Bridge Owners Forum No. 61

Making Assets Smart
Digitally Enabled Asset Management on The Forth Road Bridges

Ewan Angus
Major Bridges Director, Forth Bridges, Amey

Why do we need smart infrastructure?

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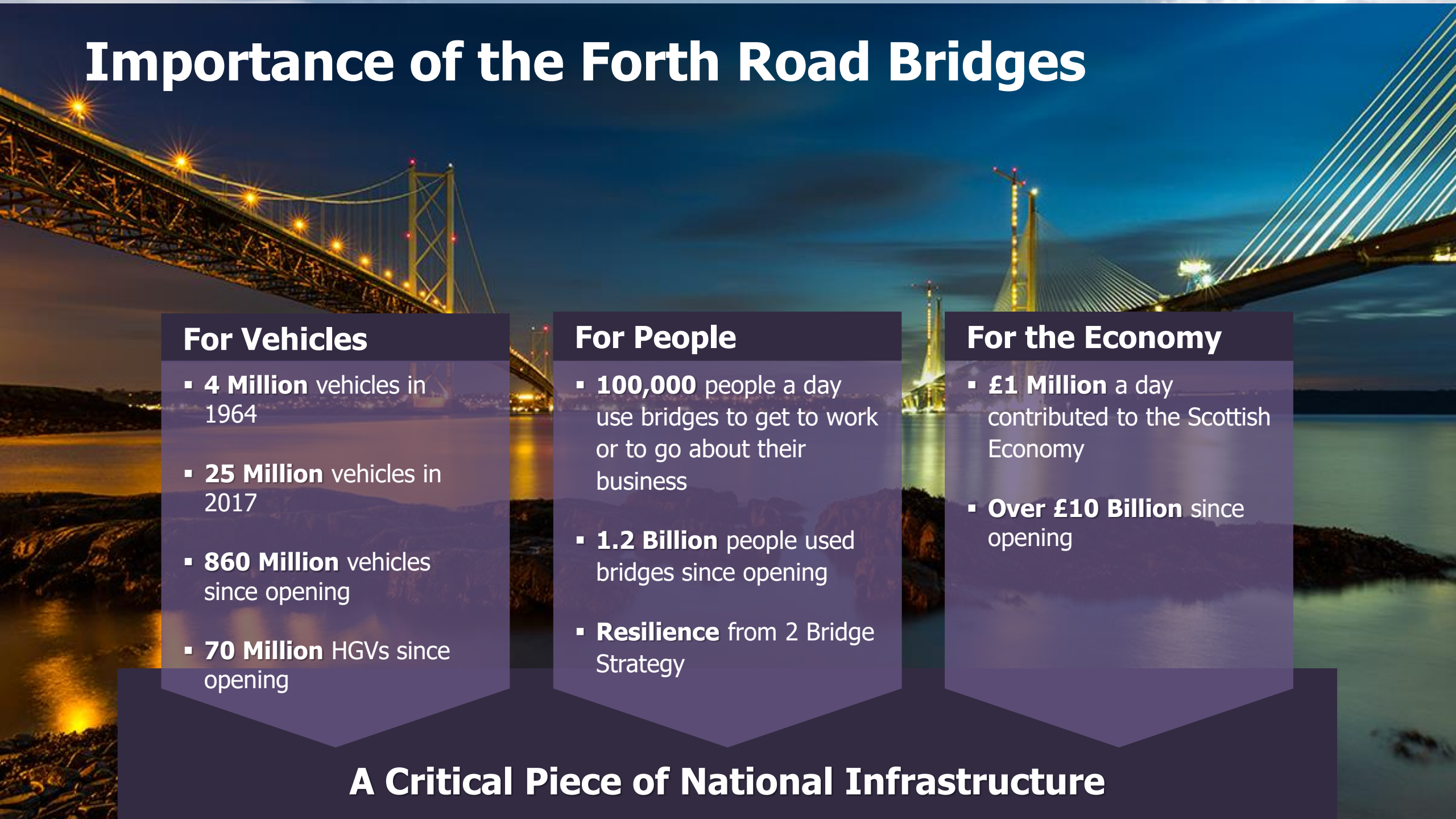
Importance of the Forth Road Bridges



For Vehicles

- **4 Million** vehicles in 1964
- **25 Million** vehicles in 2017
- **860 Million** vehicles since opening
- **70 Million** HGVs since opening

For People

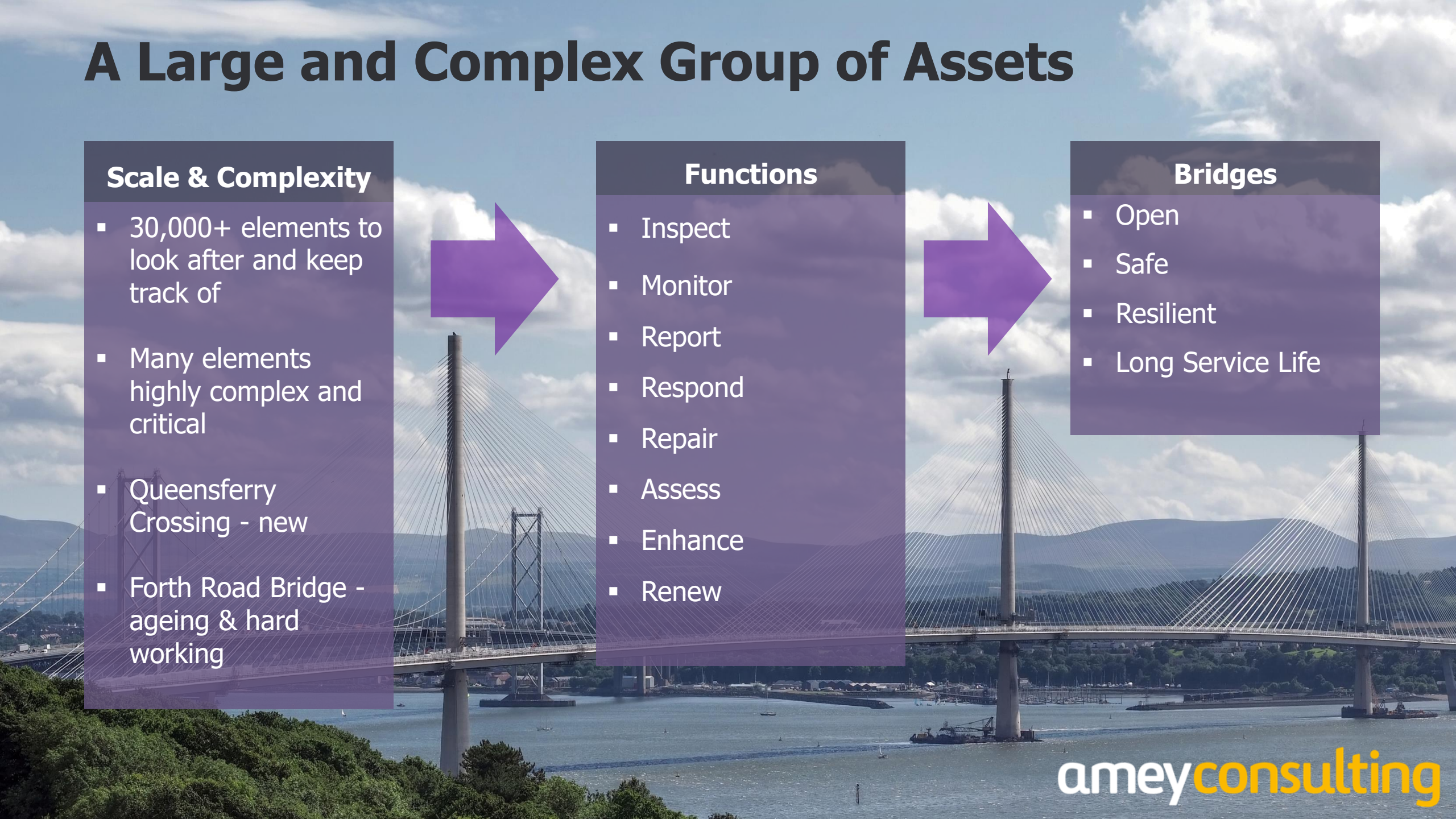
- **100,000** people a day use bridges to get to work or to go about their business
- **1.2 Billion** people used bridges since opening
- **Resilience** from 2 Bridge Strategy

For the Economy

- **£1 Million** a day contributed to the Scottish Economy
- **Over £10 Billion** since opening

A Critical Piece of National Infrastructure

A Large and Complex Group of Assets



Scale & Complexity

- 30,000+ elements to look after and keep track of
- Many elements highly complex and critical
- Queensferry Crossing - new
- Forth Road Bridge - ageing & hard working

Functions

- Inspect
- Monitor
- Report
- Respond
- Repair
- Assess
- Enhance
- Renew

Bridges

- Open
- Safe
- Resilient
- Long Service Life

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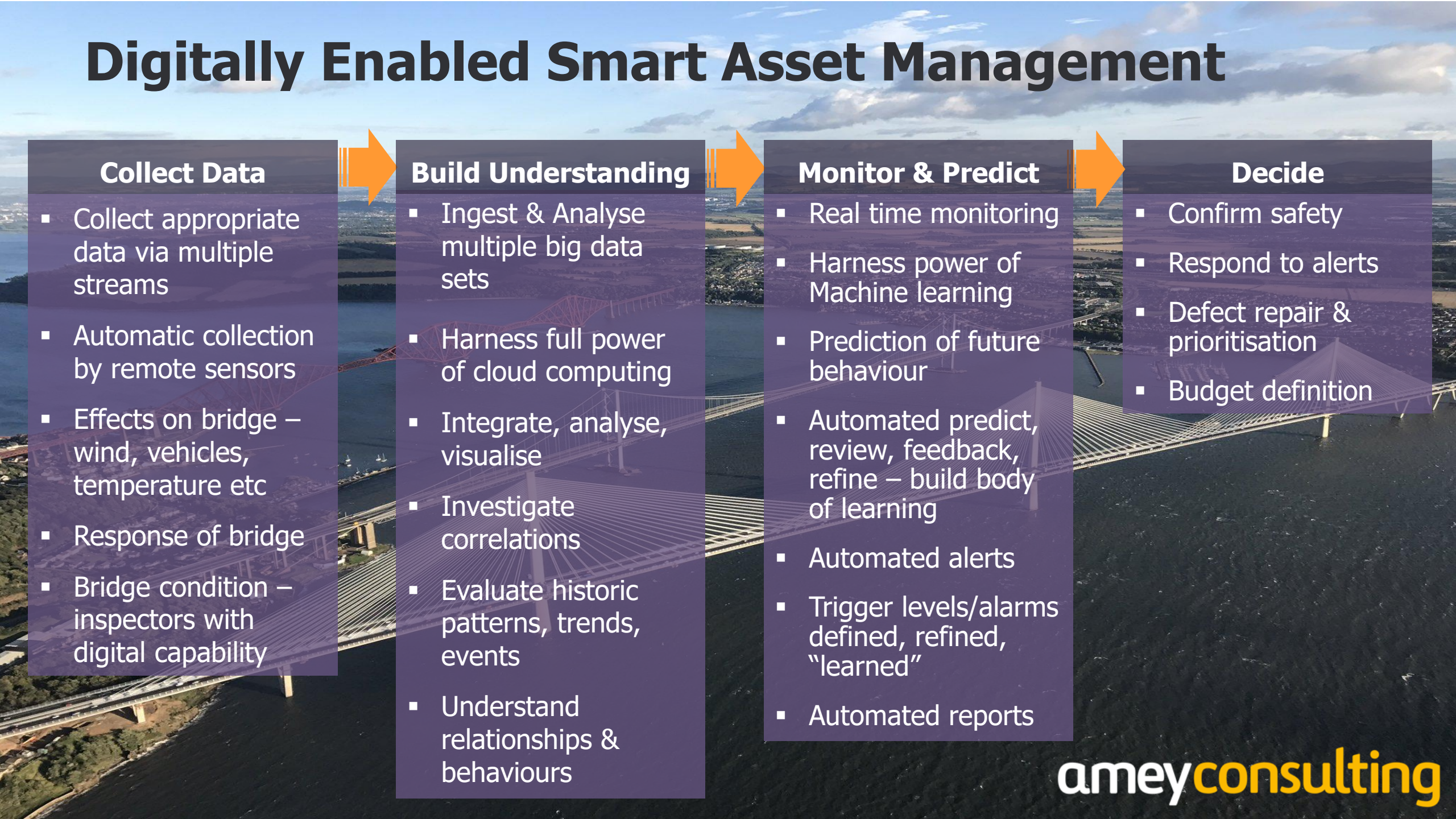
We don’t want this happening


XXX
And we need to ensure this can never happen here!

The Solution

Digitally Enabled
Smart Asset Management

Digitally Enabled Smart Asset Management



Collect Data

- Collect appropriate data via multiple streams
- Automatic collection by remote sensors
- Effects on bridge – wind, vehicles, temperature etc
- Response of bridge
- Bridge condition – inspectors with digital capability

Build Understanding

- Ingest & Analyse multiple big data sets
- Harness full power of cloud computing
- Integrate, analyse, visualise
- Investigate correlations
- Evaluate historic patterns, trends, events
- Understand relationships & behaviours

Monitor & Predict

- Real time monitoring
- Harness power of Machine learning
- Prediction of future behaviour
- Automated predict, review, feedback, refine – build body of learning
- Automated alerts
- Trigger levels/alarms defined, refined, "learned"
- Automated reports

Decide

- Confirm safety
- Respond to alerts
- Defect repair & prioritisation
- Budget definition

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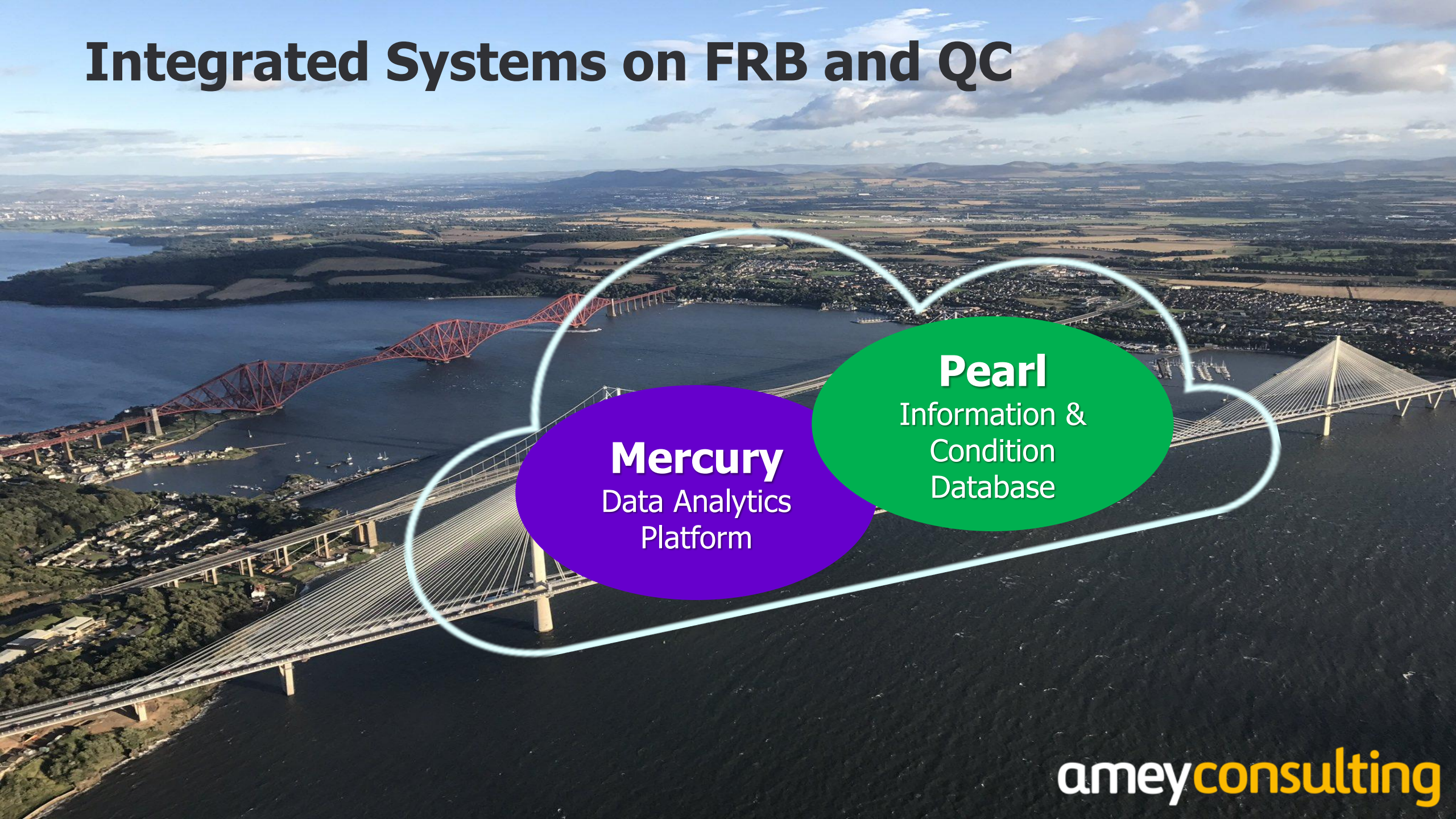
Implementation

In-House Bespoke Integrated Systems

Integrated Systems on FRB and QC



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Integrated Systems on FRB and QC

- SHM IoT sensor data
- Condition data
- Structural effects & capacities

Data Analytics Platform – "Mercury"

- Cloud based SENSOR AGNOSTIC analytics platform which ingests and compiles remote sensor and maintenance record DATA from MULTIPLE SOURCES
- Uses machine learning algorithms to understand bridge behavior and actively monitors and reports on sensor and condition data
- Interprets data to provide rich custom visualisations of bridge behavior, intelligent alerts and lifecycle records
- Intelligent alarms are specified (or even "learnt" from the data) to send SMS and email alerts, or notifications to other systems
- Other data sources, such as analysis and modelling outputs can be included to provide a rich, integrated picture of the bridge

- Automated monitoring & reporting
- On demand analytics & visualisation
- Intelligent alerts

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Integrated Systems on FRB and QC

- Historic records
- Project records
- Live entry of inspection data from Mobile App

Bridge Information & Condition Database – "Pearl"

- Cloud storage of all records and data relating to each of 30,000 elements. Batch upload of records based on Metadata
- Management of inspection programmes, Outlook calendar style scheduling
- Recording of type and severity of all identified element defects
- Automatic inspection report generation including online approvals
- Automated update of bridge condition indices from inspection findings
- Document management module for storage of archive files & project records
- Full description of the structure and key components, including maintenance/project history

- Automated inspection reporting
- Bridge condition reporting
- Maintenance budgeting

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SHM/Mercury System Overview

FRB and QC

Forth Road Bridges Smart System

WIND & TEMP

APPLIED LOADS

BRIDGE RESPONSE

Anemometers
Temperature Sensors

Weigh-in-motion (traffic)

Strain Gauges
Displacement Transducers
GPS Sensors
Accelerometers

MERCURY DATA ANALYTICS PLATFORM

MONITORING DATA

BRIDGE COMPONENTS

COMPONENT RESISTANCE

DATA STORAGE

DATA PROCESSING

CORRELATION OF PROCESSED DATA

TRIGGER LEVELS AND ALARMS

MACHINE LEARNING ALGORITHMS

DATA ANALYTICS

BRIDGE INFORMATION

Bridge components
Structural capacities
Baseline conditions

WEB BROWSER

Bridge Operations
Realtime data monitoring
Trigger levels and alarms

AUTOMATIC USER ALERTS & ACTIONS EMAIL & SMS

AUTOMATICALLY GENERATED REPORTS & USER REQUESTED REPORTS

Traffic Loading
Movements
Component stress
Bridge Geometry
Wind
Temperature

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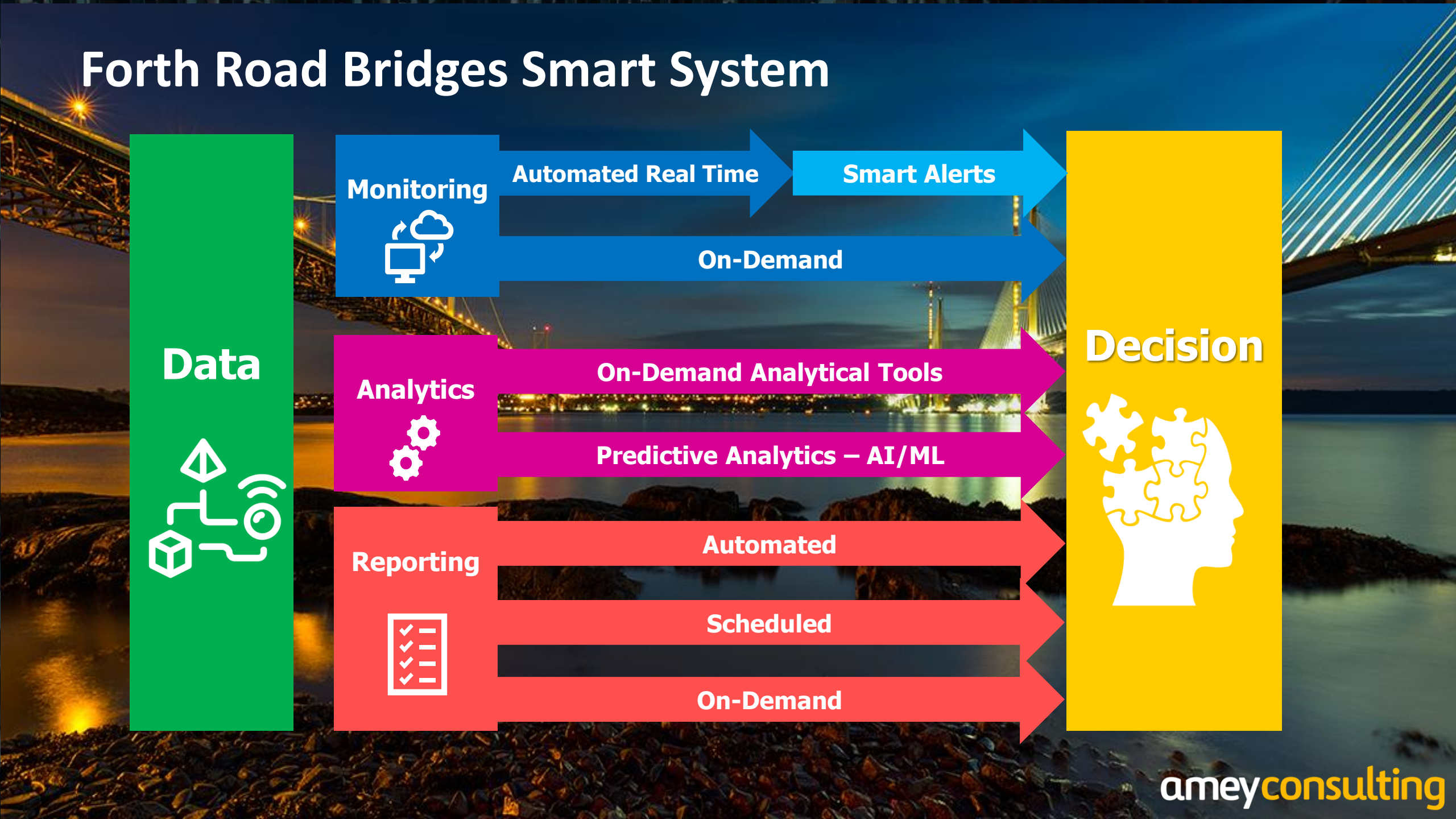
Forth Road Bridges Smart System



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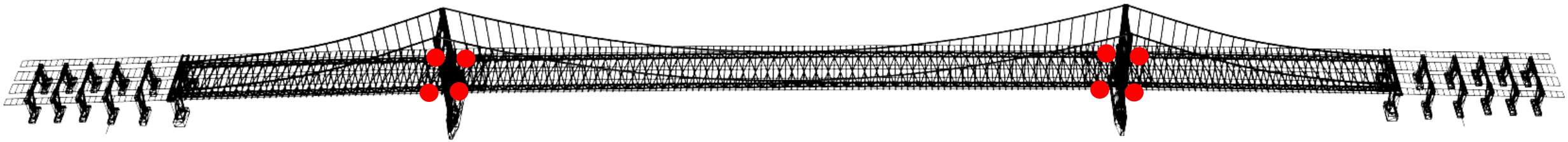
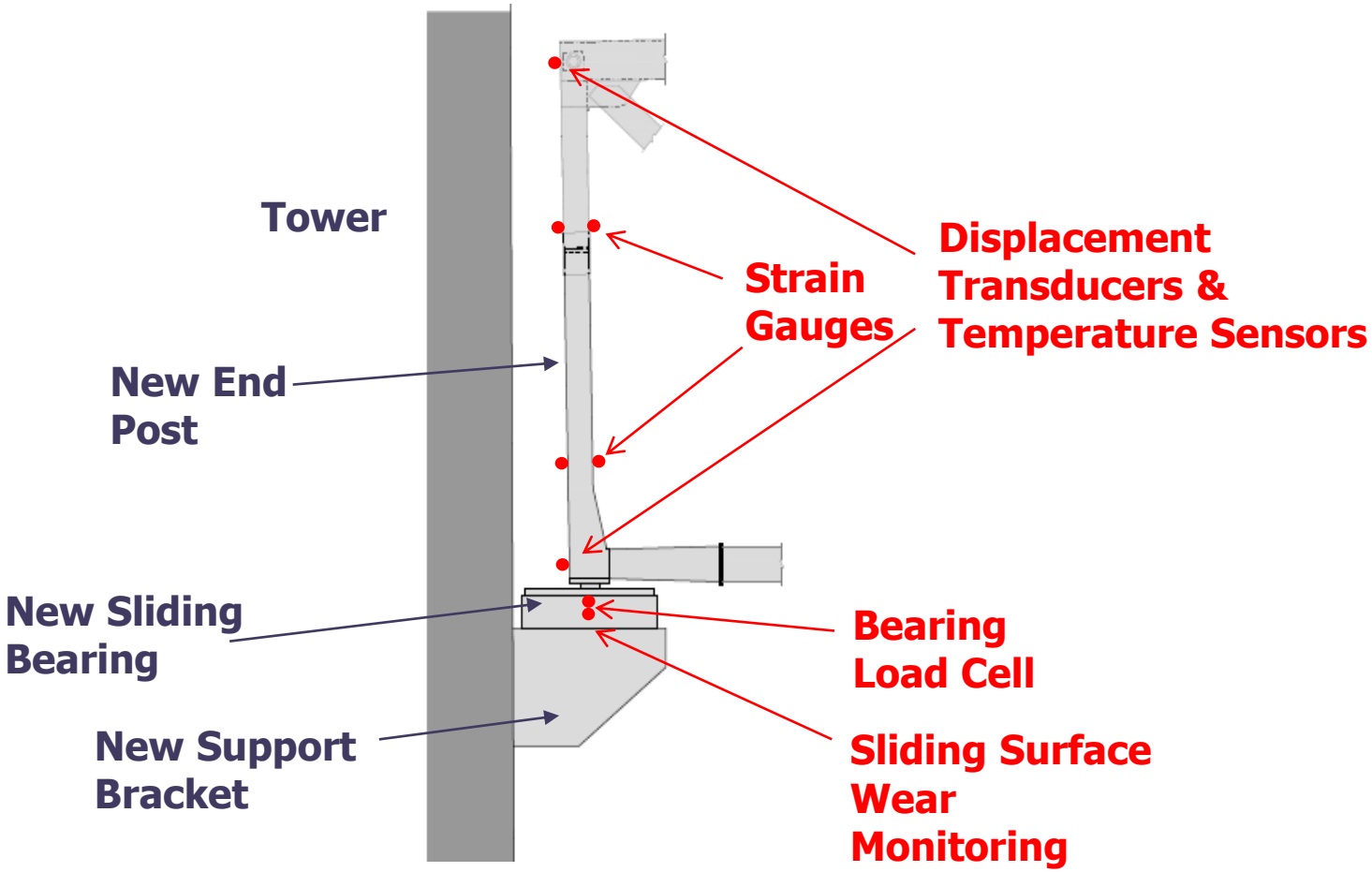
IoT Sensor Arrangements

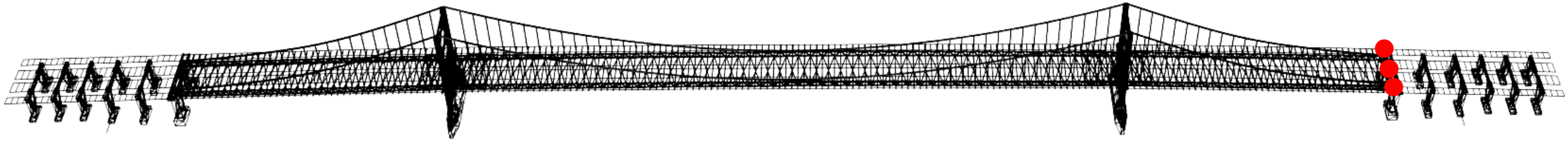
Forth Road Bridge SHM – Arrangement at New Truss Ends

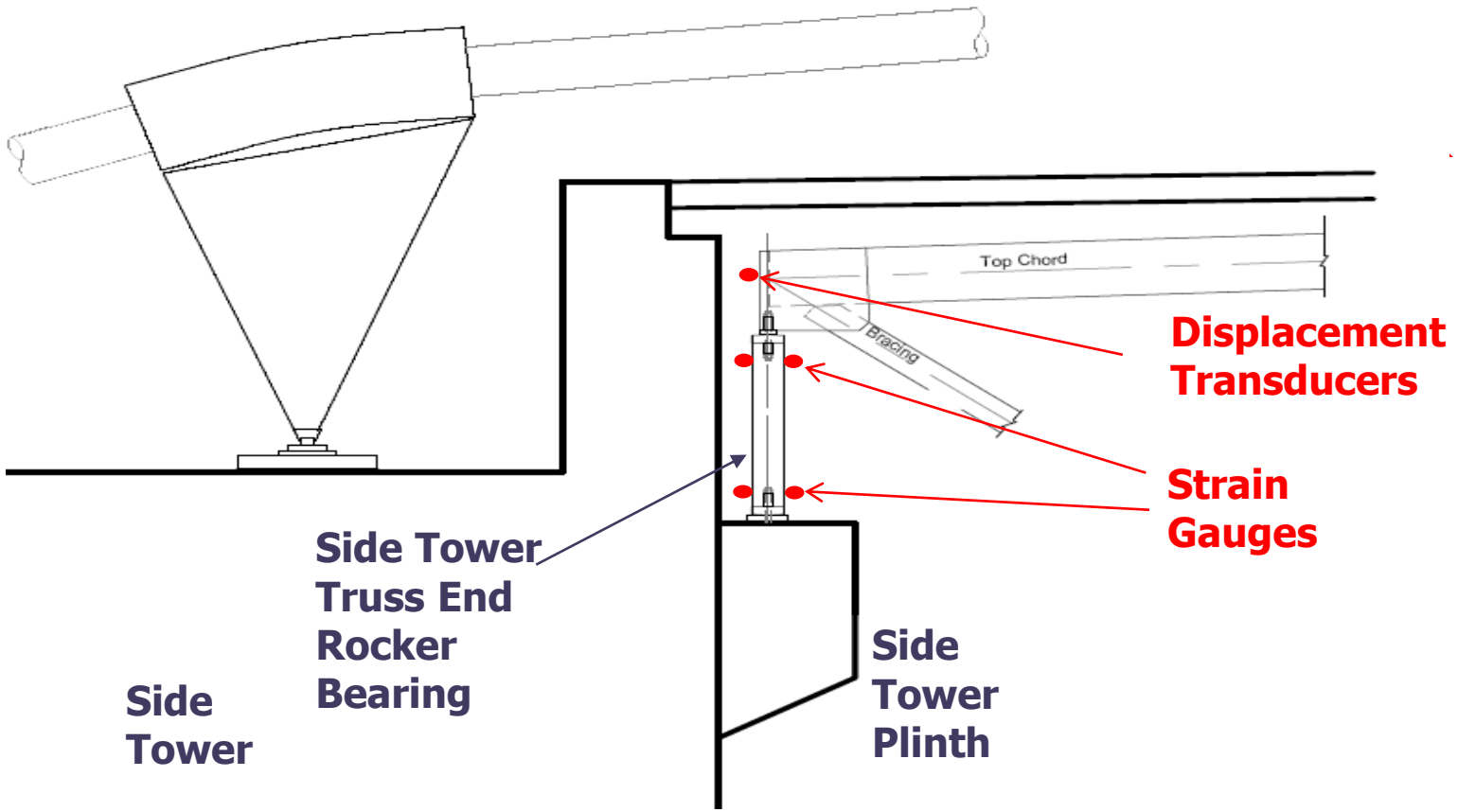


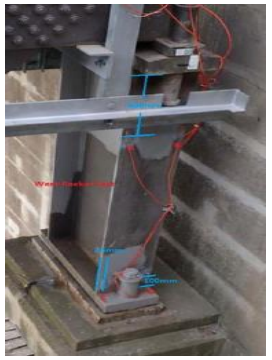


- End post stress
- Bearing load
- Bearing wear
- Truss end movement

Forth Road Bridge SHM – Arrangement at Side Towers

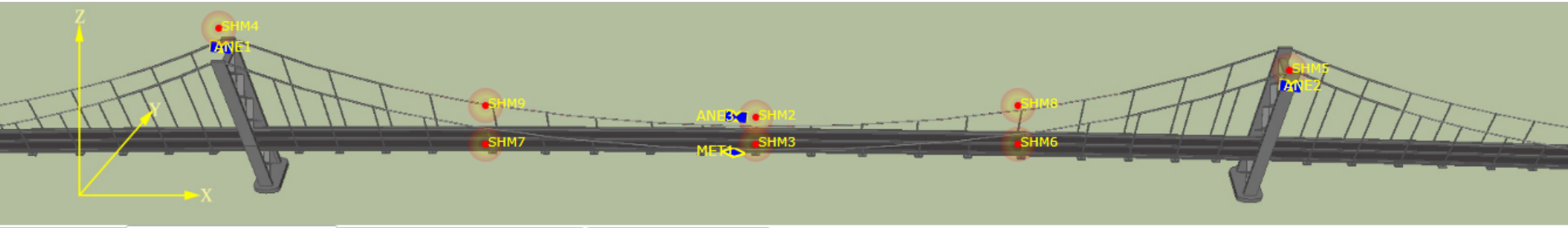






- Rocker rotation
- Rocker stress
- Truss end movement
- Stress in Laterals

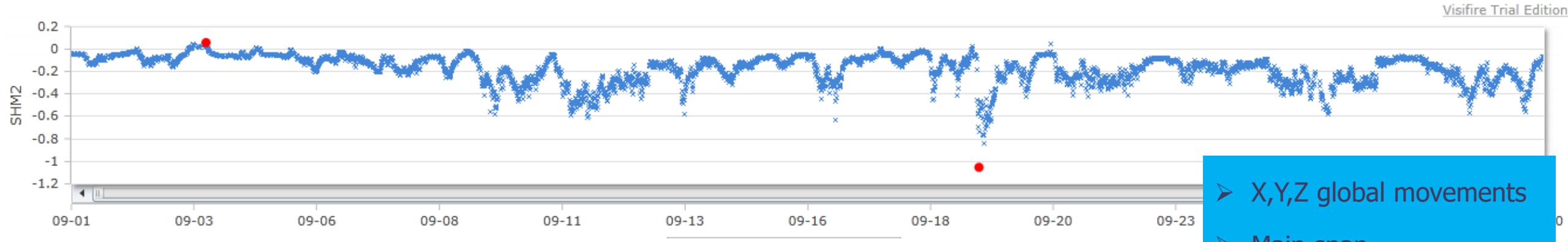
FRB Road Bridge SHM – GPS Displacements & Wind



RT Monitoring | Historical Data Query | Wind Loading-Responding | Real Time Warning

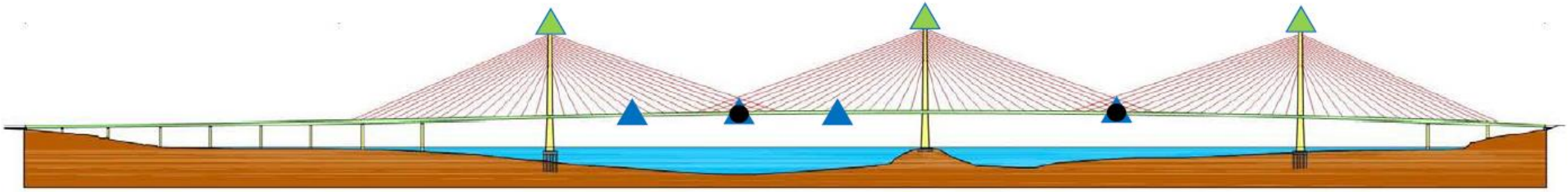
Sensors data transmitting is OK

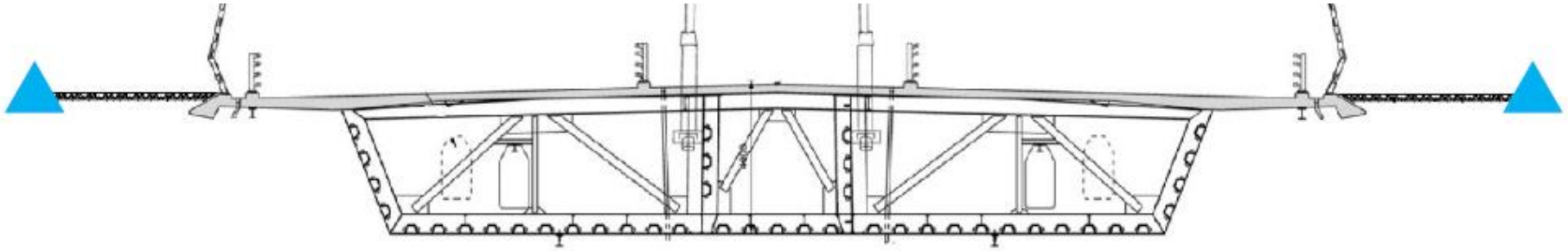
rom: 01/09/2018 To: 30/09/2018 Sensor: SHM2 Data Type: Y Data Type 2: Average Pick one Day Process



- X,Y,Z global movements
- Main span
- Tower tops
- Wind speed & direction

Queensferry Crossing SHM – Wind and Weather Sensors





Installation of Anemometer

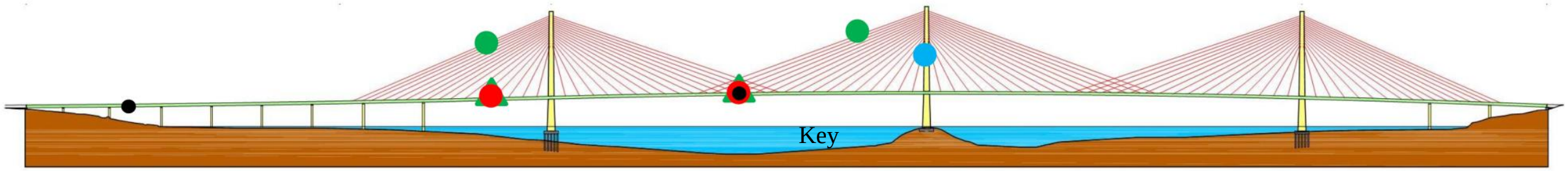
Barometer

Key

- Anemometers (1 no)
- Anemometers (2no)
- Rainfall gauge and barometer

- Integrity following storms.
- Wind buffeting & wind / structure interaction.
- High wind vehicle management
- Impact of climate change

Queensferry Crossing SHM – Temperature Sensors

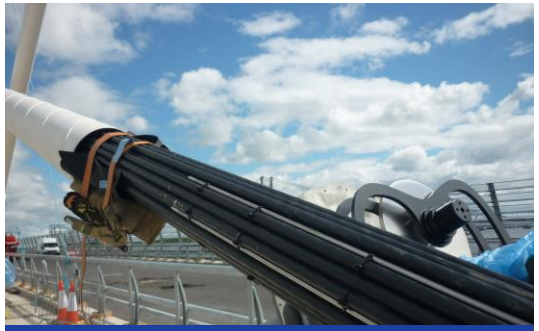


Asphalt TMU

Concrete TMUs

Deck section
Transverse Bracing
Towers (concrete and air temp/humidity)
Asphalt
Stay Cables

Steel TMUs

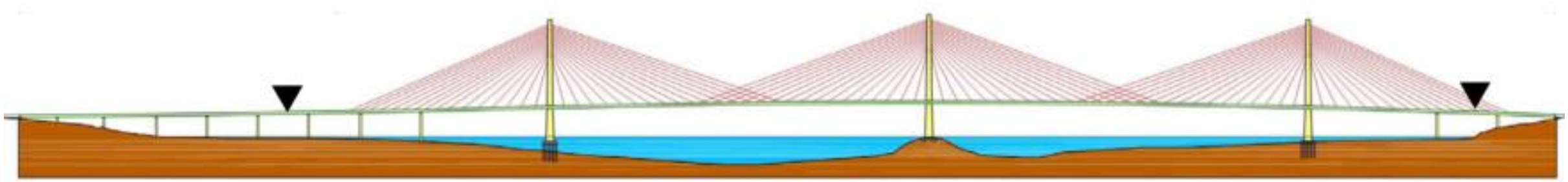


Stay Cable TMUs

External Air TMUs

- Bridge Articulation and Geometry.
- Temperature Compensation of Strains.
- Temperature Distribution and Induced Stresses.

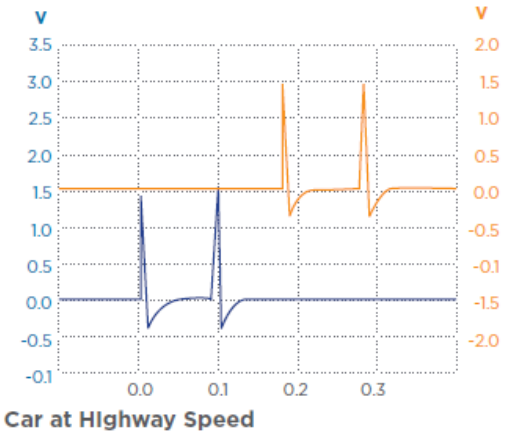
Queensferry Crossing SHM – Weigh in Motion



Installation of Piezoelectric Transducer Weigh-in-Motion System.

Key

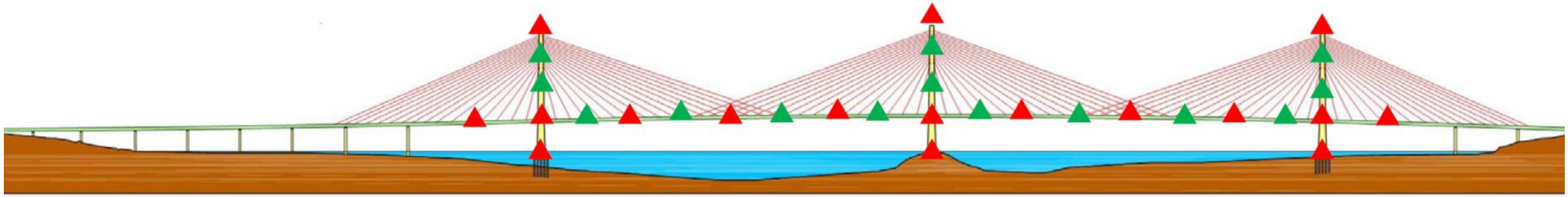
▼ Dynamic Weigh in Motion (Bending Plate)



Car at Highway Speed

- Traffic modelling and congestion.
- Trends in HGV loading.
- Two bridge managed strategy

Queensferry Crossing SHM – Accelerometers

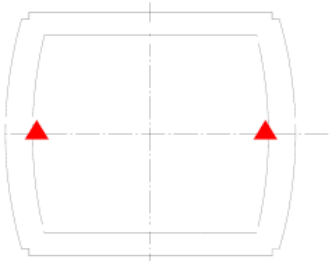


Accelerometer (Tower)

Housing (Tower)

Key

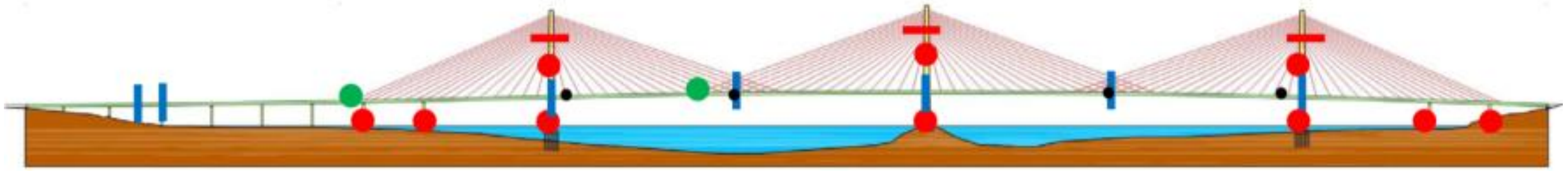
▲	Permanent accelerometer
▲	Accelerometer Housing (in addition each stay cable to fitted with an acceleration housing)

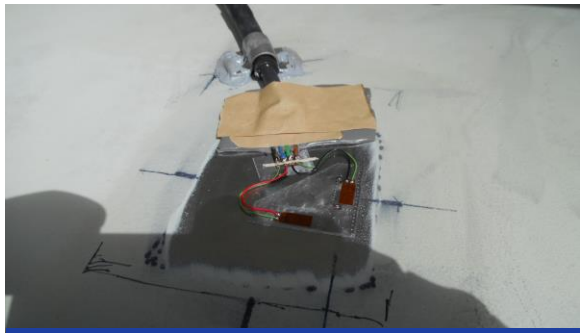


Accelerometer arrangement in towers

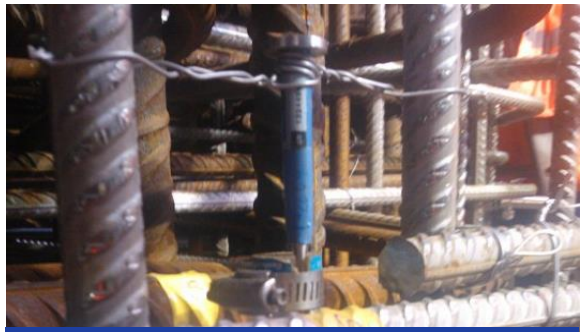
- Dynamic behaviour of deck, towers and cables.
- Ship impact.
- Changes in dynamic characteristics

Queensferry Crossing SHM – Strain Gauges





Dynamic Strain Gauge



Static Strain Gauge

Deck Section (bottom plate)

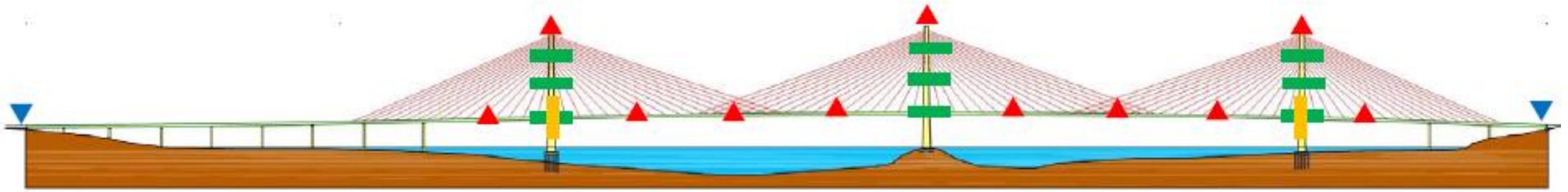
Key

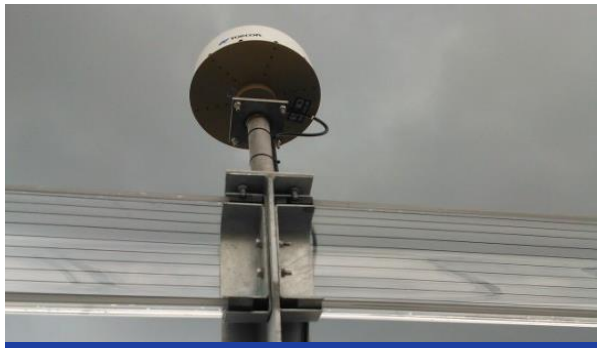
- Static strain gauges (tower)
- Dynamic strain gauges (tower anchorage)
- Strain gauges deck anchorages
- Deck section
- Transverse bracing

Internal Bracing

- Derivation of stresses and global effects (forces & bending moments).
- Correlation of extreme events with predicted design values.
- Calibration of fatigue models

Queensferry Crossing SHM – GPS & Displacement Sensors



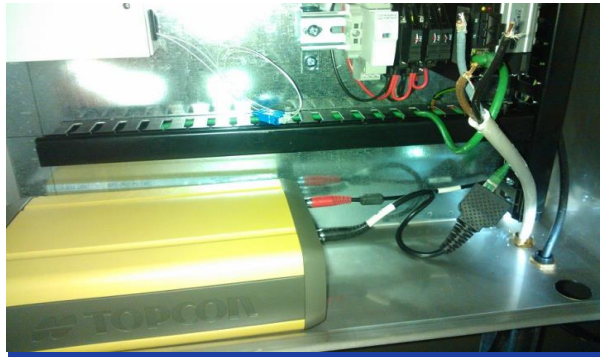


GPS Antenna

Antenna & Anti-Snow Dome

Key

- GPS receiver
- 2D Tiltmeter
- Bearing gauge
- Displacement transducer



GPS Data Acquisition Unit

Tiltmeter

Ultrasonic Displacement Sensor

- Bridge articulation.
- Bridge geometry and navigational clearances.
- Bridge response applied loads and extreme events.

Data Monitoring

Trigger Levels Alarms and Automation

FRB Data Analytics – Mercury – Entry Screen

mercury

Ewan Angus

Select a system to view:

FRB

QFC

FRB Data Analytics – Mercury – Entry Screen

mercury FRB Summary Locations Asset Types Assets Reports Analytics Ewan Angus

Home 3D

TRANSPORT SCOTLAND Forth Road Bridge

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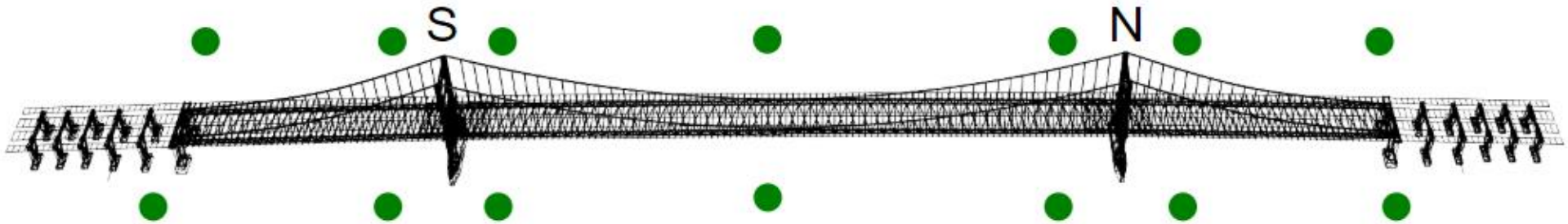
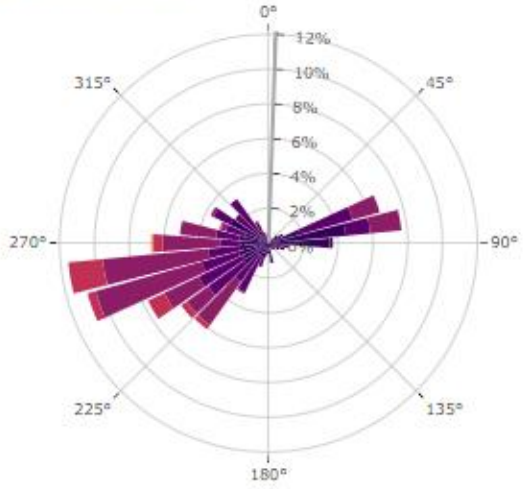
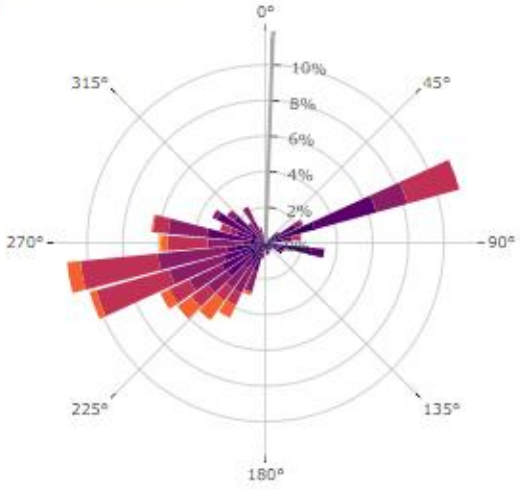


Wind Speed - last week



Wind Gusts - last week



Showing information for all locations

Alerts

Search

Location	Asset	Sensor	Triggered At	Message	Alert Level	Details	Actions
EXTERNAL	EXTERNAL North West	Vaisala Wind Gust Speed	08/03/2019 21:49	Threshold passed. Reading: 46.08 mph Threshold: 45.0 mph		Acknowledged by Ewan Angus on 10/03/2019 18:15	
EXTERNAL	EXTERNAL North West	Vaisala Wind Gust Speed	08/03/2019 20:19	Threshold passed. Reading: 52.34 mph Threshold: 50.0 mph		Acknowledged by Ewan Angus on 10/03/2019 18:15	
NEST	Eastern Rocker	virt_ERL_stress_3478_7	08/03/2019 20:08	Threshold passed. Reading: 177.74 N/mm² Threshold: 150.0 N/mm²		Acknowledged by Ewan Angus on 10/03/2019 18:15	

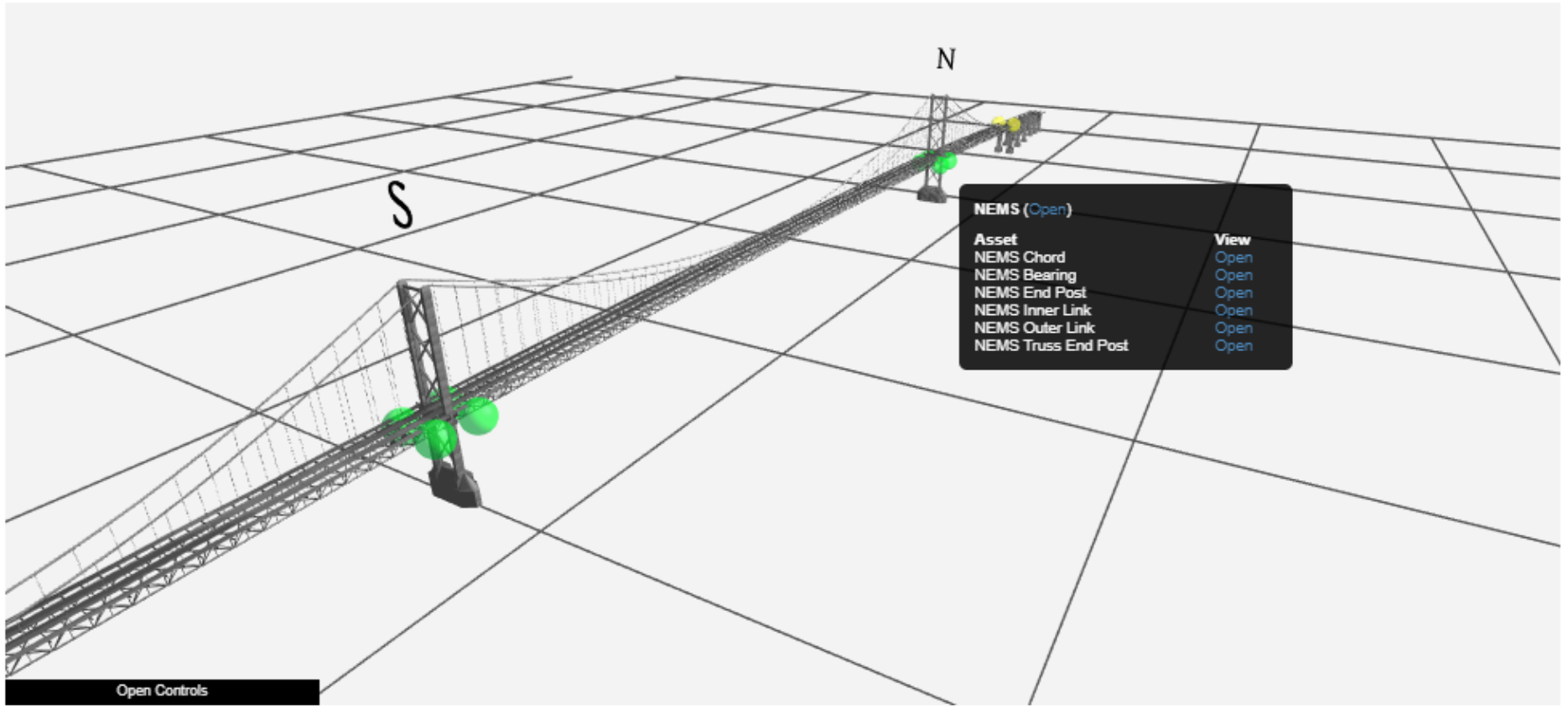
Showing 1 to 3 of 3 rows

FRB Data Analytics – Mercury – 3D Entry Screen Option

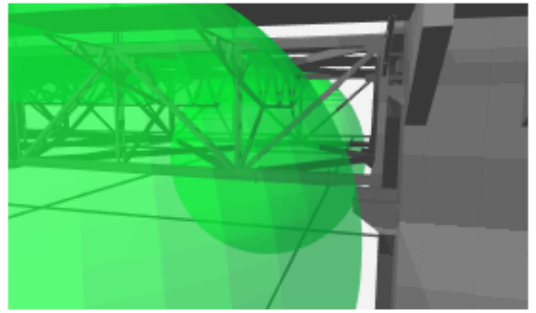
mercury | FRB | Locations | Asset Types | Assets | Reports | Analytics | Ewan Angus

Home | 3D

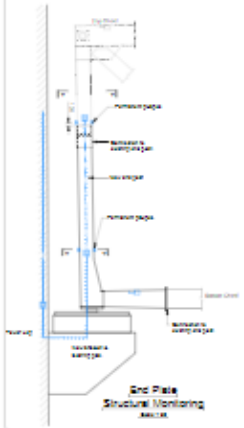
Main view



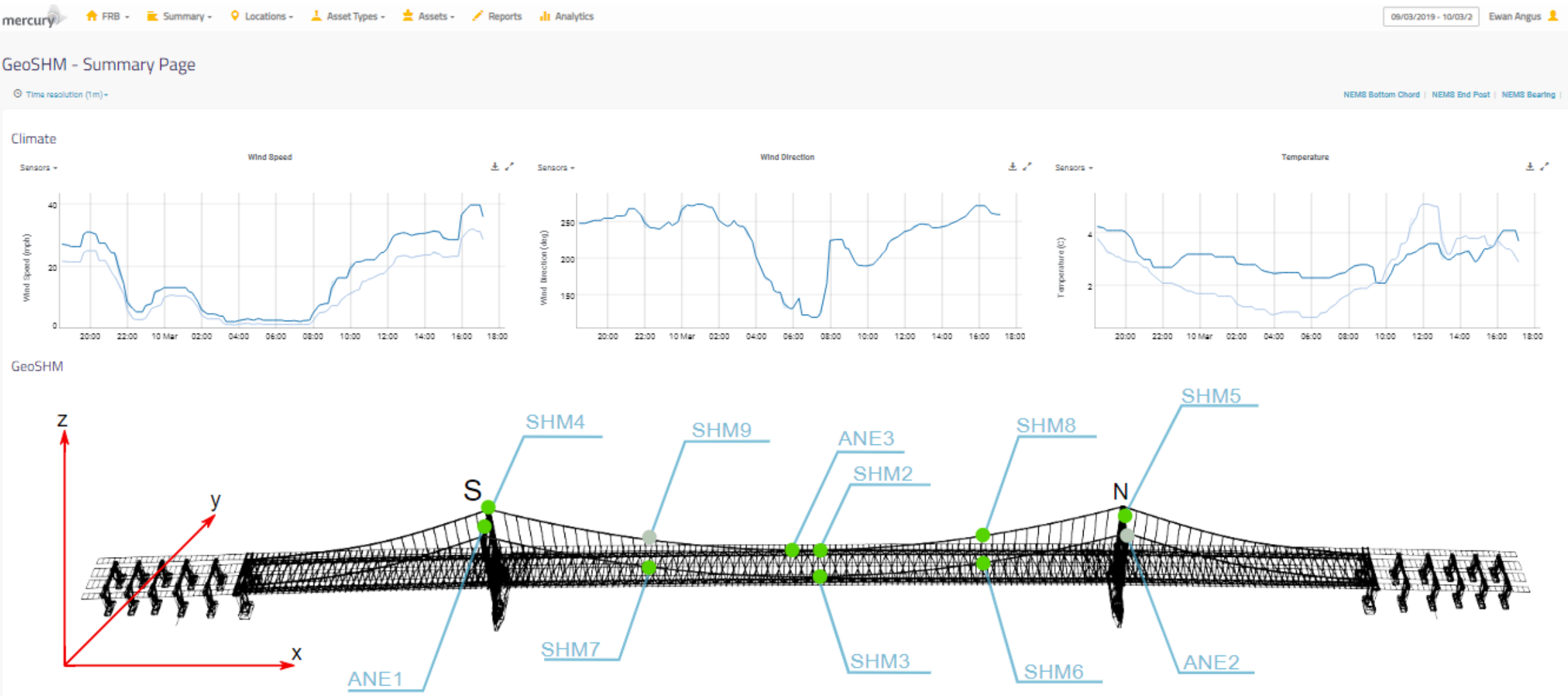
Zoomed view



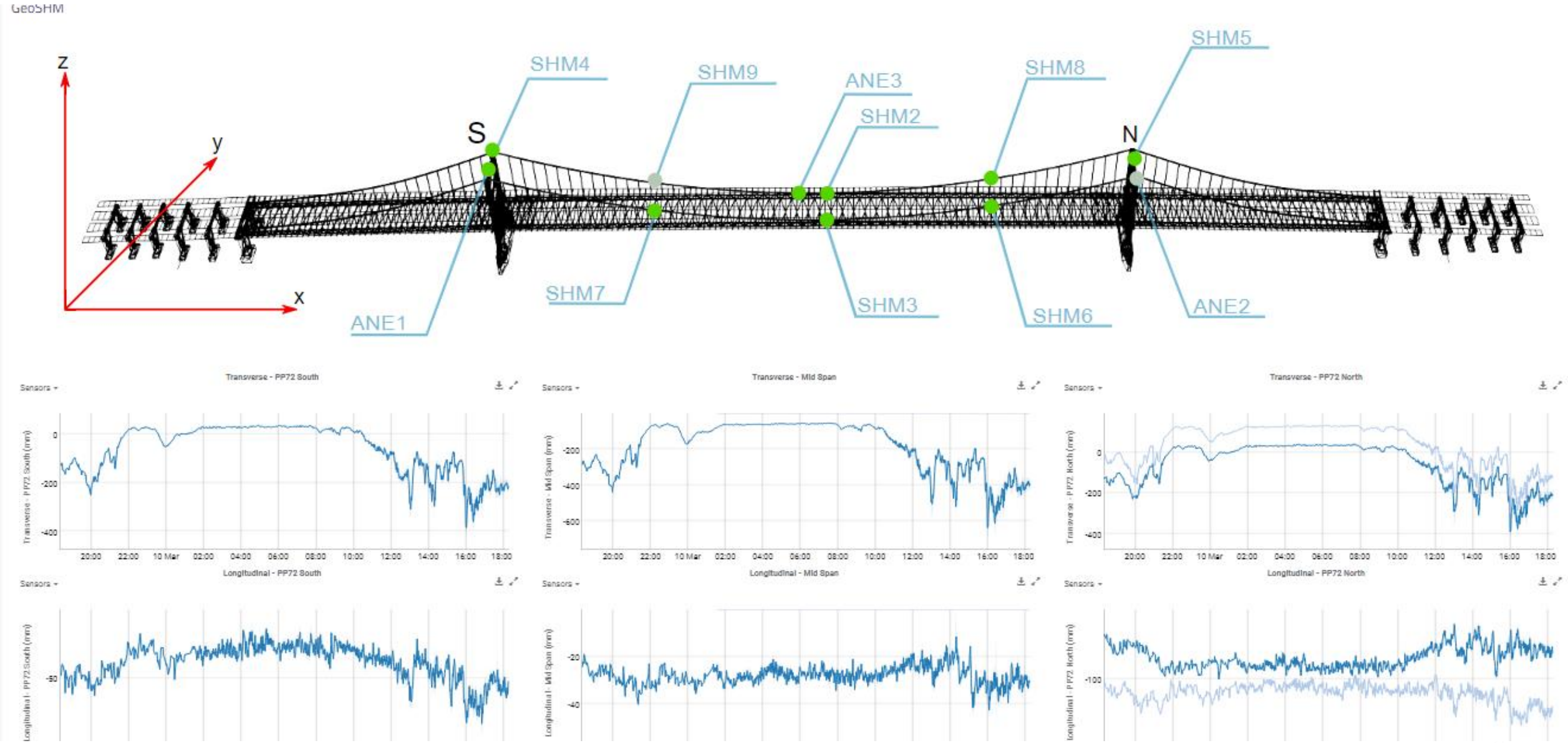
Diagrams



FRB Data Analytics – Mercury – Data Monitoring



FRB Data Analytics – Mercury – Data Monitoring



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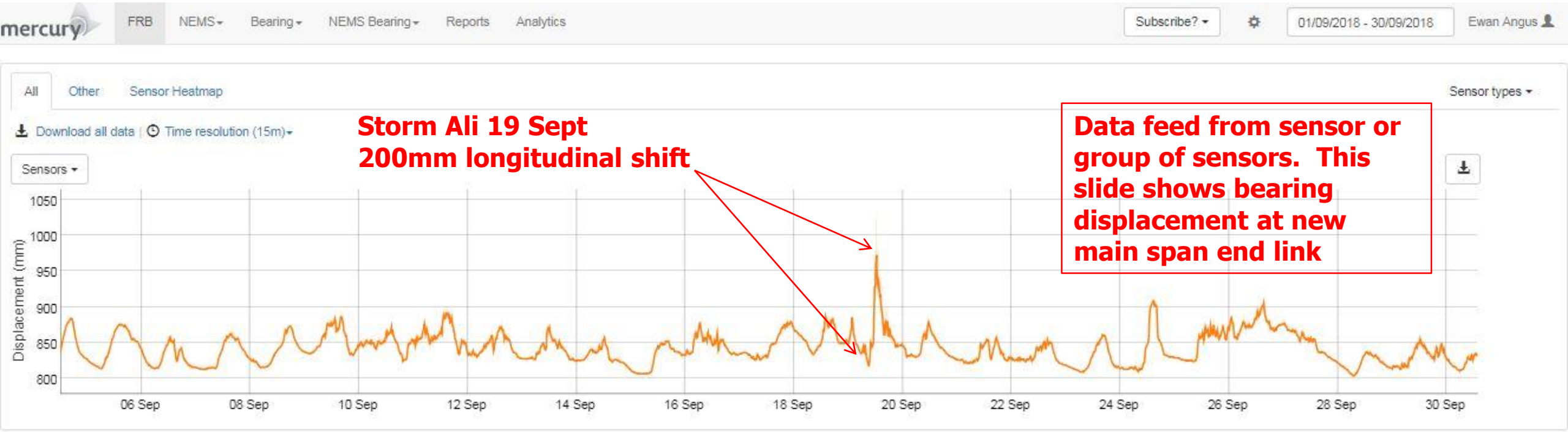
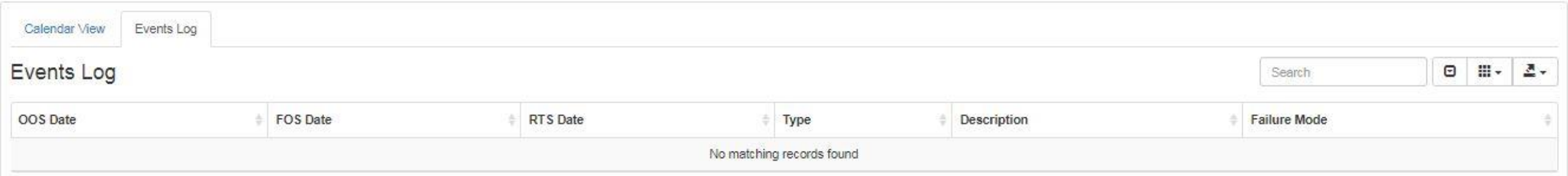
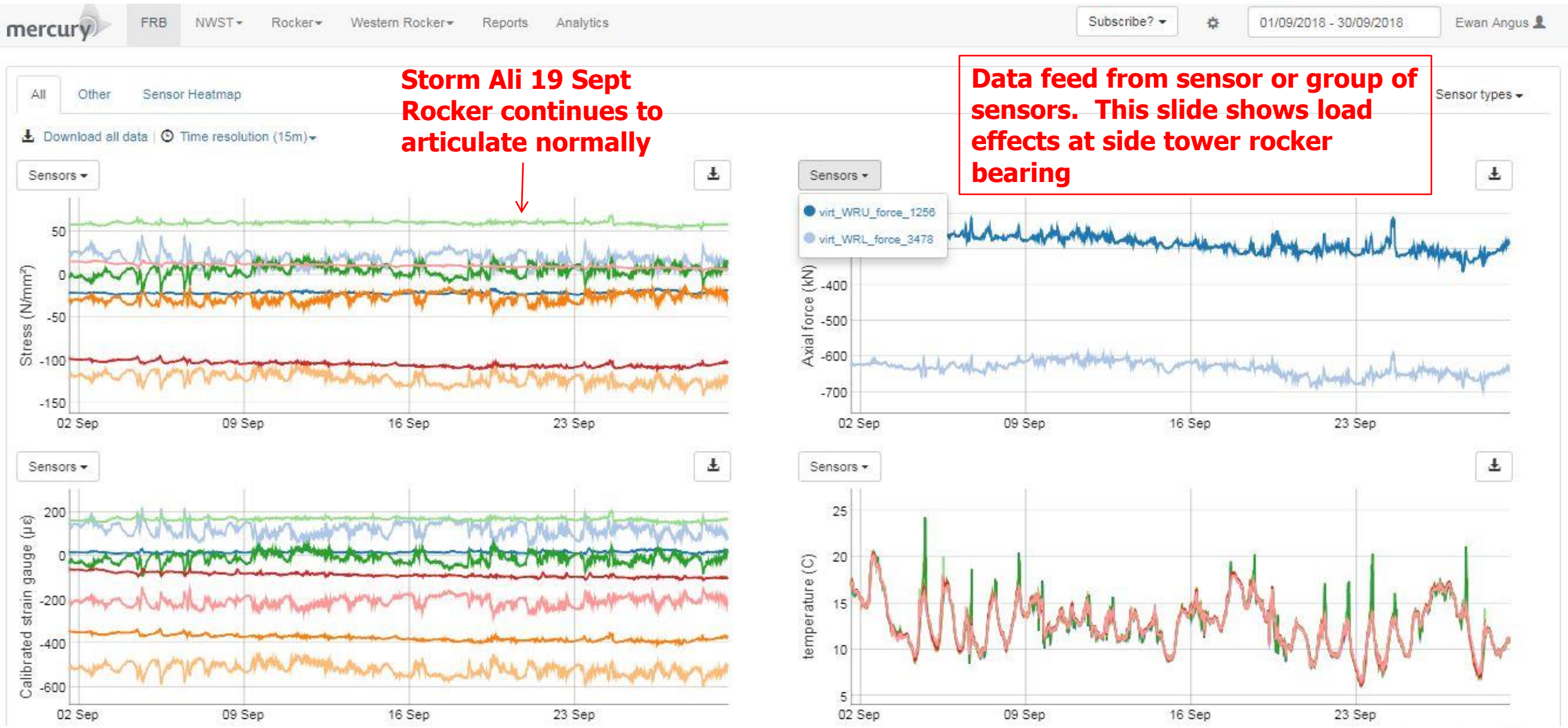


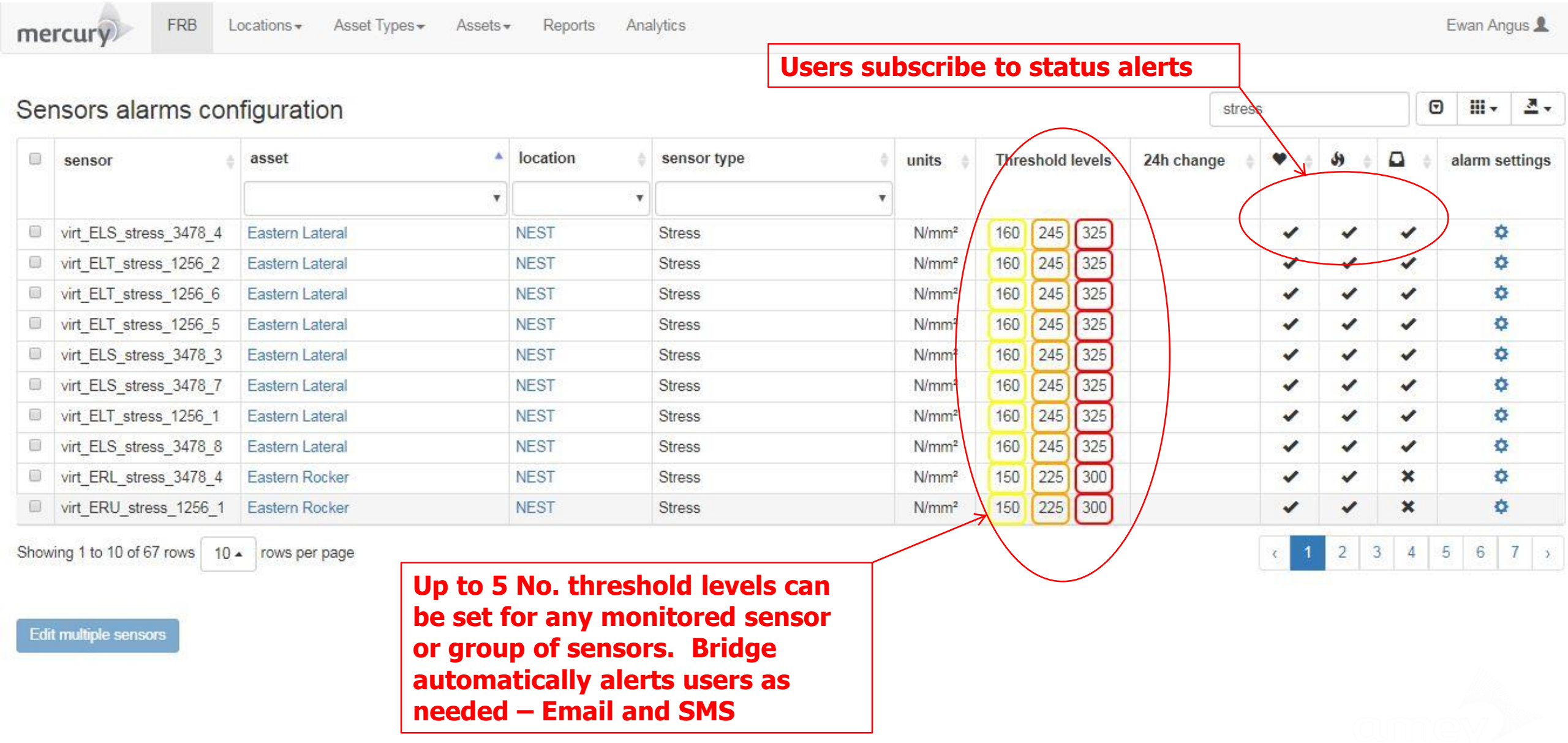


FRB Data Analytics – Mercury – Data Monitoring

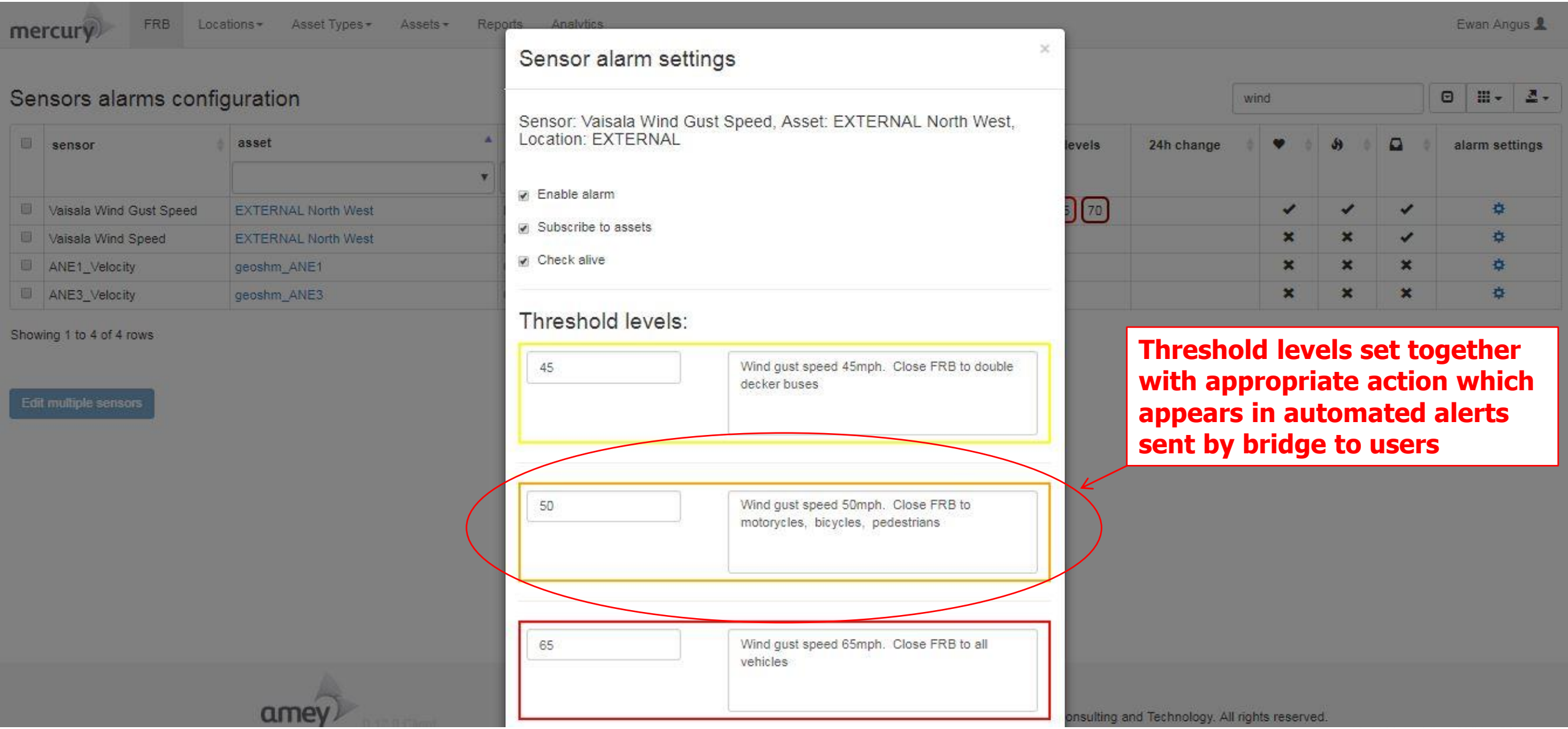
FRB Data Analytics – Mercury – Data Monitoring



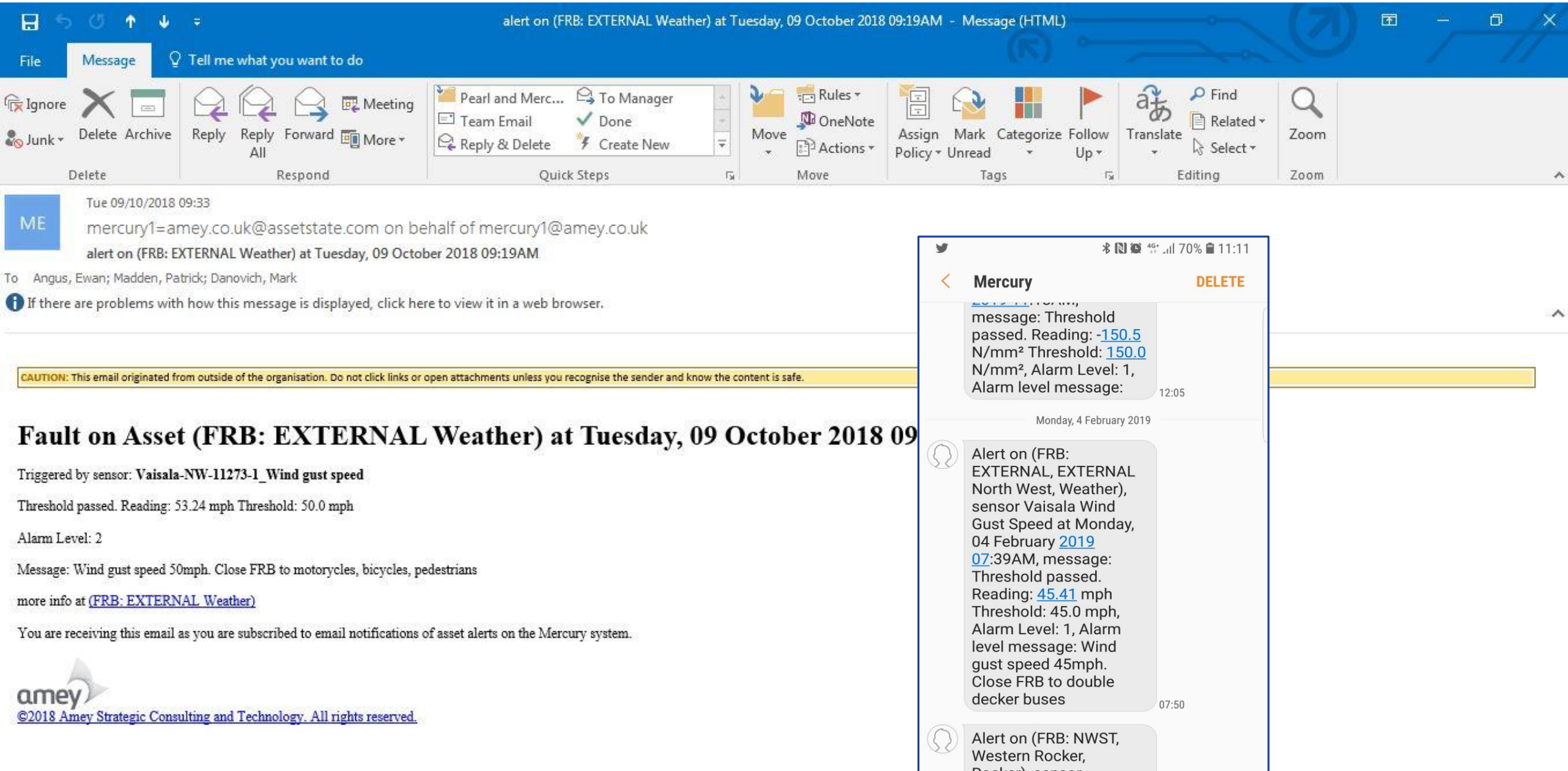
FRB Data Monitoring – Mercury – Setting Smart Alarm Levels



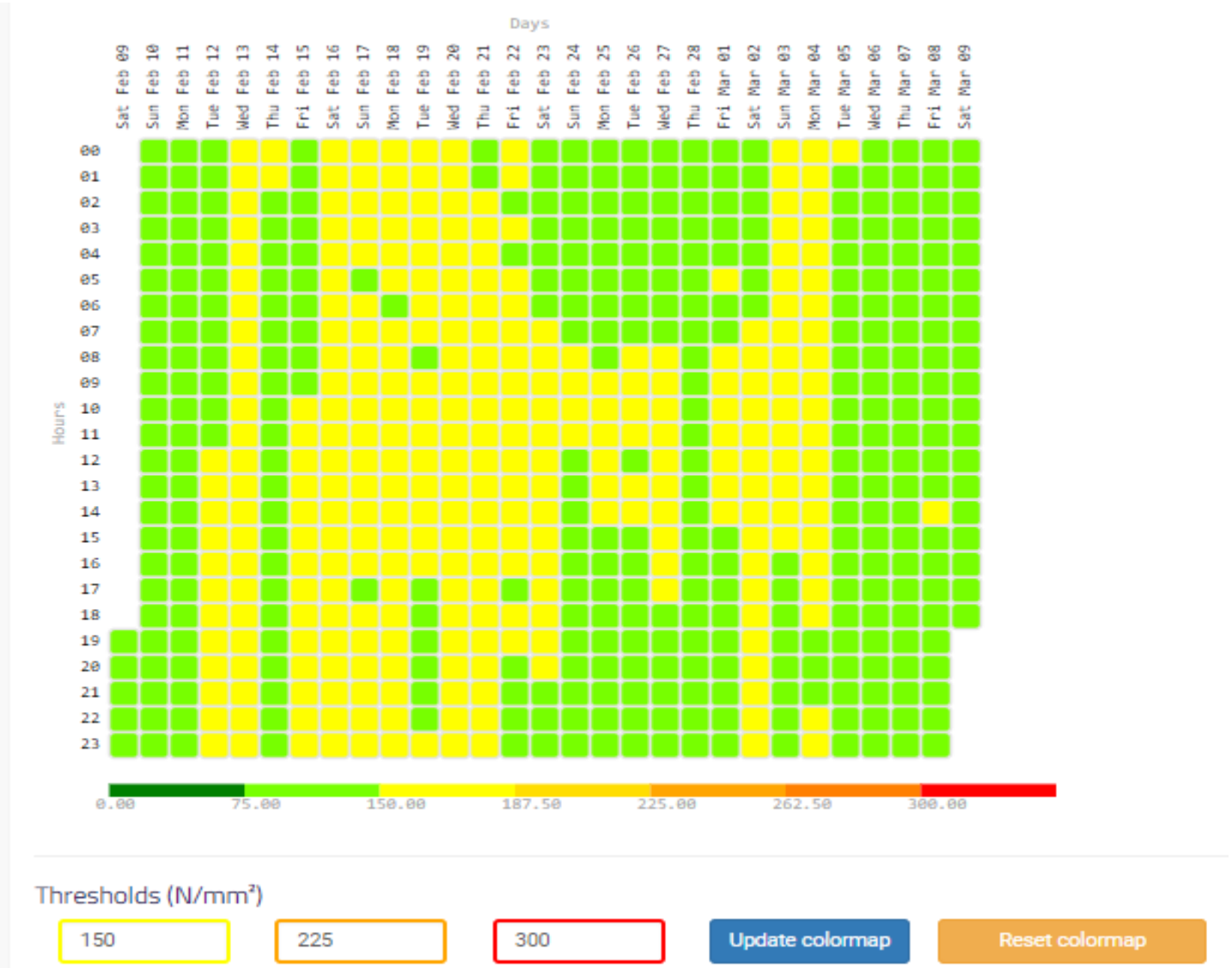
FRB Data Monitoring – Alarm Level Messages & Actions



FRB Data Monitoring – Email & SMS Alarms and Alerts



FRB Data Monitoring – Sensor Heatmaps



Thresholds (N/mm²)

150 225 300 Update colormap Reset colormap

Sensor Heatmaps used to visualise recorded value compared to threshold values each hour of each day of user selected period.

Analytical Tools

Data Visualisation to enhance understanding and provide perspective and insight

FRB Data Analytics – Correlation of Data Sets

mercury | FRB | Locations | Asset Types | Assets | Reports | Analytics

Correlation analysis | Histogram analysis | Time series analysis

Time range

January 1, 2018 - October 23, 2018

Asset I - X

EXTERNAL North West

Sensor I - Types

Temperature

Sensor I - X

Vaisala Air Temperature

Asset II - Y

Western Rocker

Sensor II - Types

Stress

Sensor II - Y

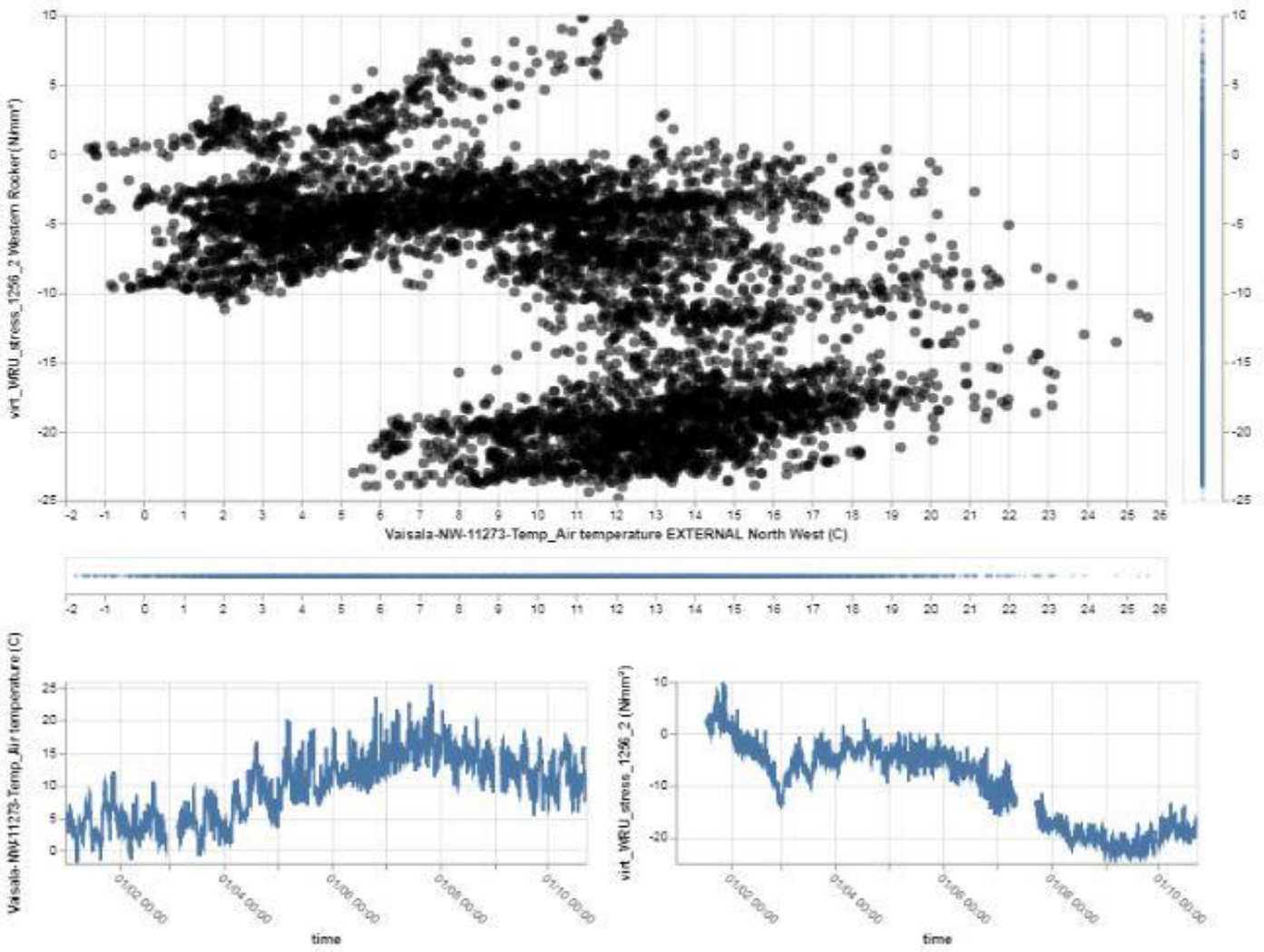
virt_WRU_stress_1256_2

Time resolution

Automatic

Correlate

Any 2 data sets any time period showing correlation of points to give insight into behaviour. This case shows no linear relationship between temperature and rocker bearing stress – thus confirming rocker articulating properly



FRB Data Analytics – Histogram of Sensor Data

mercury | FRB | Locations | Asset Types | Assets | Reports | Analytics | Ewan Angus

Correlation analysis | Histogram analysis | Time series analysis

Time range

October 1, 2017 - October 23, 2018

Asset

EXTERNAL North West

Sensor - Types

Temperature

Sensor

Vaisala Air Temperature

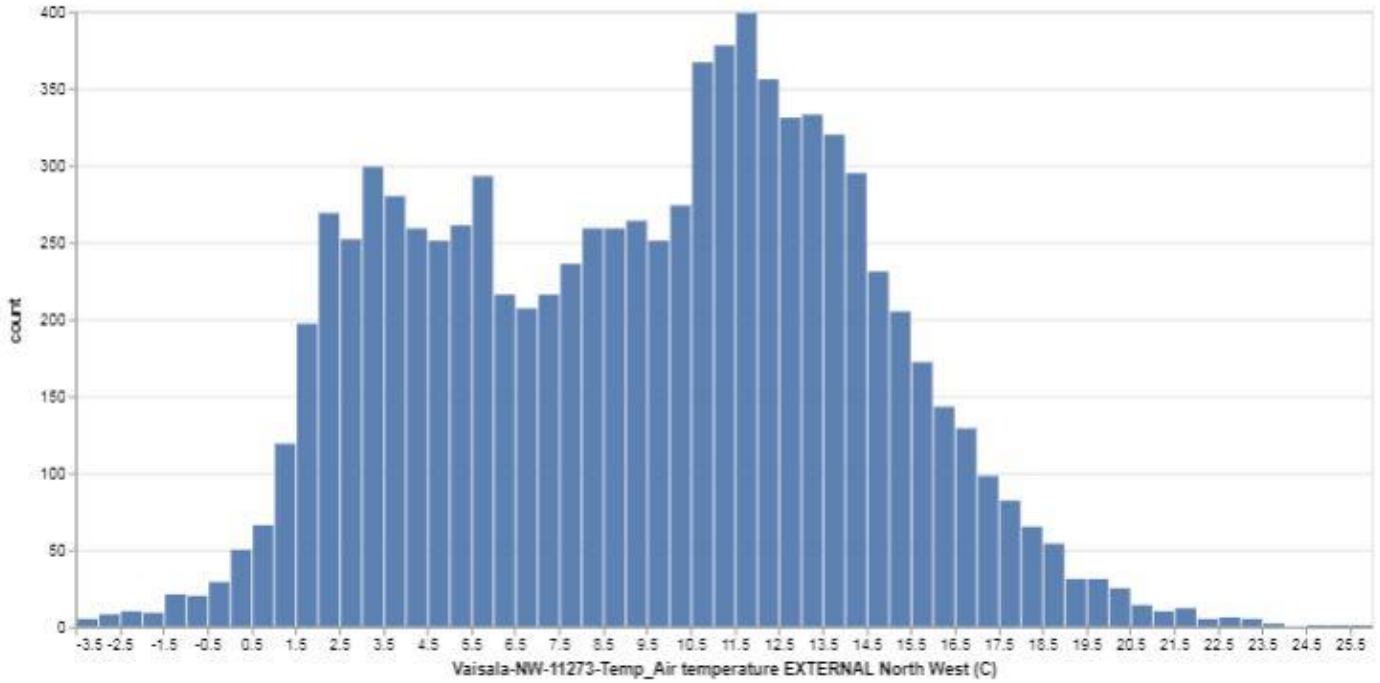
Time resolution

Automatic

Max number of bins

100

Histogram



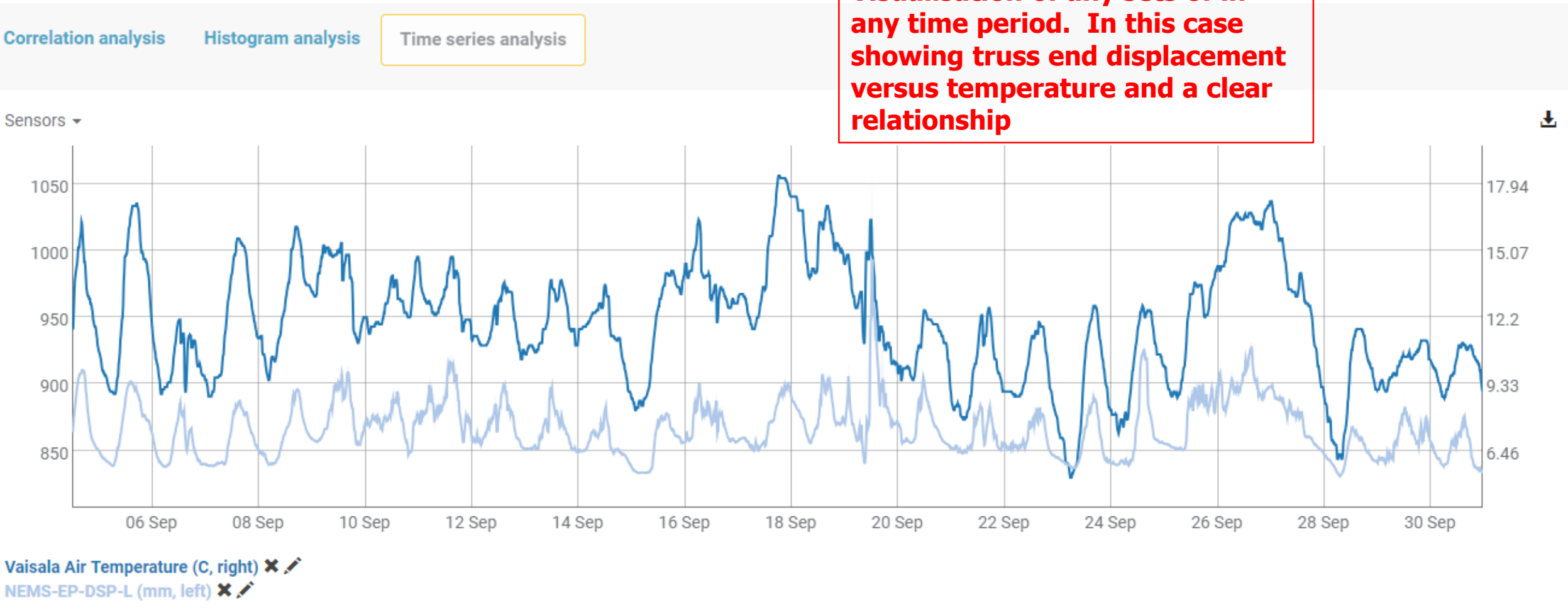
Save as SVG Save as PNG

	total	mean	std	min	25% quantile	median	75% quantile	max
Vaisala-NW-11273-Temp_Air temperature	8982.00	9.33	4.89	-3.28	5.20	9.75	13.03	25.53

Histogram of any single sensor over any period showing distribution of values, mean, max etc

FRB Data Analytics – Time Series Data Set Analysis

Visualisation of any sets of in any time period. In this case showing truss end displacement versus temperature and a clear relationship

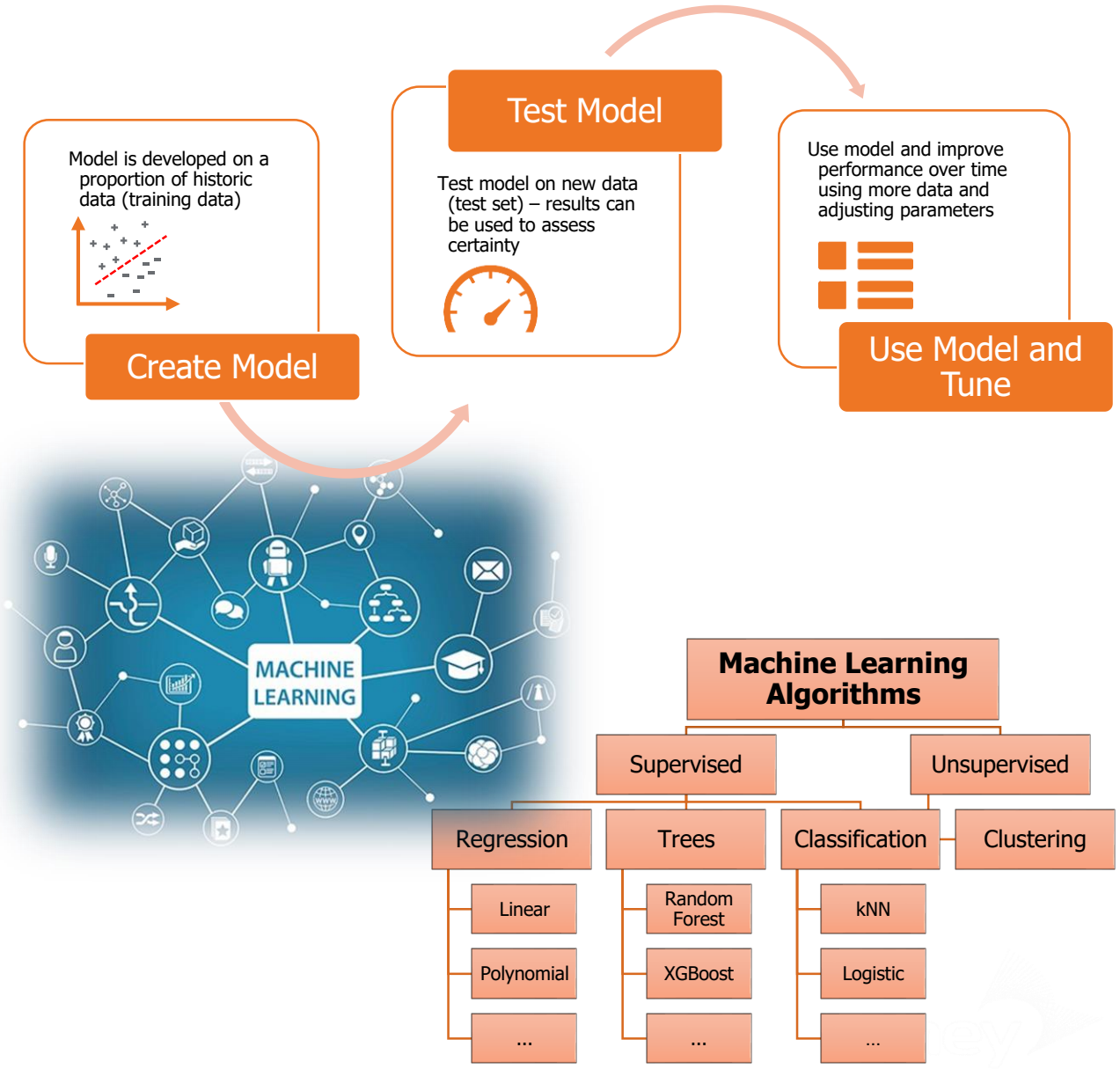


Machine Learning

Predicting near future values and the learning cycle

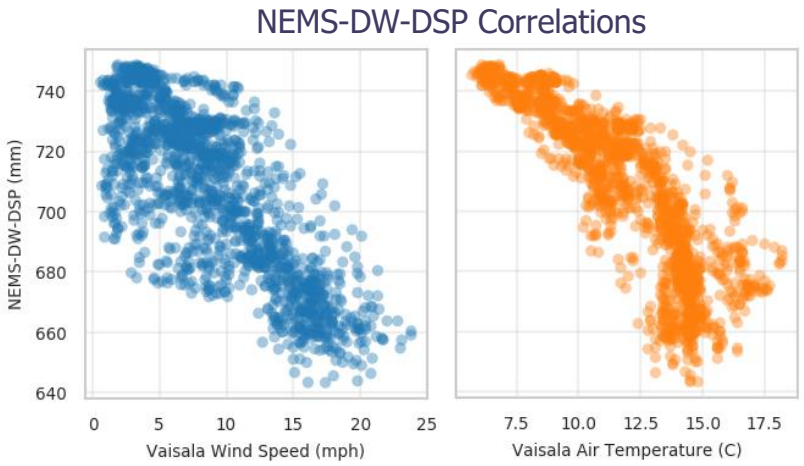
FRB Data Analytics – Machine Learning

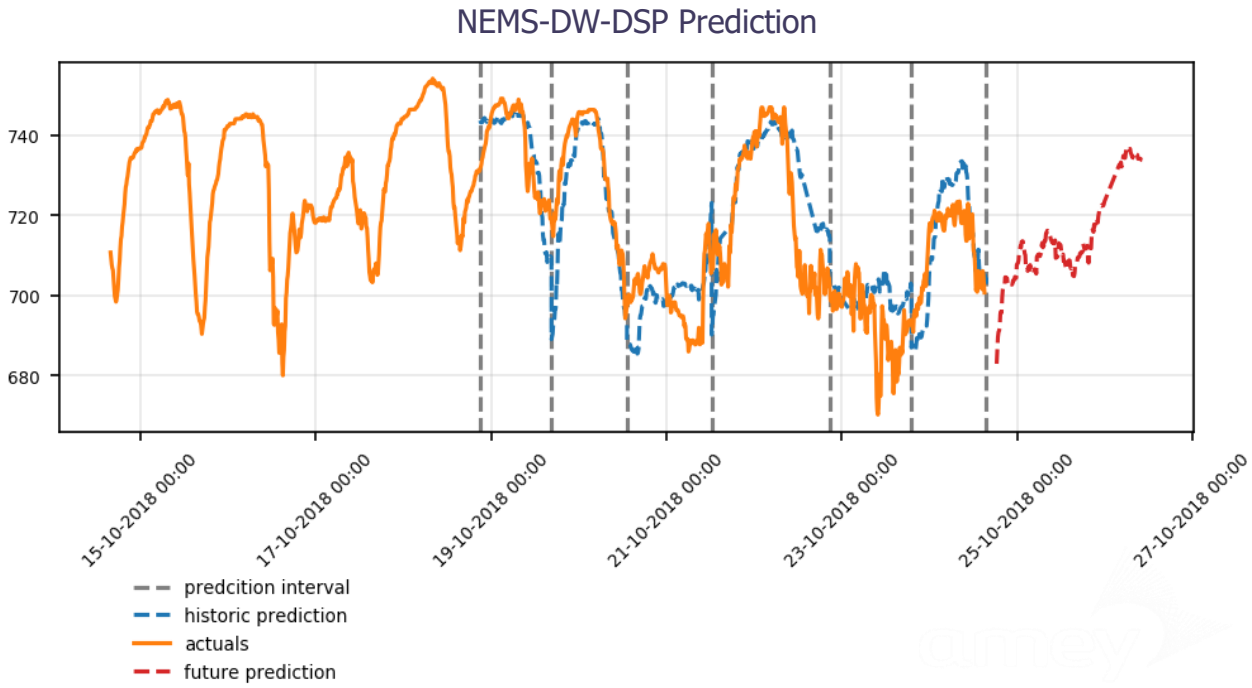
- Machine Learning includes a broad set of algorithms which infer unknowns from knowns without being explicitly programmed to do so
- Useful when relationships and correlations are hidden in large quantities of multidimensional data and the required knowledge is large
- Deployed at FRB (then QC) to predict near future bridge behaviour and identify anomalies in advance
- Useful in “What-if” scenarios for differing loading or events such as storms
- Body of “Learning” constantly increases as data/learning cycle continues – even suggesting refined alert levels



FRB Data Analytics – Machine Learning

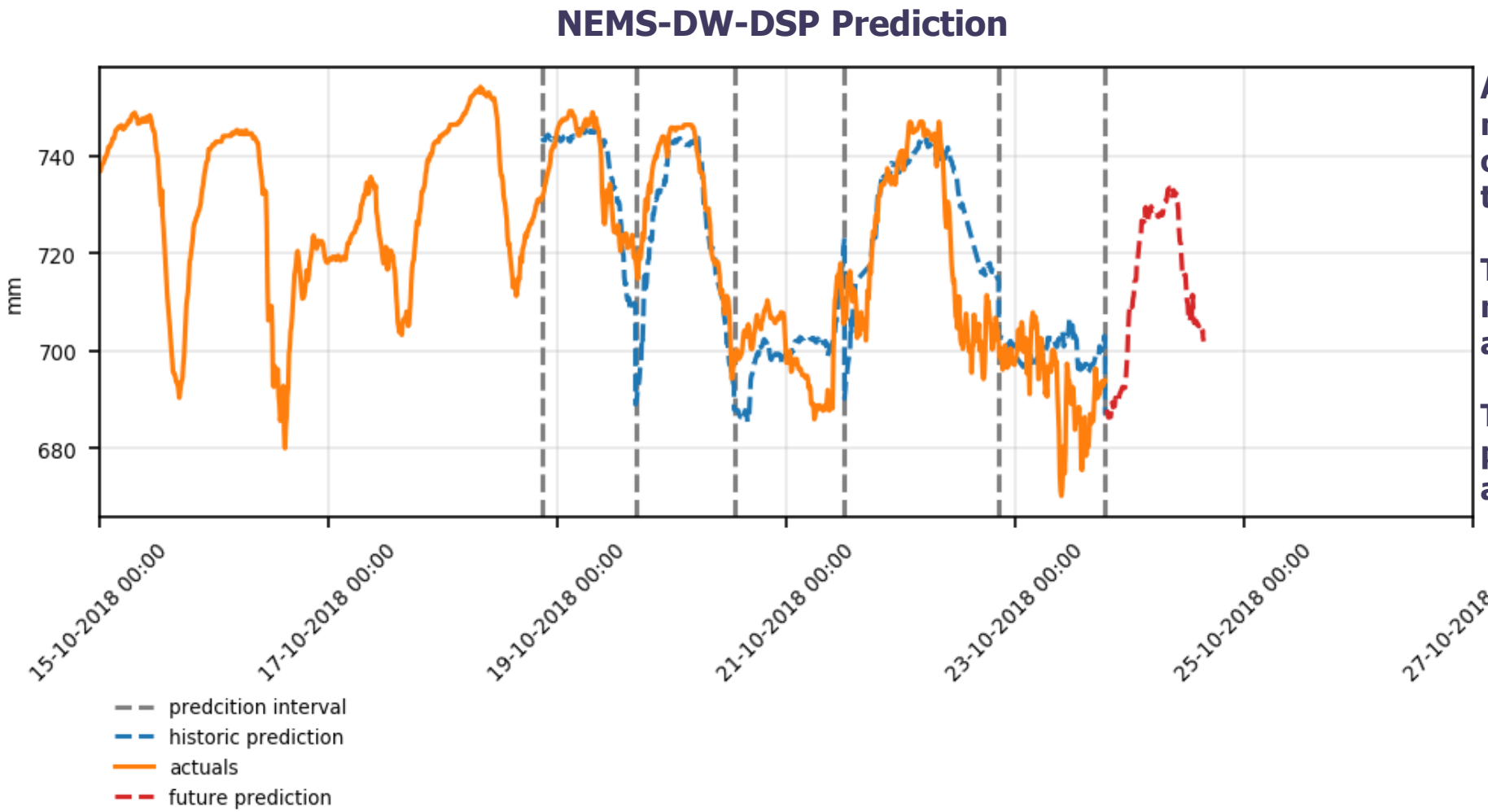
- In Mercury one can observe strong correlations between the response of the bridge and weather conditions (wind, temperature)
- One can thus use the weather forecast to estimate future bridge response
- To predict bearing displacements we have used a combination of historic time-series data and weather forecasts with machine learning models
- The current 24-hour prediction results for 23 October are show as an example





FRB Data Analytics – Machine Learning

- Prediction at 7pm 23rd October and then refreshed at 3pm the next day



At each vertical grey line, a new prediction is made based on the weather forecast at that point in time.

The blue line shows the results of historic predictions against actuals in orange.

The red line shows the current prediction which rolls forward as new data is learned

FRB Data Analytics – Machine Learning

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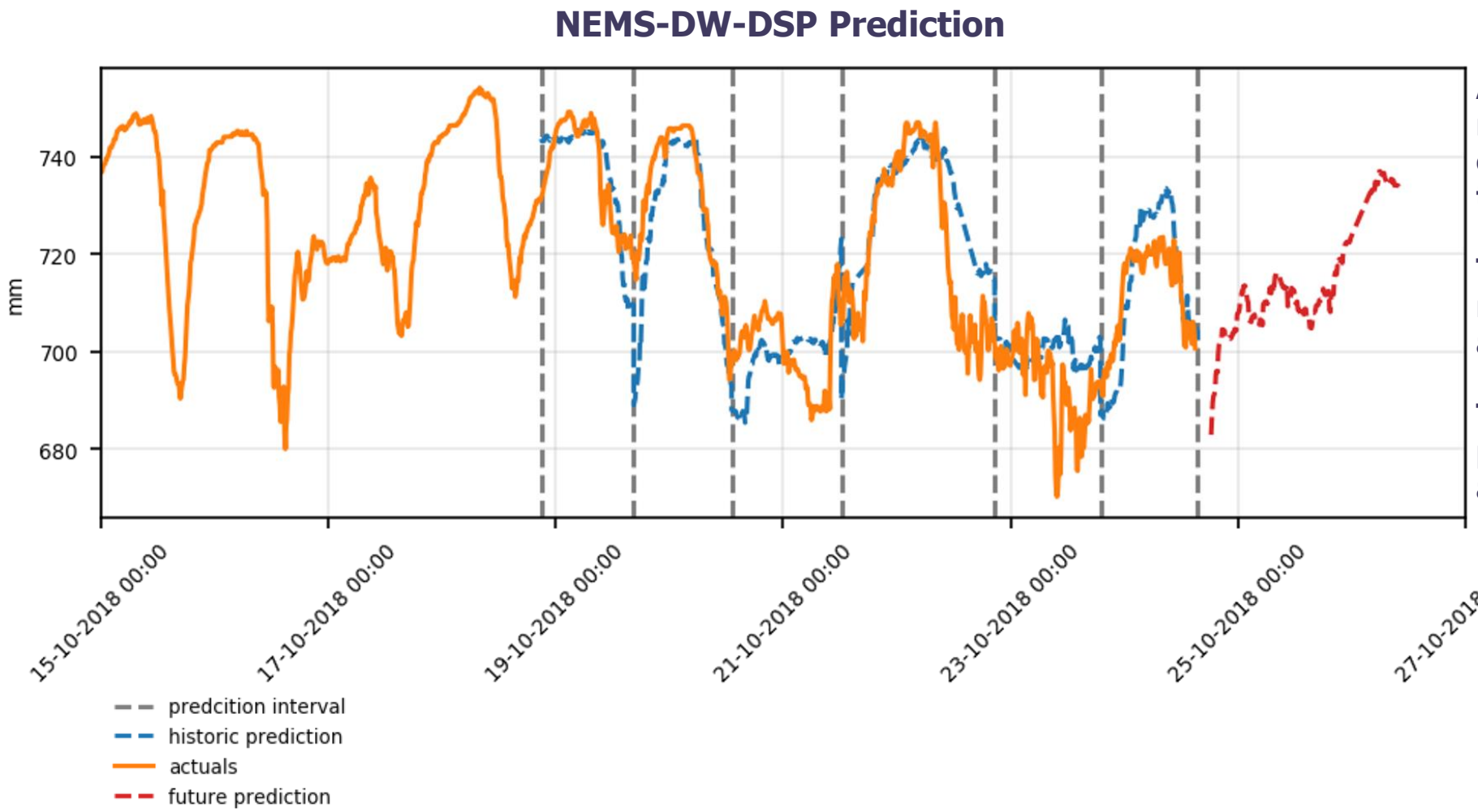

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The blue line shows the results of historic predictions against actuals in orange.

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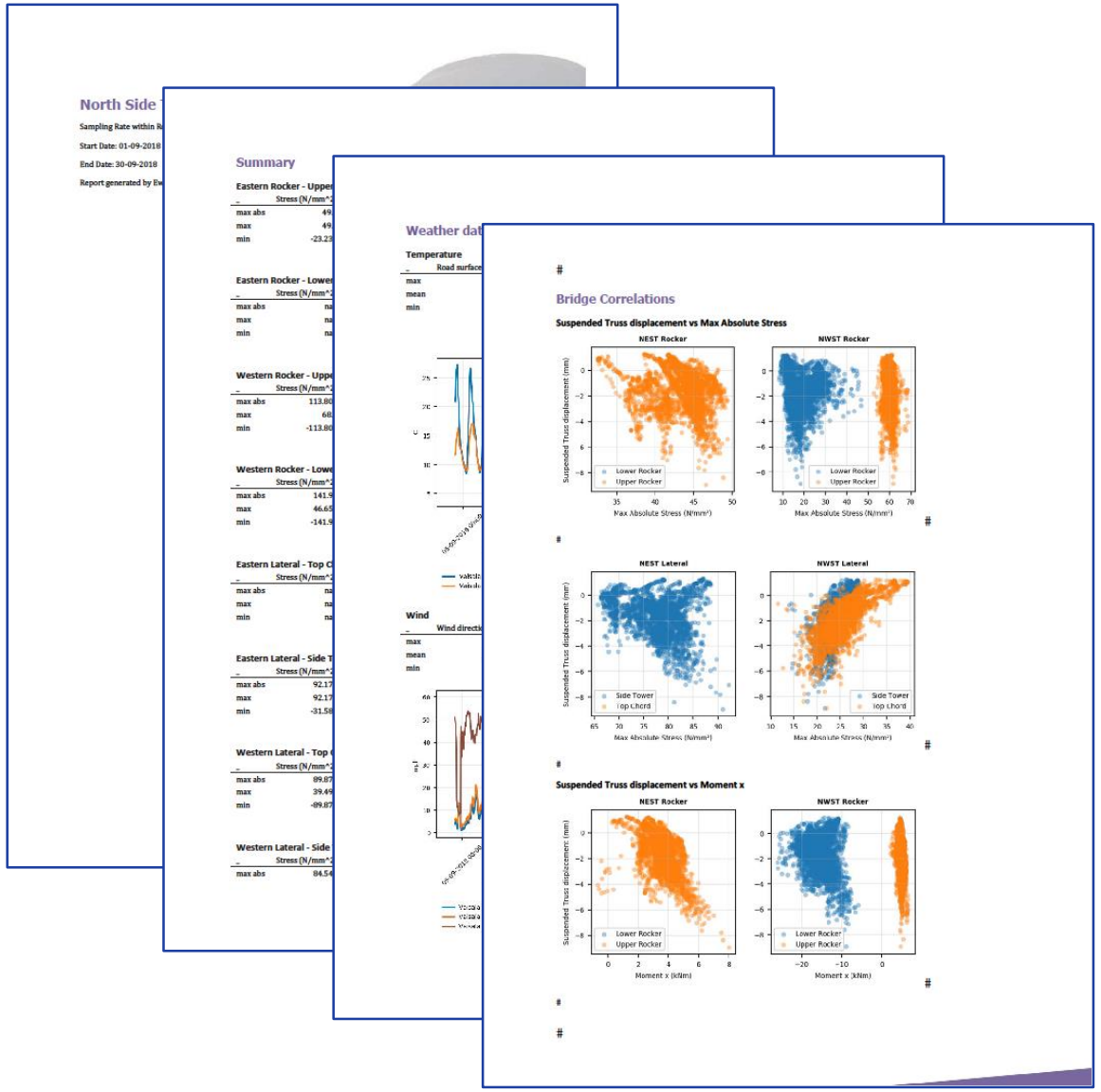
FRB Data Analytics – Machine Learning

- Recent 2 weeks – model prediction versus actual

Reporting

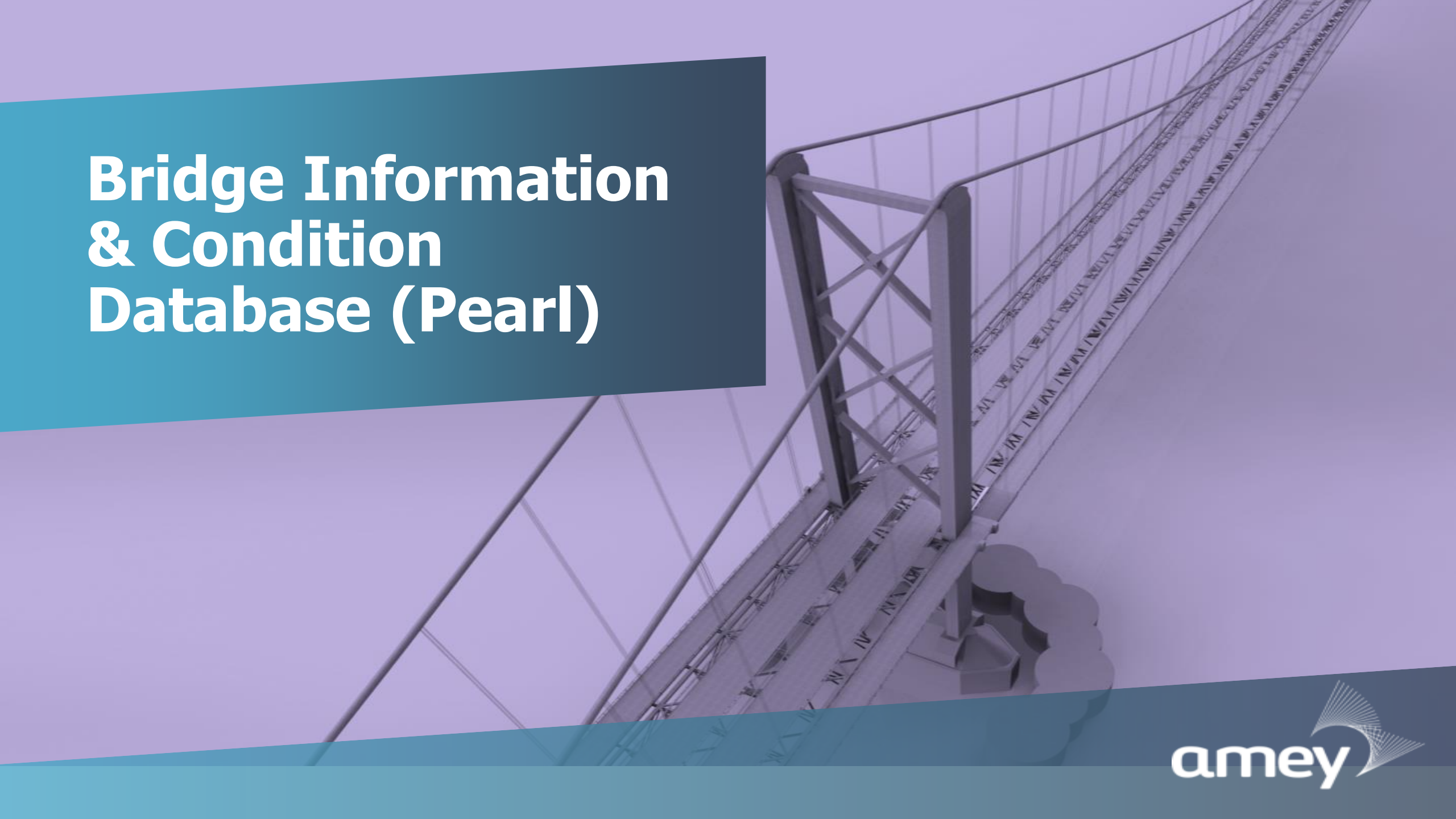
Automated, Scheduled & On-Demand Reports

FRB Data Analytics – Automated and On Demand Reporting

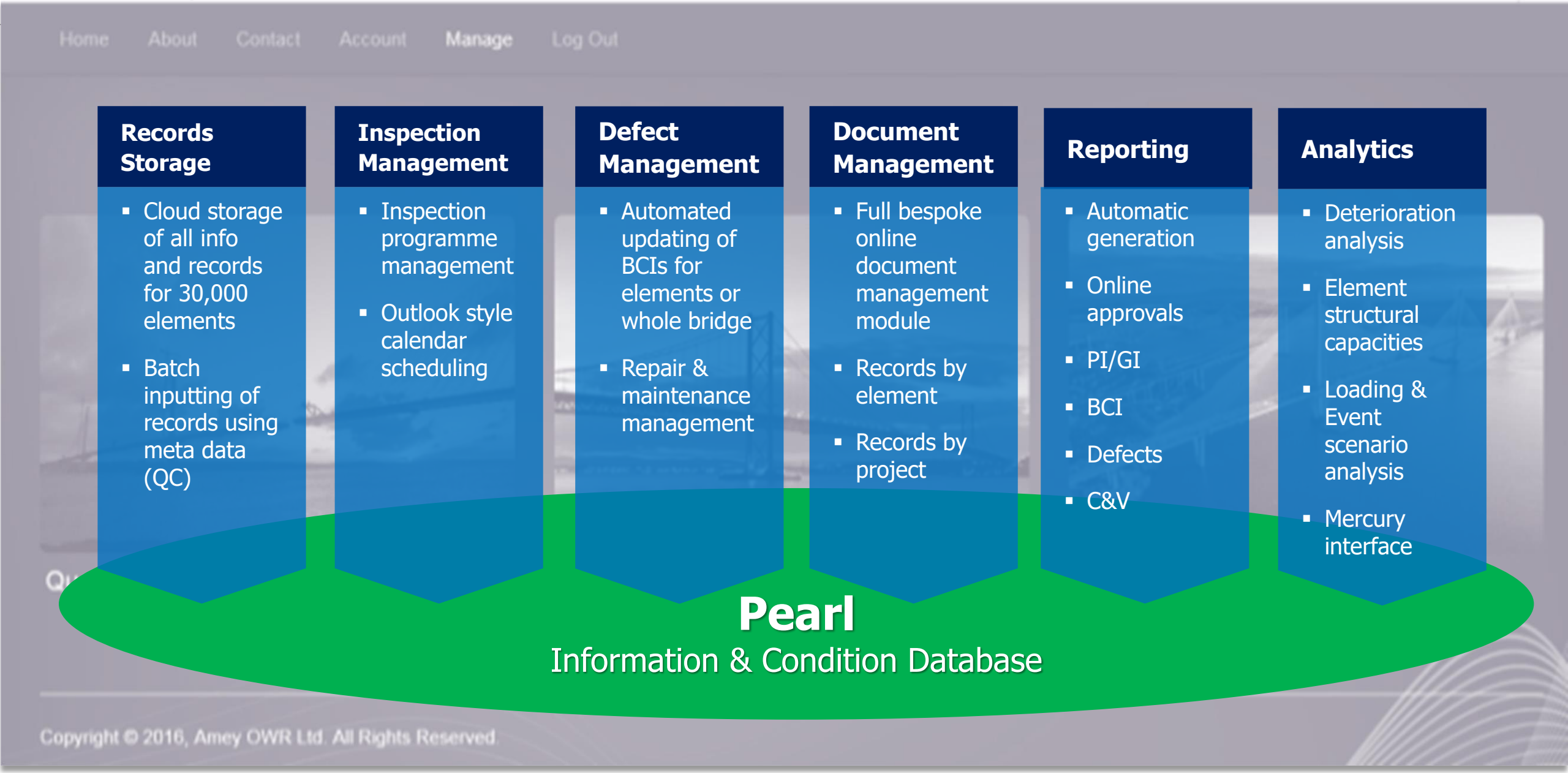


- Data monitoring and analytics tools can be grouped and applied for any chosen period to create **automated or scheduled or on demand** reports
- Suite of reports developed for FRB, each report configured once manually then coded into system to become automated
- Suite of reports being planned for QC once fully online
- Routine reports set up for client reporting
- Special event reports for use in after storm reviews for Named Storms
- Real time, historic, or predictive

Bridge Information & Condition Database (Pearl)



Bridge Information & Condition Database (Pearl) FRB & QC



Pearl – Major Bridges Entry Screen

Home About Help Account Manage Log Out

Select Bridge

Queensferry Crossing (M90 0-1 60)

Forth Road Bridge (A9000 9)

Erskine Bridge (A989 100)

Kessock Bridge (A9 1350)

Cross-bridge Analysis and Reporting

FRB & QC Pearl – QC Overview

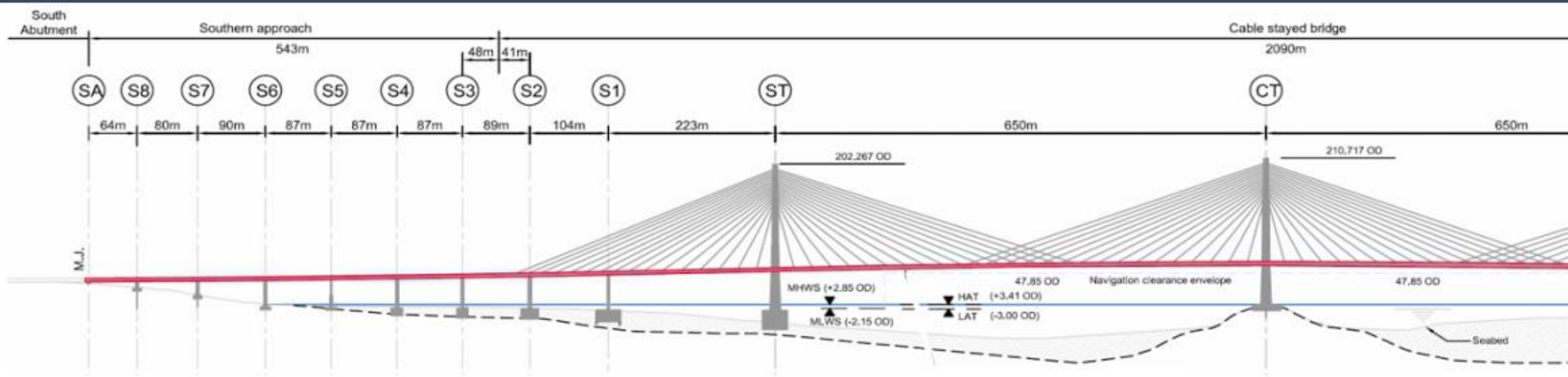
OVERVIEW
INVENTORY
SCHEDULE
HIERARCHY
REPORTS
DOCUMENTS
LOG OUT

Logged in as
Ewan.Angus@amey.co.uk

About | Help | Account

QUEENSFERRY CROSSING (M90 0-1 60)

QUEENSFERRY CROSSING (M90 0-1 60)



Overview

No Description Available.

Agenda -7 Days

Today ◂ ▸ 07 May 2019-14 May 2019

Agenda +7 Days

Today ◂ ▸ 14 May 2019-21 May 2019

FRB & QC Pearl – FRB Overview

OVERVIEW

INVENTORY

SCHEDULE

HIERARCHY

REPORTS

DOCUMENTS

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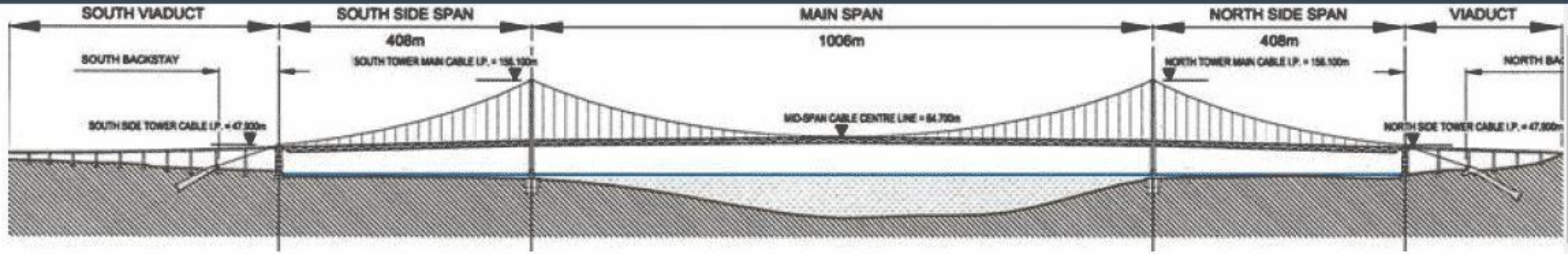
Ewan.Angus@amey.co.uk

LOG OUT

About | Contacts | Account

FORTH ROAD BRIDGE IDRMDB

FORTH ROAD BRIDGE IDRMDB



Overview

The Forth Road Bridge is a long span suspension bridge which was opened in September 1964.

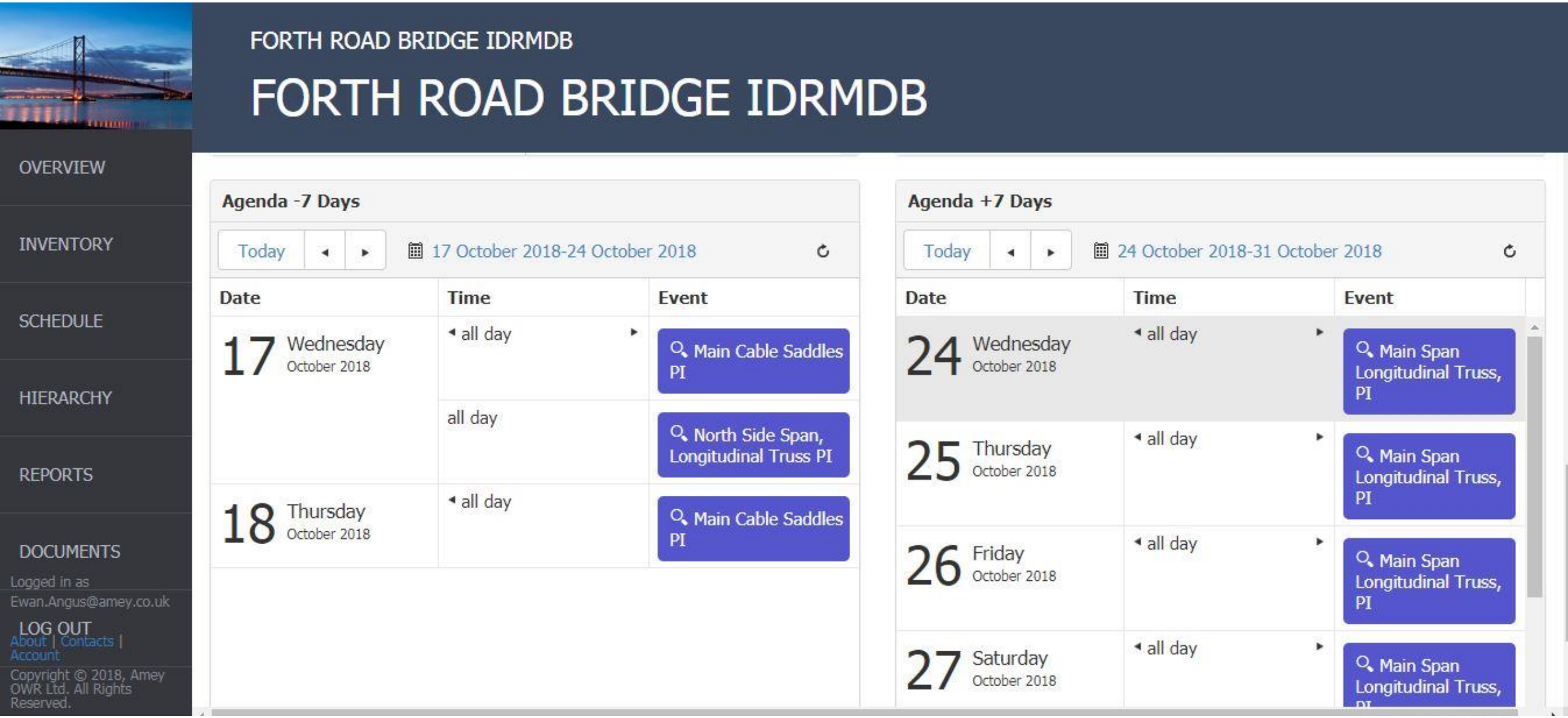
The bridge crosses the Firth of Forth some 15km west of Edinburgh and is a vital link in Scotland's strategic road network. The bridge deck supports a dual two lane carriageway without hard shoulders or strips. There is a separate footway / cycletrack on either side.

The historic importance of the structure to Scotland was recognised in 2001 when the bridge was classed as a Category A listed Structure.

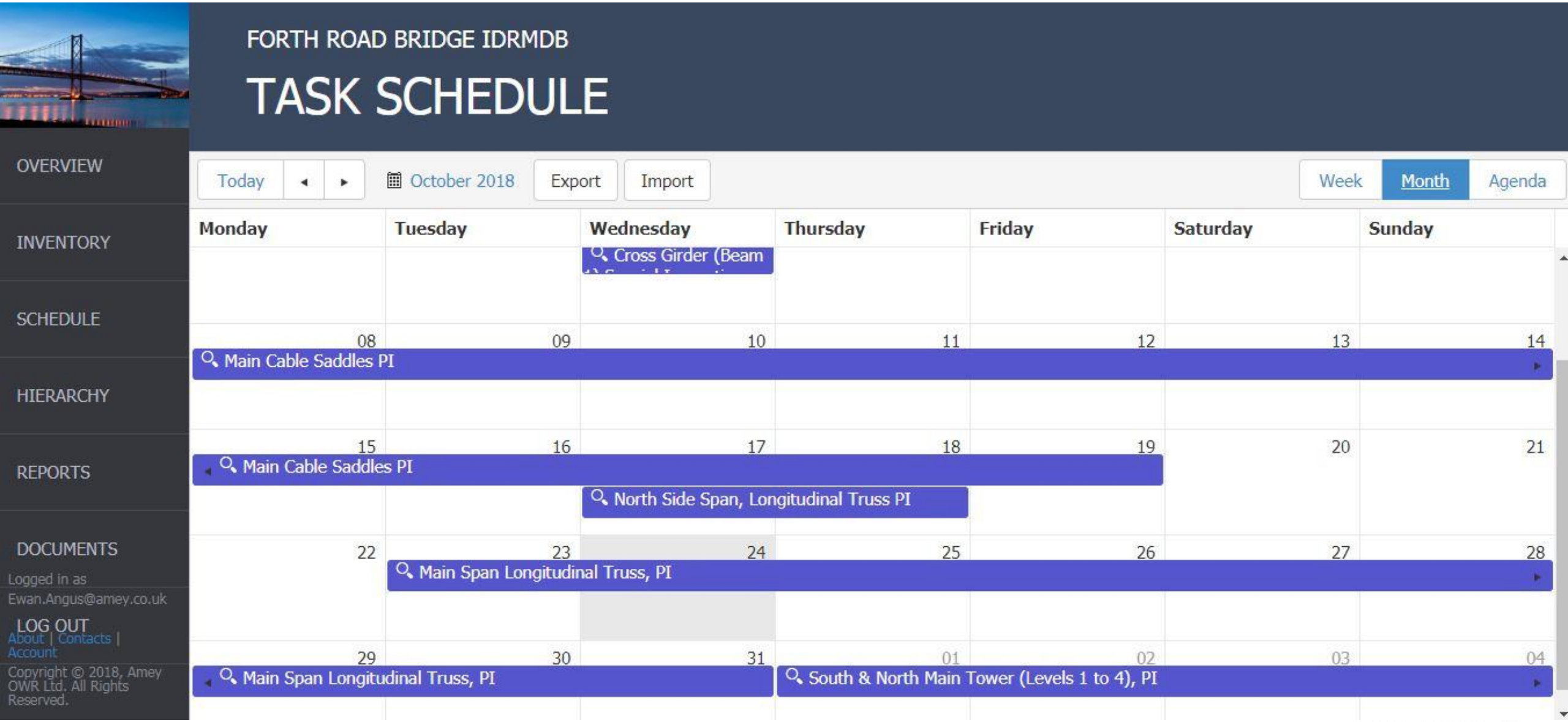
Bridge Information

Favourite Documents

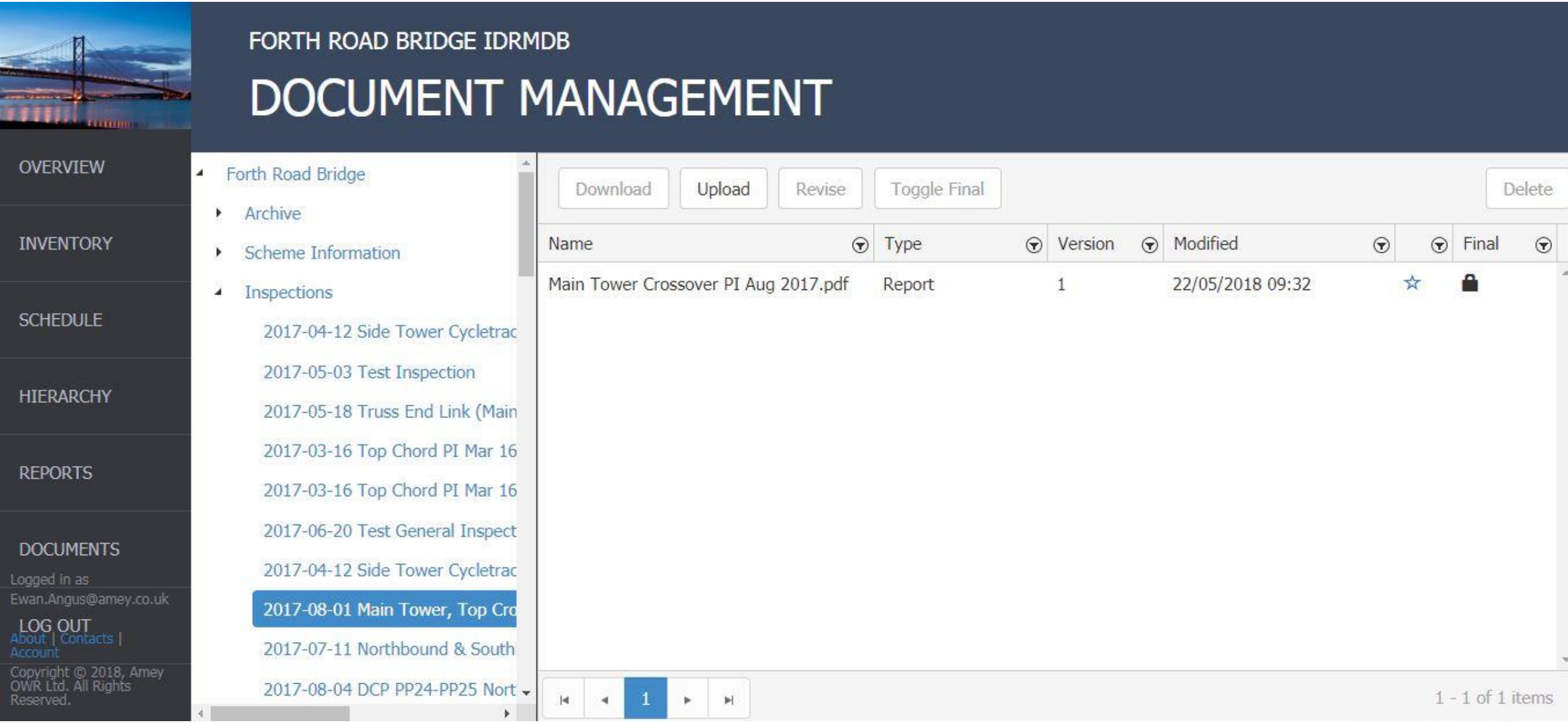
FRB & QC Pearl – Agenda Page



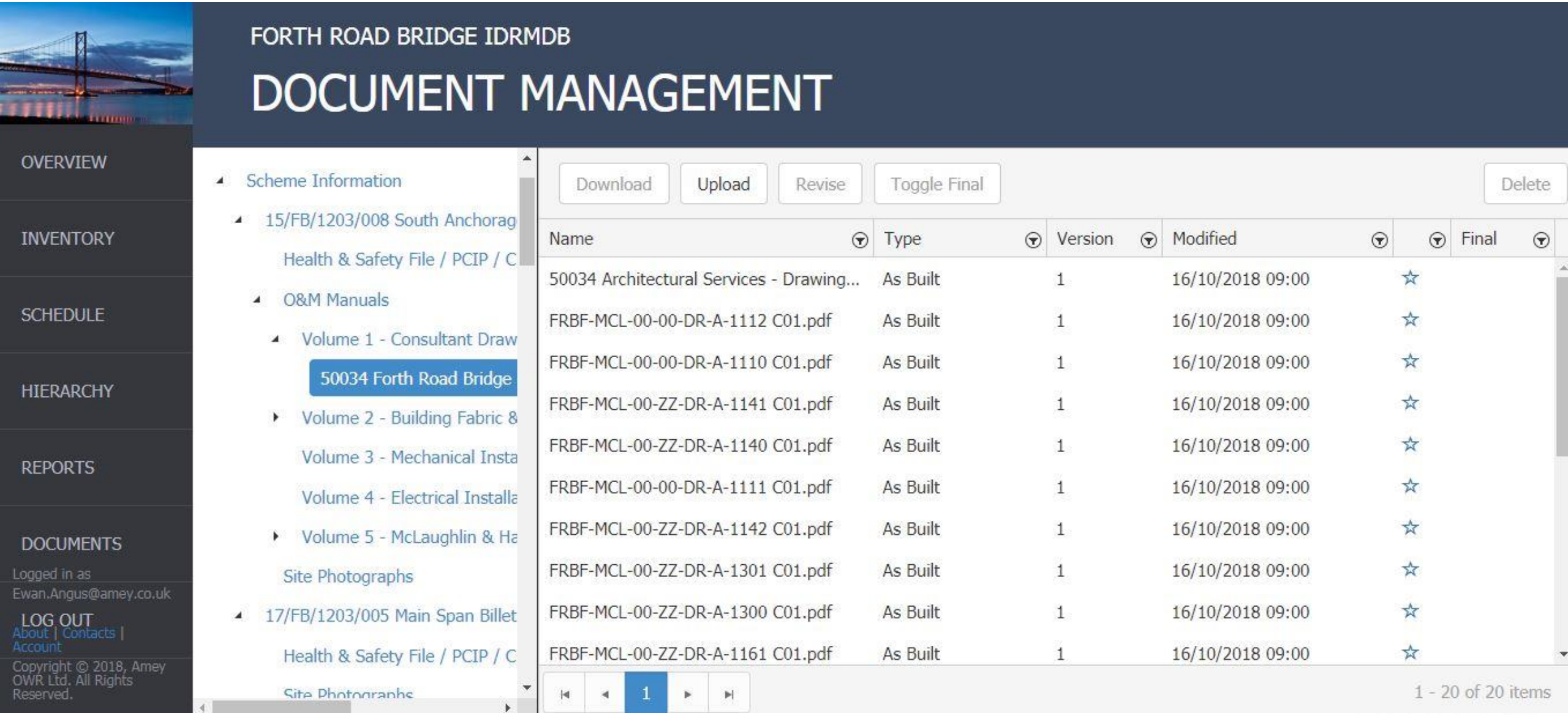
FRB & QC Pearl – Outlook Style Inspection Diary



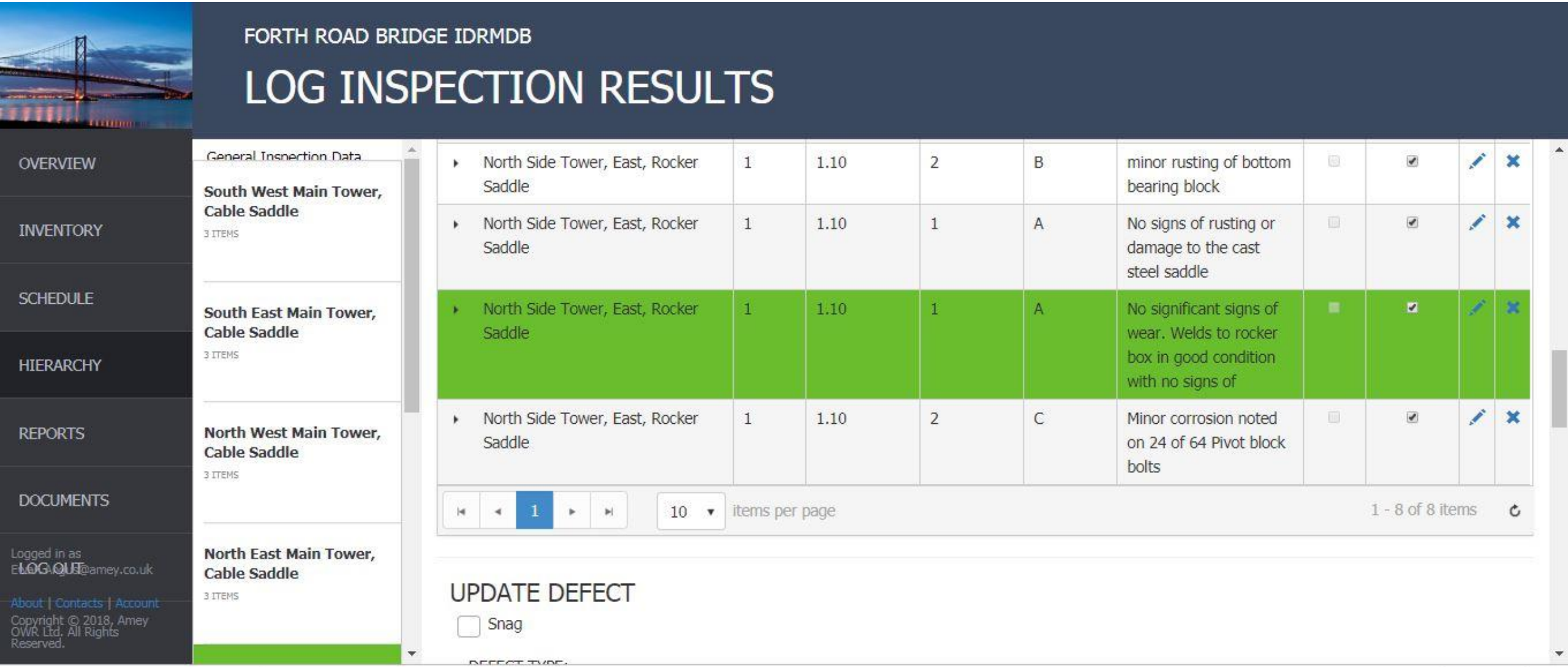
FRB & QC Pearl – Document Management Module



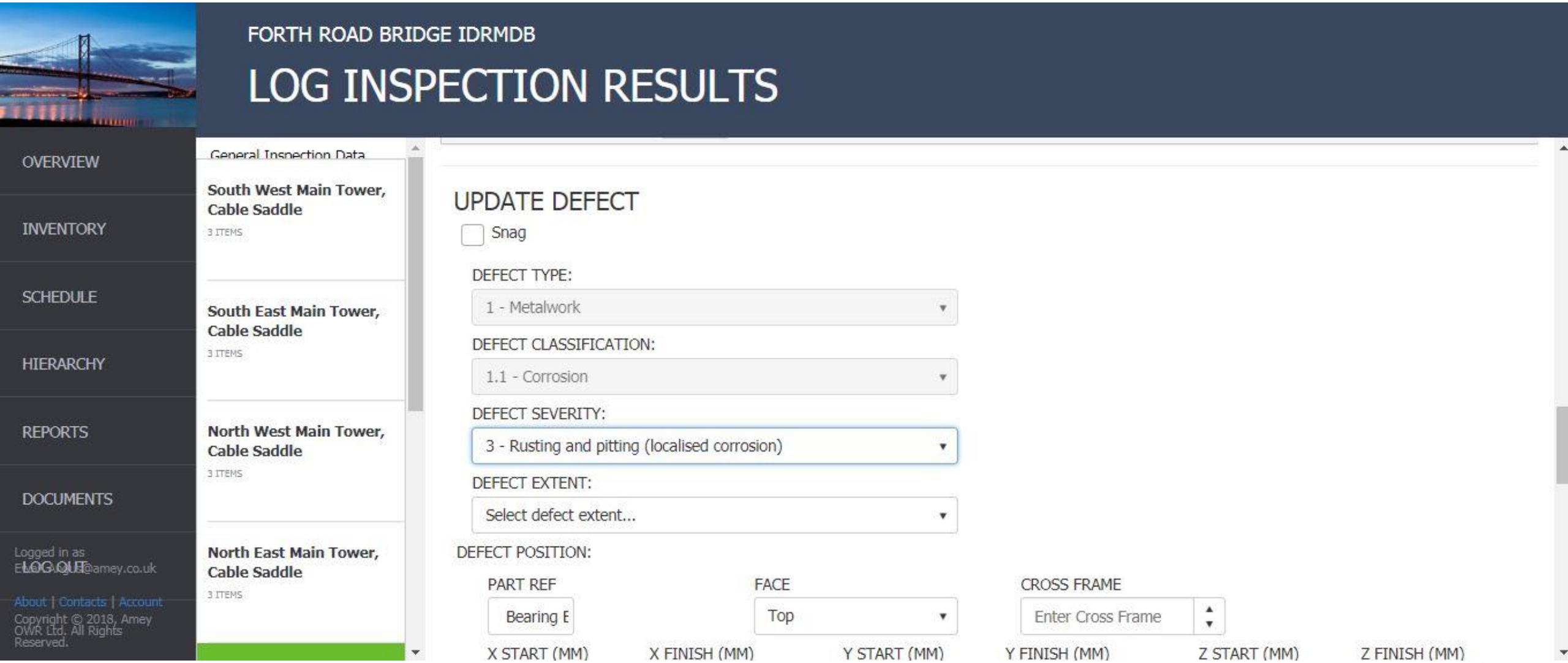
FRB & QC Pearl – Document Management Module



FRB & QC Pearl – Logging of Defects



FRB & QC Pearl – Logging of Defects



FRB & QC Pearl – Report Generation

FORTH ROAD BRIDGE IDRMDB

GENERATE REPORTS

USER: EWAN.ANGUS@AMEY.CO.UK

USER TYPE: ADMINISTRATOR, MANAGER, INSPECTOR, STAKEHOLDER, IMPORTANCE CONTROLLER, EXTERNAL REVIEW

SCHEDULE
GANTT
HIERARCHY
REPORTS
LOG OUT

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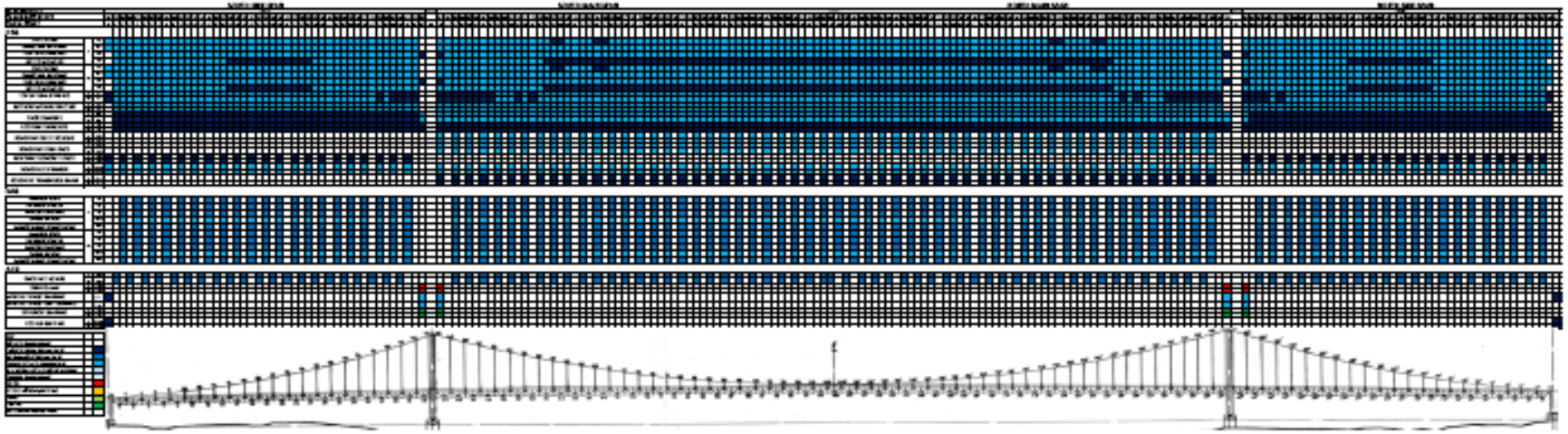
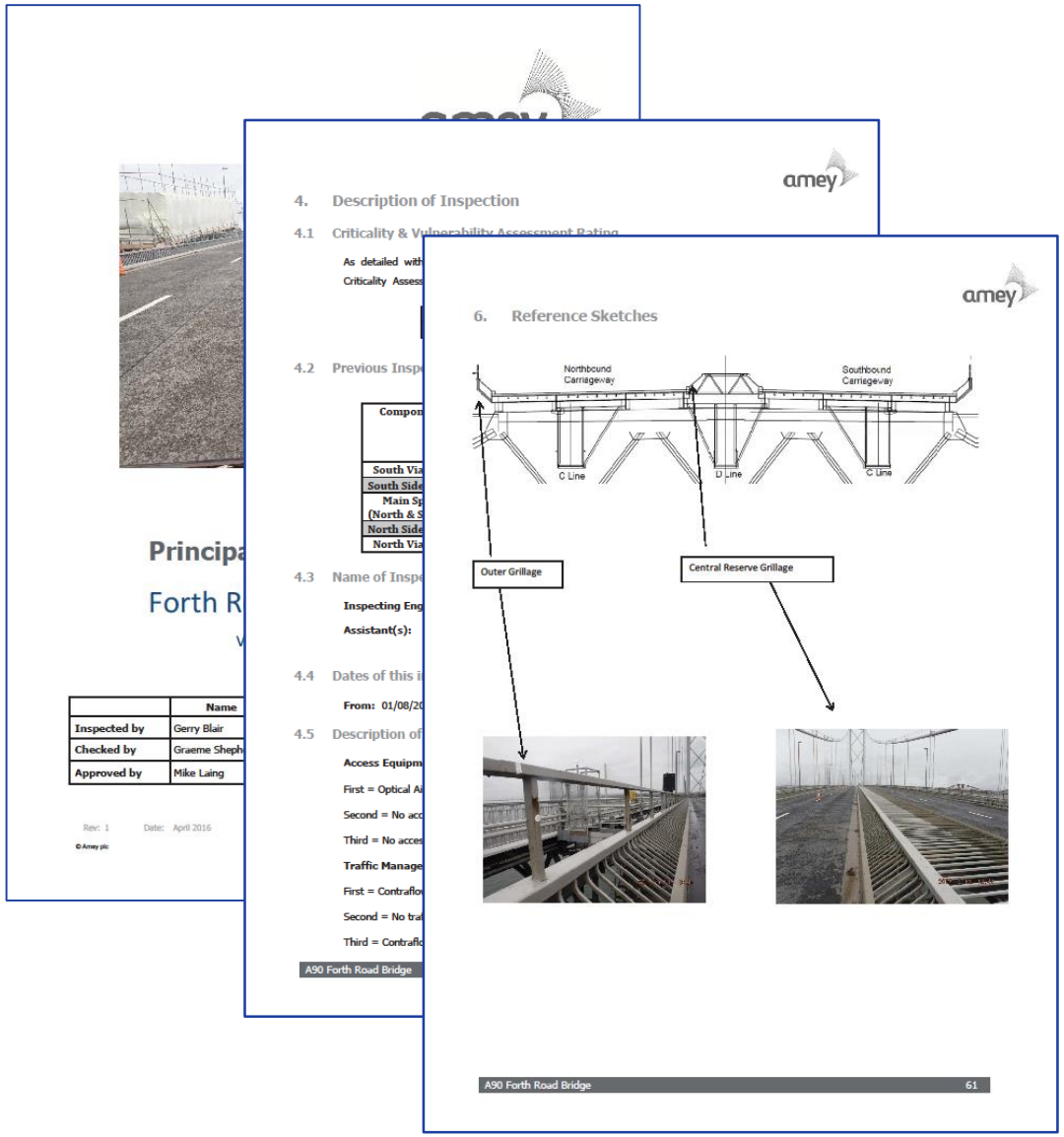
SELECT REPORT

- **Inspection Reports**
- **Compliance Report**
- **Bridge Condition Indices**
- **Criticality and Vulnerability Reports**
- **Schedule and Condition Heatmaps**
- **Defect Report**

Schedule	Produce a schedule based heatmap, where each cell represents the urgency of a specific component's inspection.
BCI (average)	Produce a heatmap showing average BCI scores for each component.
BCI (critical)	Produce a heatmap showing critical BCI scores for each component.



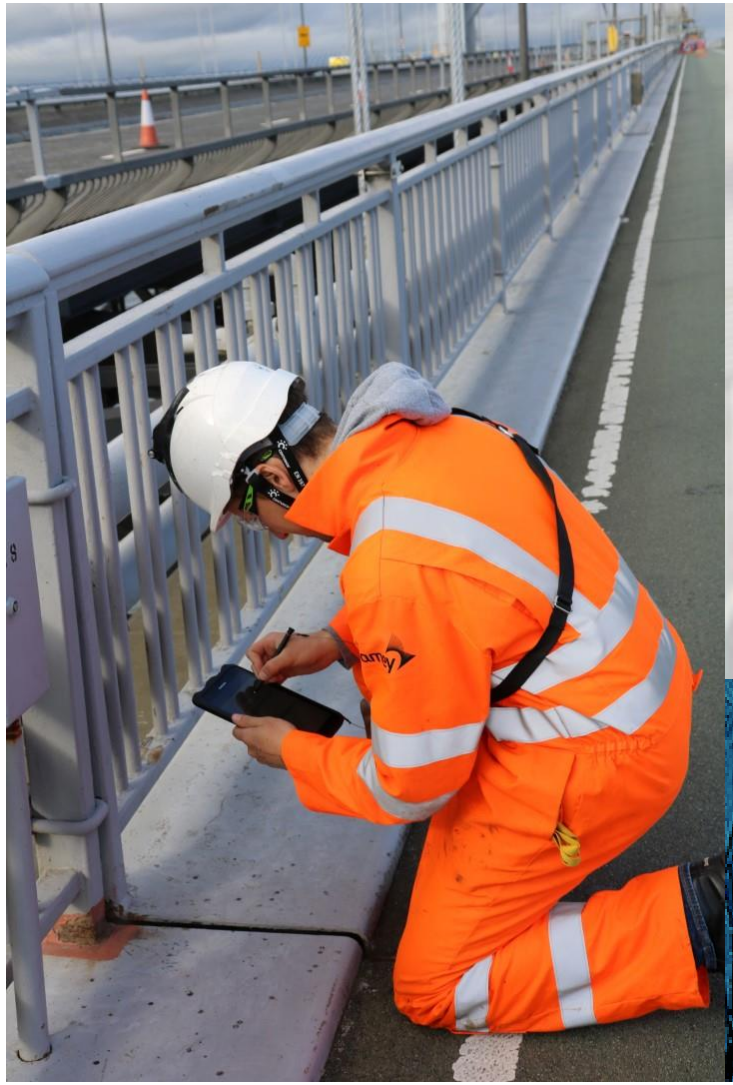
FRB & QC Pearl – Automated Inspection Report Generation

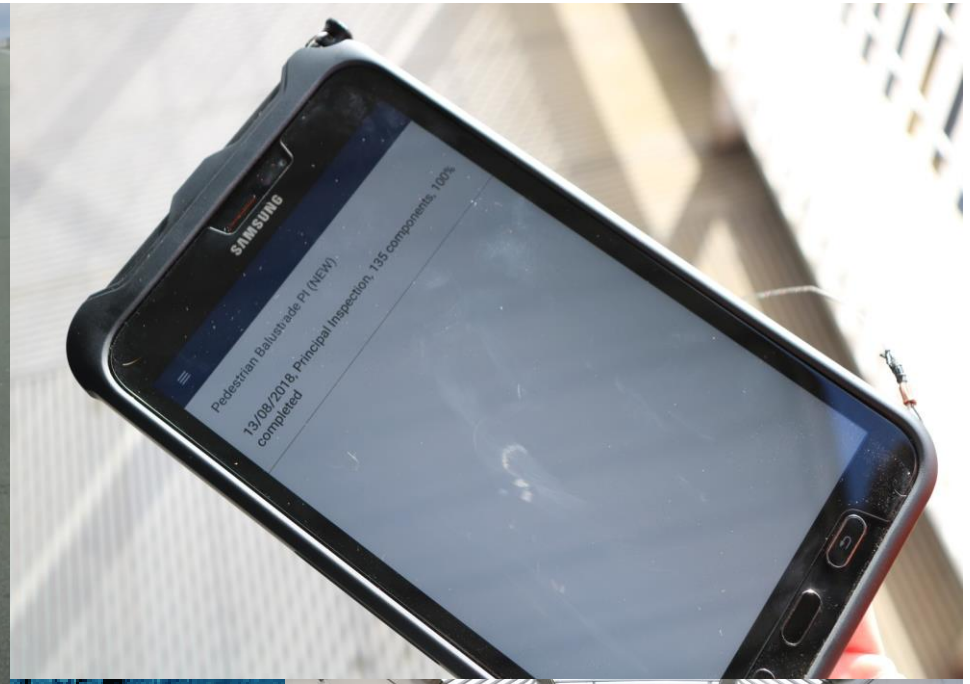


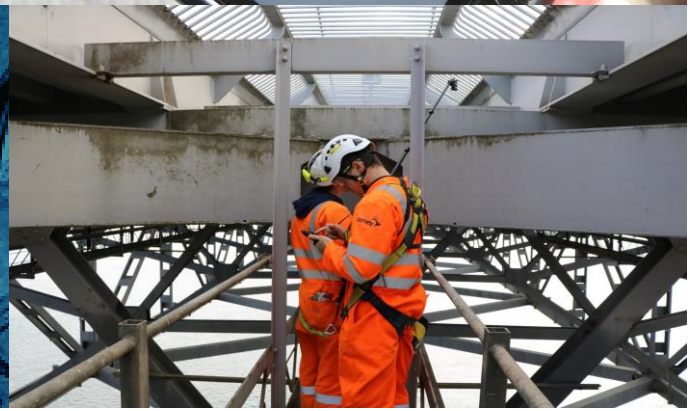
- Inspection reports generated by system automatically or on-demand
- Huge increase in efficiency – report template only needs set up once by engineers then coded into system
- Automatically set up to demonstrate compliance with contract KPIs
- Client approval of reports online

FRB & QC Pearl – Mobile Device Input via PearlApp

- Defects recorded directly on site by inspectors using Wifi enabled Mobile App
- Element records and defect history available to inspectors
- Bridge Wifi allows Bridge Condition Indices to be automatically updated and inspection reports created automatically
- 360º camera and VR system being trialled







Pulling It All Together

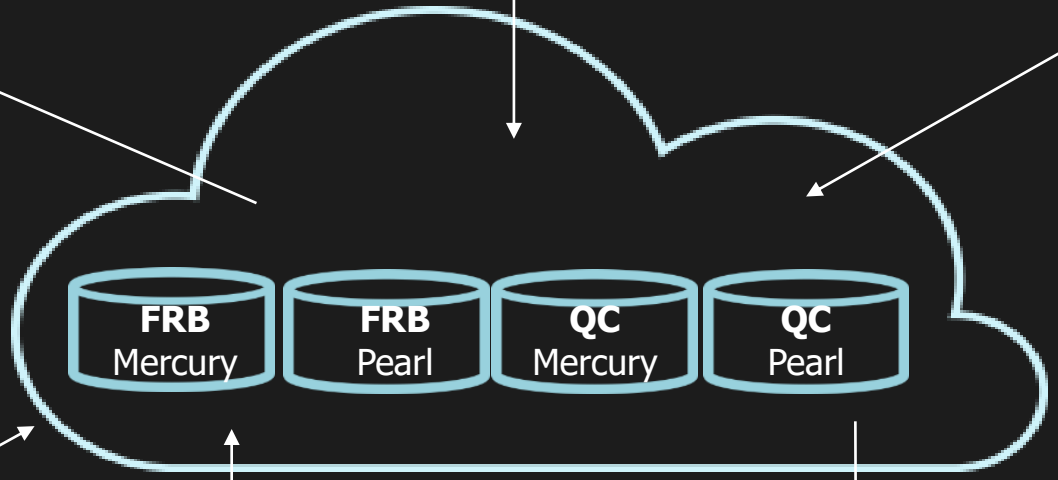
CONTROL ROOM

Real Time Monitoring
Alerts
3D Visualisation

BRIDGE REPAIRS & MAINTENANCE

BRIDGE INSPECTIONS

Inspectors / Tablet Input
360º Camera
VR/AR



SENSORS

Bridge Loading
Wind & Temperature
Bridge Response

BRIDGE INFORMATION

Structural Capacities
As-Built Records
Baseline Conditions

WEB BROWSER

Bridge Operations
Scheduling Inspections/Repairs
Monitoring
Economic Modelling

AUTOMATICALLY GENERATED REPORTS

Inspection Reports
Monitoring Reports
Bridge Condition Indices
Maintenance Budgets

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In Conclusion

- This is all about Data! Lots of assets generate lots of data but many don't make full use of it
- The systems we have developed have put these bridges in a world leading position
- Resilience and confidence can be increased with proper use of technology and data
- Owners of smart assets can make better informed decisions
- Integration, automation, and harnessing the full power of Data Analytics are key to success
- Engineering judgement will always be needed but the analytics free up time for this

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Live Demonstration
ameyconsulting