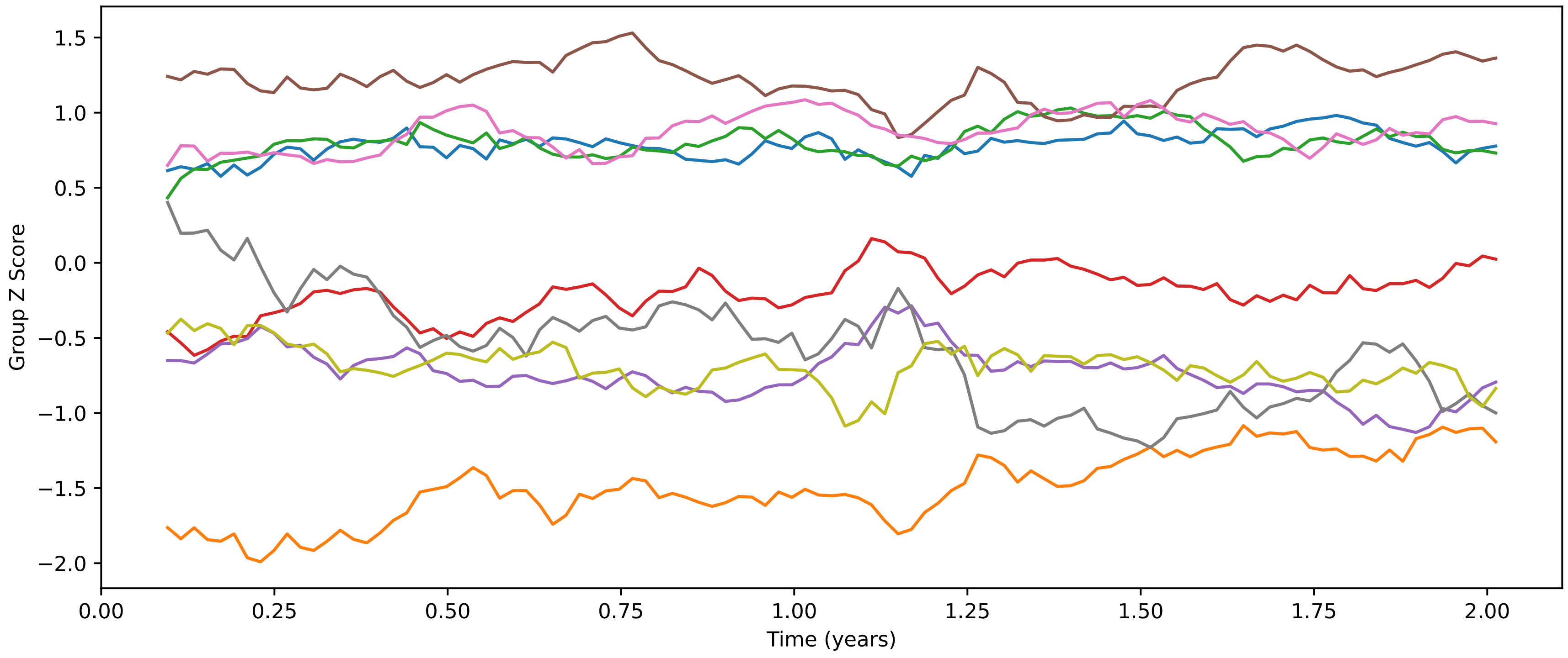
# Group and Self Comparison

**Evaluating statistics of the group clarifies the picture and minimizes seasonal noise**

- Some turbines are simply “healthier” than others
  - Stiffer soils
  - Higher strength concrete
  - Variation in foundation design
  - Variation in towers
  - etc.



# Data-driven Foundation Management

- Comparison of the rate of changes shows outliers that are likely the first to experience unacceptable performance
  - When to conduct more detailed measurements
  - What foundations to inspect
  - Determine how much longer before thresholds are crossed
  - Defer or eliminate retrofits and repairs on stable foundations

| | WTG03 | WTG09 | WTG12 | WTG15 | WTG17 | WTG19 | WTG23 | WTG38 | WTG48 | Average |
|---|---|---|---|---|---|---|---|---|---|---|
| **Frequency Slope** | 0.0002 | 0.0005 | 0.0001 | 0.0003 | -0.0003 | 0.0000 | 0.0002 | -0.0010 | -0.0003 | 0.0000 |
| **Group Health Slope** | 0.08 | 0.36 | 0.07 | 0.18 | -0.14 | 0.00 | 0.09 | -0.54 | -0.11 | 0.00 |
| **Self Health Slope** | 0.05 | 0.17 | 0.06 | 0.10 | -0.13 | 0.02 | 0.08 | -0.31 | -0.11 | -0.01 |

| ***Minimum Frequency*** | WTG03 | WTG09 | WTG12 | WTG15 | WTG17 | WTG19 | WTG23 | WTG38 | WTG48 |
|---|---|---|---|---|---|---|---|---|---|
| **Current** | 1.0009 | 0.9973 | 1.0005 | 0.9983 | 0.9977 | 1.0014 | 1.0002 | 0.9983 | 0.9981 |
| **Projected 1 Year** | 1.0009 | 0.9973 | 1.0005 | 0.9983 | 0.9974 | 1.0014 | 1.0002 | 0.9973 | 0.9978 |
| **Projected 2 Years** | 1.0009 | 0.9973 | 1.0005 | 0.9983 | 0.9971 | 1.0014 | 1.0002 | 0.9963 | 0.9975 |
| **Projected 3 Years** | 1.0009 | 0.9973 | 1.0005 | 0.9983 | 0.9968 | 1.0014 | 1.0002 | 0.9953 | 0.9972 |

# Conclusions

- The industry is currently relying on periodic inspections and measurements on a subset of the total wind farm, which results in:
  - Un-inspected turbines
  - Long periods of possibly un-observed degradation
  - Qualitative results that are difficult to map to decision criteria
  - Possibly erroneous decisions by comparing theoretically required stiffness to measured stiffness
- Frequency/stiffness is an indicator of health
- Some CMS systems can monitor the frequency
- Ongoing frequency monitoring with proper analysis can identify foundation degradation both onshore and offshore
  - Failure mechanisms differ but a similar monitoring approach can be employed