Multiple Experts Making Multiple Assessments:

A Case Concerning Infrastructure Assessment

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Also thanks to Barry Colford (Bridge Master)
Colin Clark (Technical Director) Fairhurst and Partners
and colleagues at Forth Road Bridge

Outline

- Background to the problem
- Modelling methodology
- Application and findings
- Motivations for Working Group 1

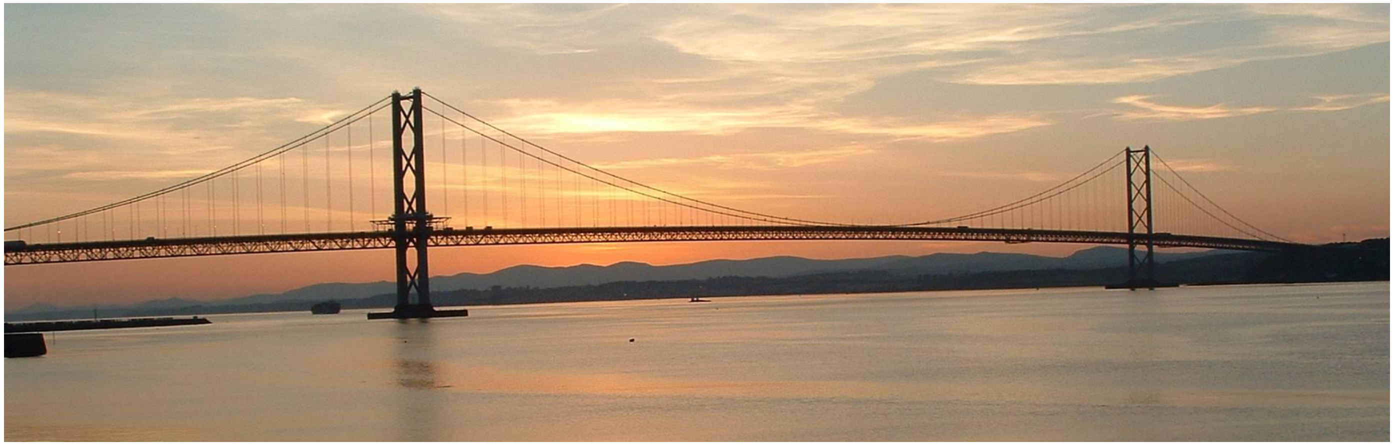
Engineering Problem

Investigation into the capacity and condition of the main cable anchorages of the Forth Road Bridge given there is uncertainty about condition of anchorages

Objective:

To support assessment of the condition of strands and capacity of anchorages

Forth Road Bridge



- Built 1964, main span 1006m, 39000tons of steel, 125,000m^3 concrete, 2.5km long, 24 million vehicles p.a.
- Originally 4th longest suspension bridge in world, now 22nd
- Motto “Guid Passage” reflects role as modern transportation corridor on historically important pilgrim and trade route for many centuries
- Capital asset maintenance project for Technical Director Fairhurst Consulting Engineers contracted by Forth Estuary Transportation Authority (FETA) who report to Scottish Government

http://www.forthroadbridge.org

Reality of Bridge in November

University of Strathclyde Business School



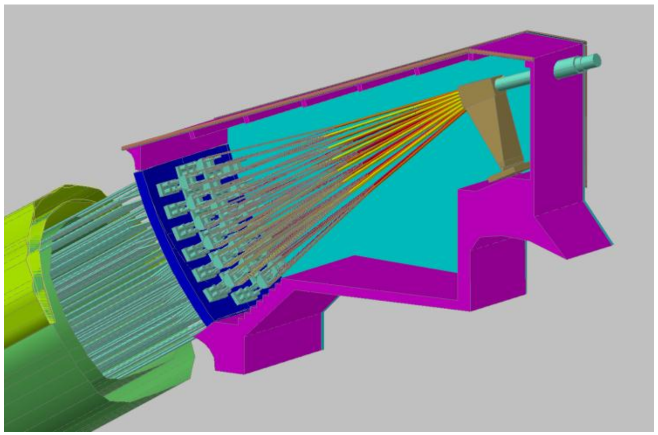

Project Background

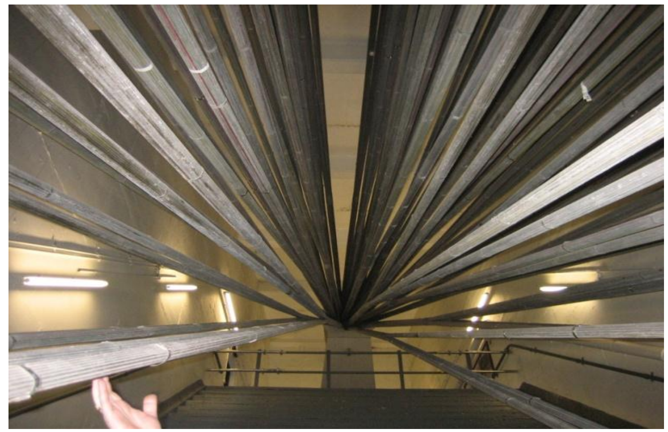
"The ***anchorages of the main cables*** *of a suspension bridge are* ***critical elements*** *of the structure. At Forth, tunnels were formed within the rock at each of the four anchor points and filled with concrete. The main cable wires splay out in the anchorage chambers and loop round strand shoes which are in turn bolted to the face of the concrete tunnels….the concrete in the tunnel itself is not strong enough to withstand the forces from the cables and was strengthened using pre-tensioned galvanised, high tensile steel wire strands. This use of pre-tensioning in the buried concrete anchorage tunnels at Forth was considered innovative at the time. Unfortunately, this form of construction can be* ***vulnerable to corrosion and deterioration*** *especially in a saline environment such as is found at Forth.*

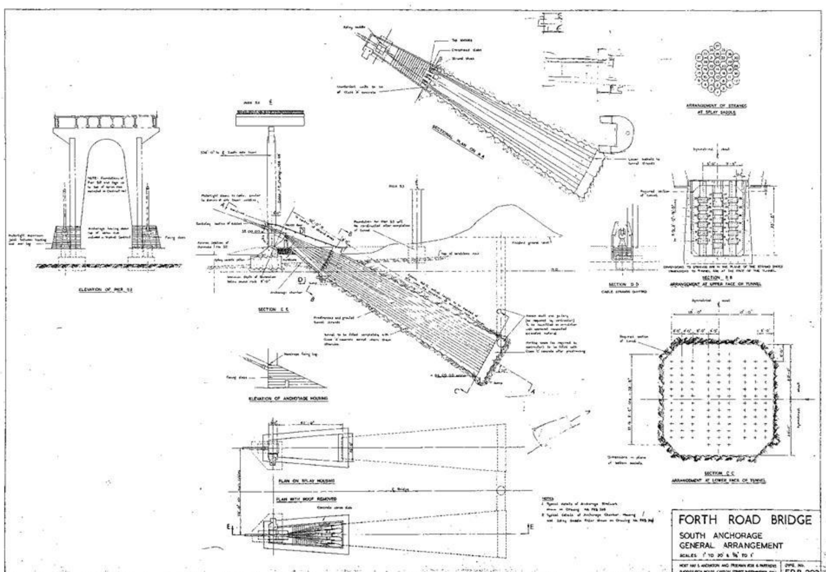
In the course of a study into the feasibility of replacing or augmenting the main cables, completed in 2008, it became apparent that further work would be required to ***prove the long-term structural integrity of the anchorages****. Records and papers acquired relatively recently relating to the construction of the existing anchorages highlighted various problems during construction particularly in relation to early depletion of the galvanising protecting the post tensioning strands which are housed* ***in grouted ducts set in the concrete tunnel****.*

The ***current safety of the bridge is not in question****. This investigation is about ensuring the long term structural integrity of the anchorages and is a pro-active measure to ensure that all accessible parts of the structure are inspected. ….. these reports determined the need to carry out a special inspection or investigation to try to establish the existing condition of the pre-tensioning strands. Work has been ongoing since 2008 to determine the best way of doing this. The* ***anchorages' unique design*** *makes this an* ***extremely difficult task****."*

Actual Anchorage Details







4 anchorage chambers
19 crosshead slabs/chamber
6 sockets/tendons per slab
=114 tendons per anchorage

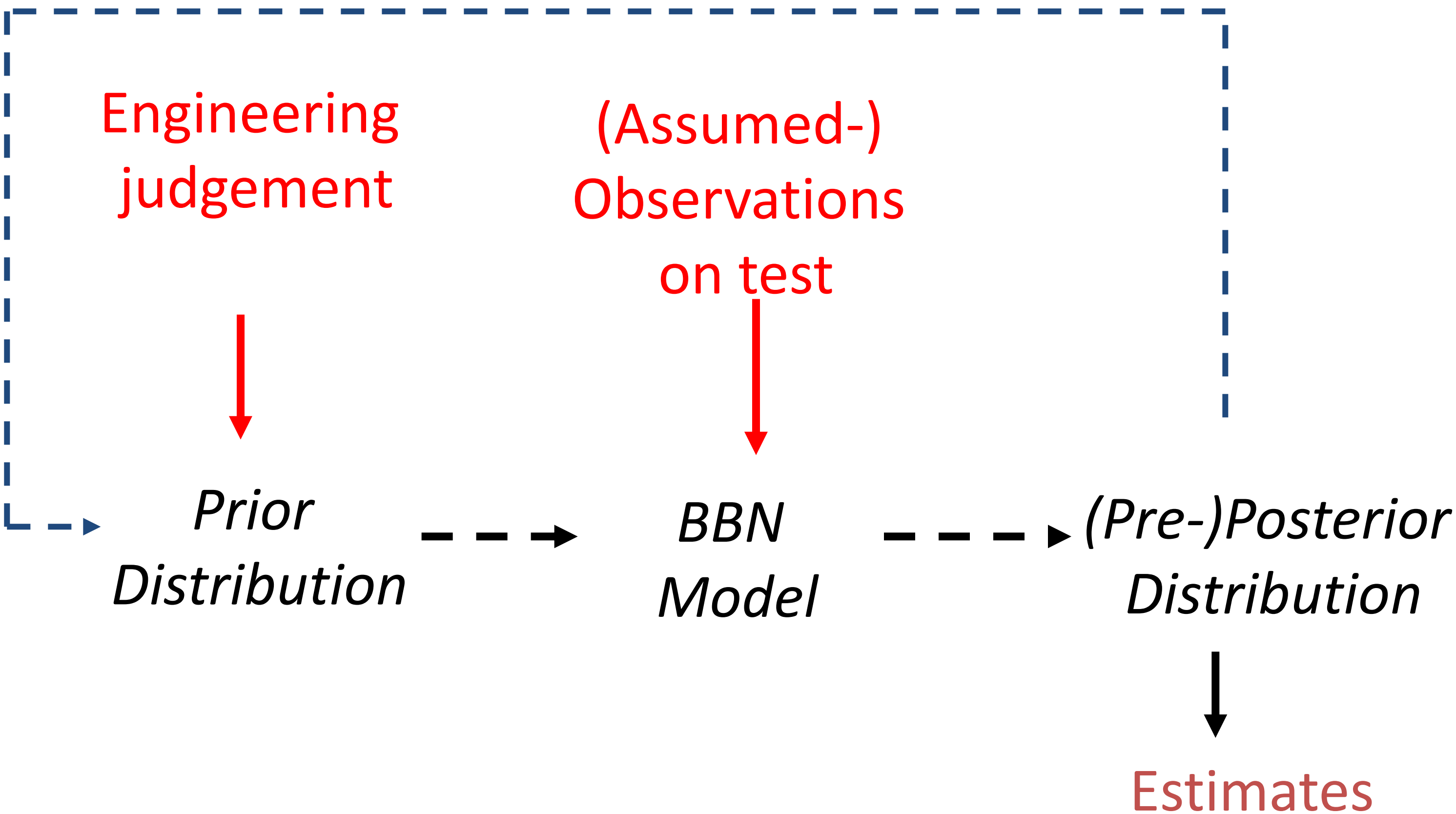
5 tests under consideration
= direct pull-off test x 1
= sample and inspection x 4

Proposed Engineering Tests

- Internal load “pull-off” test
  - External excavate down to expose top row of tendons to obtain samples
  - Access limits but able to establish current load in certain tendons and state of grout
  - Direct Pull-off Test (DPT)

- Excavate to sample and inspect strands
  - Access constraints but information about strand condition, strand strength and grout condition
  - On site inspection (OSI), Load test outcome (LTO), Lab tensile test (LTT), Lab wire inspection (LWI)

Methodology - Bayesian Method

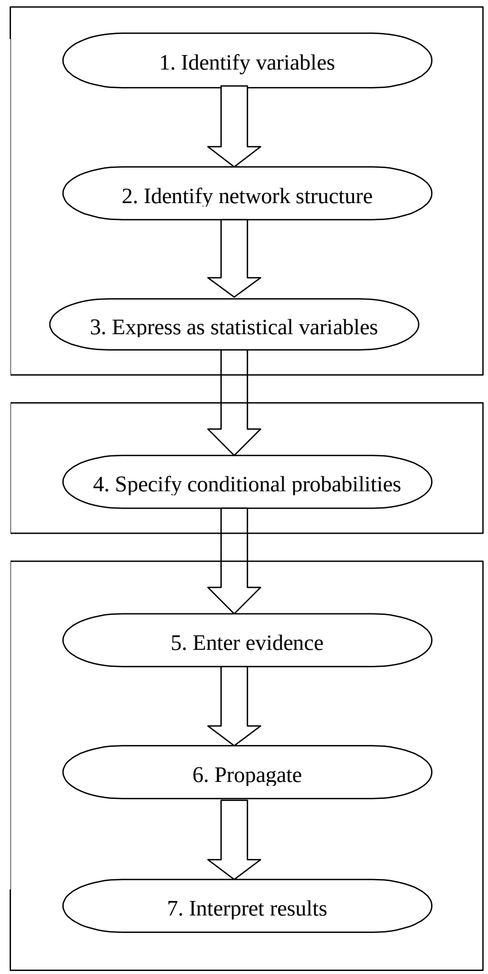


Methodology – Model Building

Problem structuring

Instantiation

Inference



BBN developed in Genie software

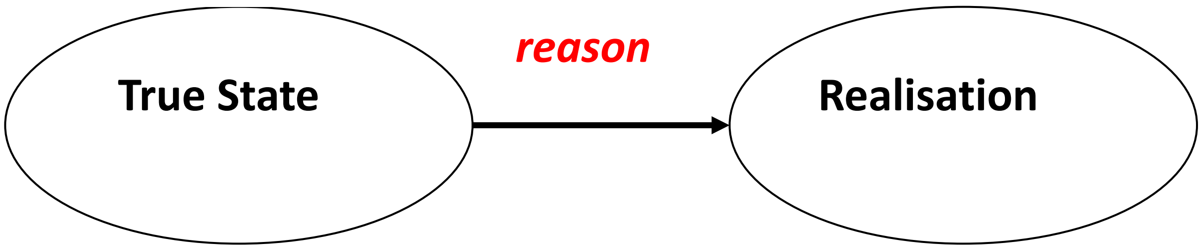
New algorithms developed & implemented in Maple software

Qualitative Structuring of BN

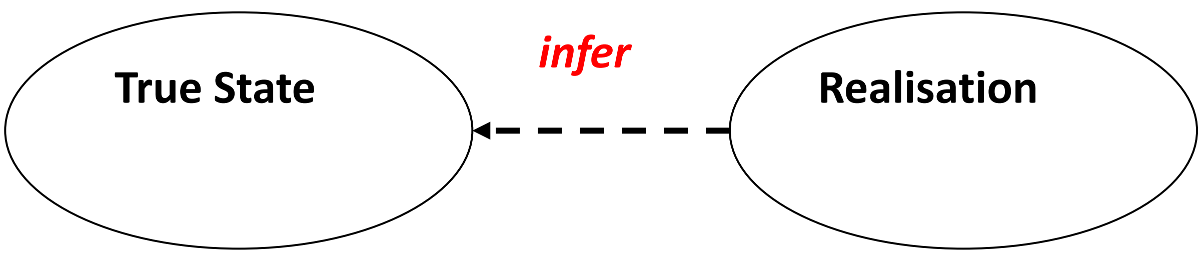
- Selection of experts
  - "*person with substantive knowledge about the events whose uncertainty is to be assessed*" (Ferrell)
  - primary domain expert = client, 20+years working with bridge and equivalent structures
  - others = Bridge Master, Engineering Services Manager, Risk Manager, Project Engineer
- Two analysts (Quigley and Walls)
  - facilitated questioning, listening and recording, role swapping
- Multiple workshops
  - 8 semi-structured sessions with primary client, 2-3 hours each
  - 1 managed and structured workshop with other engineering experts to challenge and refine
  - agree nodes, arcs, definitions of variables and states

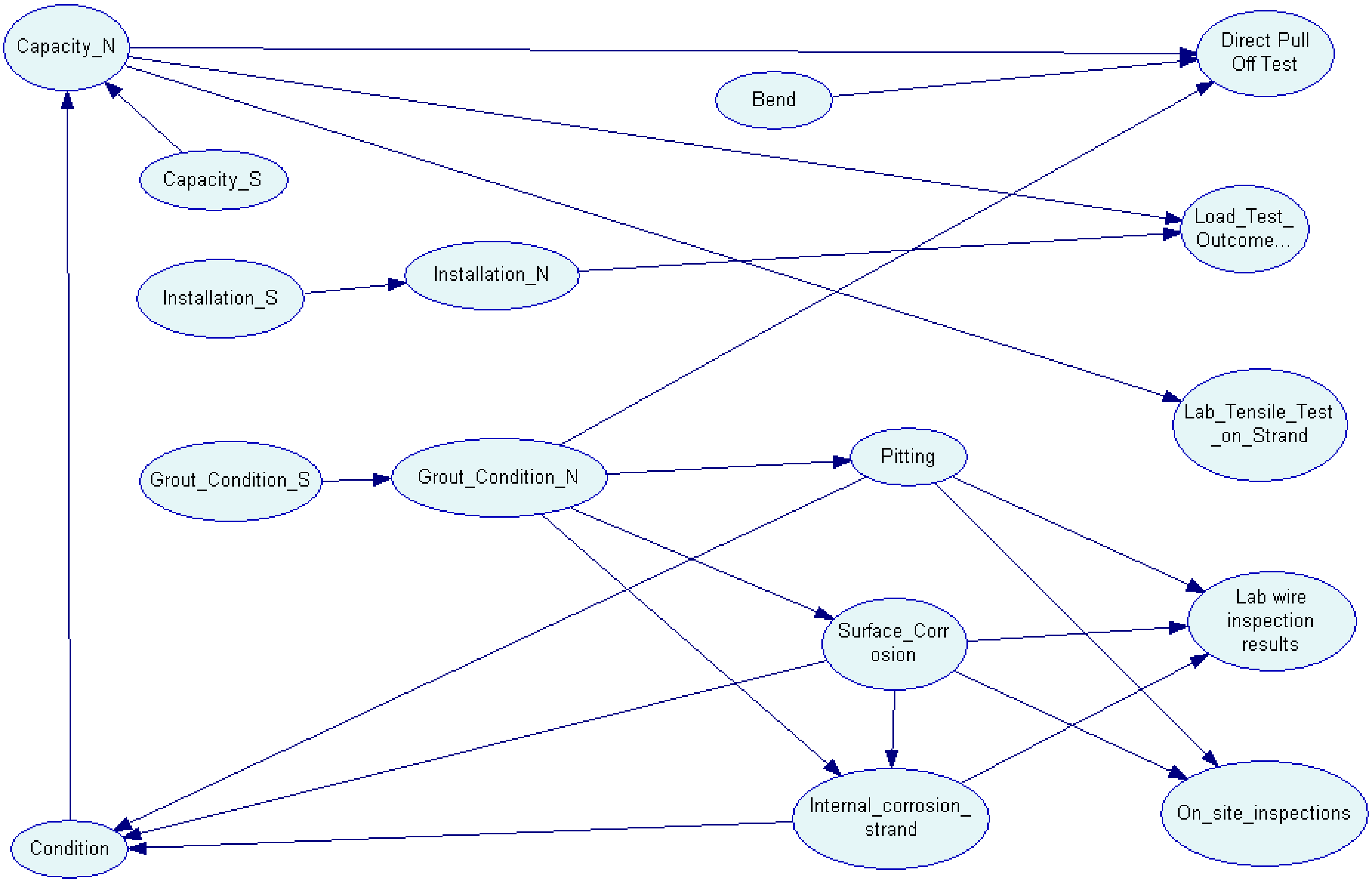
BBN Reasoning Process

Prior to Test and Inspection



Post (assumed) Observations from Test and Inspection




Capacity_N
Direct Pull Off Test
Bend
Capacity_S
Load_Test_ Outcome...
Installation_N
Installation_S
Lab_Tensile_Test _on_Strand
Grout_Condition_S
Grout_Condition_N
Pitting
Lab wire inspection results
Surface_Corr osion
Internal_corrosion_ strand
On_site_inspections
Condition

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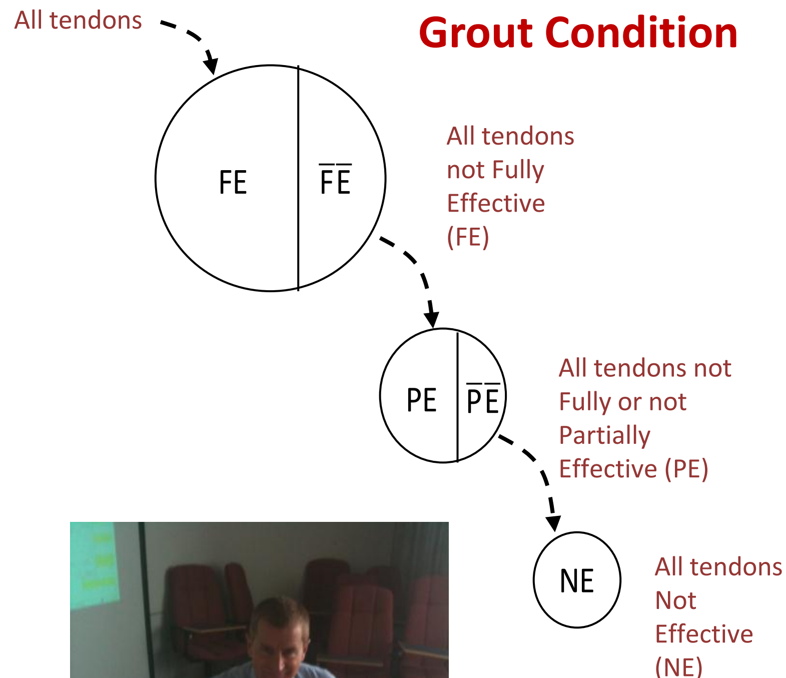
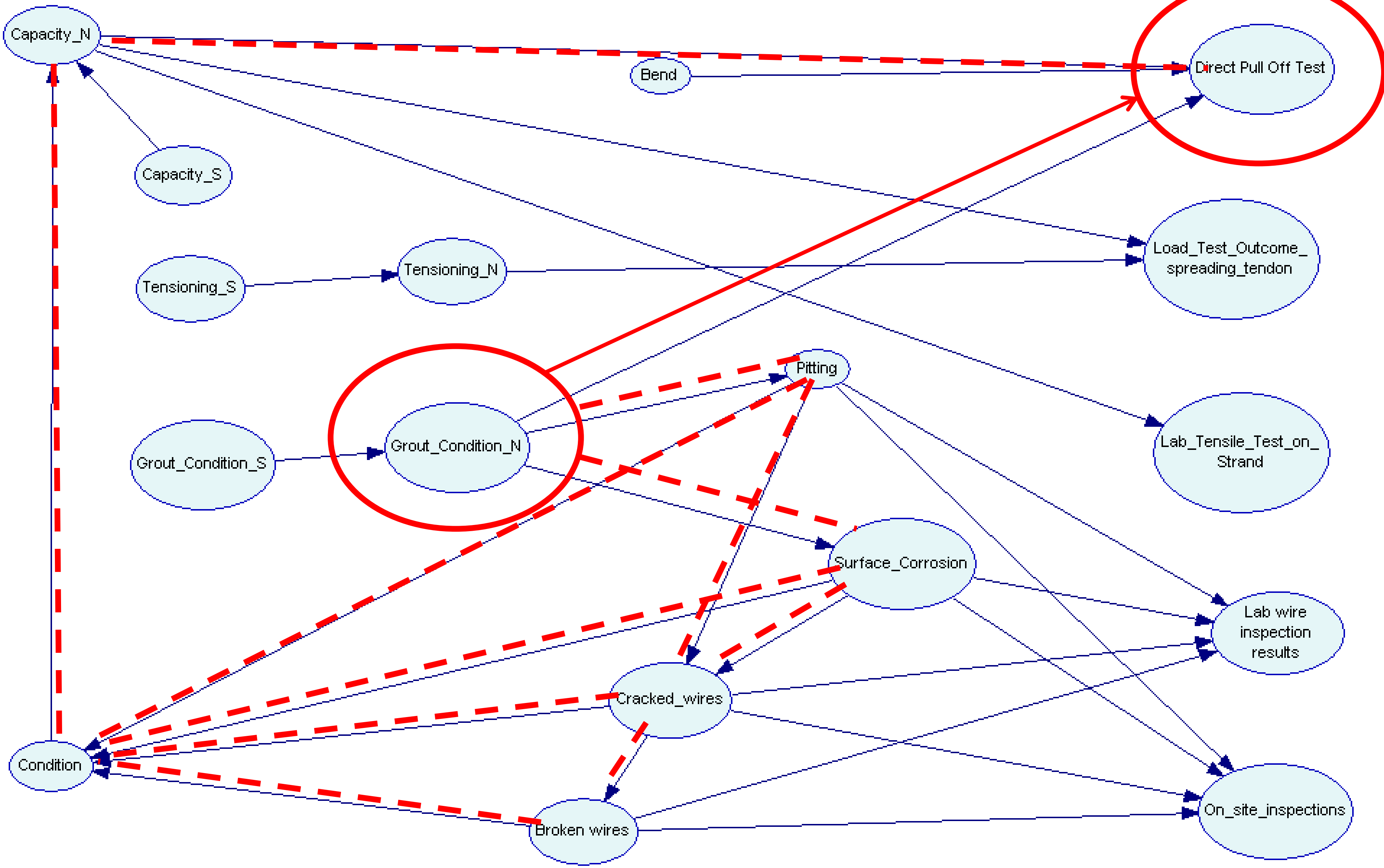
Elicitation of Subjective Probabilities

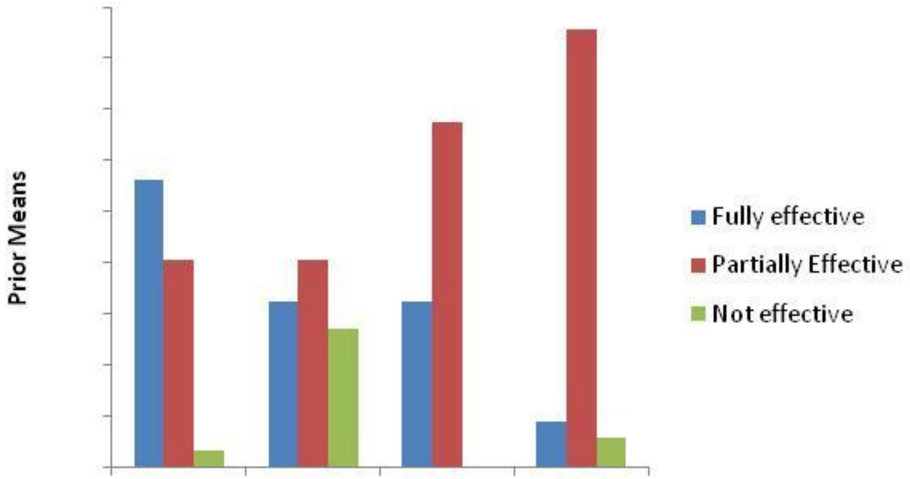
- Practice informed by Stanford Research Institute (SRI) theoretical process
- Group briefing session (motivate, structure, condition)
- Independent off-line elicitation from engineers (encode, verify)
- Spreadsheet data forms designed to capture probability judgements
- Subjective conditional probabilities as proportions of 456 tendons for all 4 anchorages
  - best estimates (median)
  - measure of uncertainty in proportions (lower and upper prevalence)

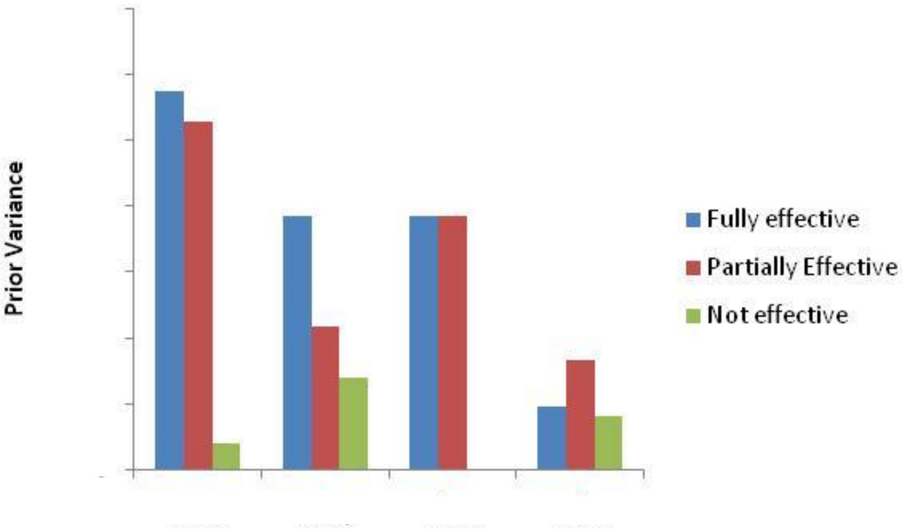


Estimating Condition Given Test Results?



Prior Assessments





Illustrative Example

Prior on Proportion Partially Effective Grout	Posterior	Test Result	Probability of Test Result
0.77	0.90	No Movement	0.08
	0.85	Total Failure	0.24
	0.75	Fully Elastic	0.31
	0.70	Juddering	0.37

Measure for Comparison

$$Var(p) = E\left[Var(p|data)\right] + Var\left[E(p|data)\right]$$

Prior

Accuracy
Posterior Means

Spread of
Possible Posterior Means

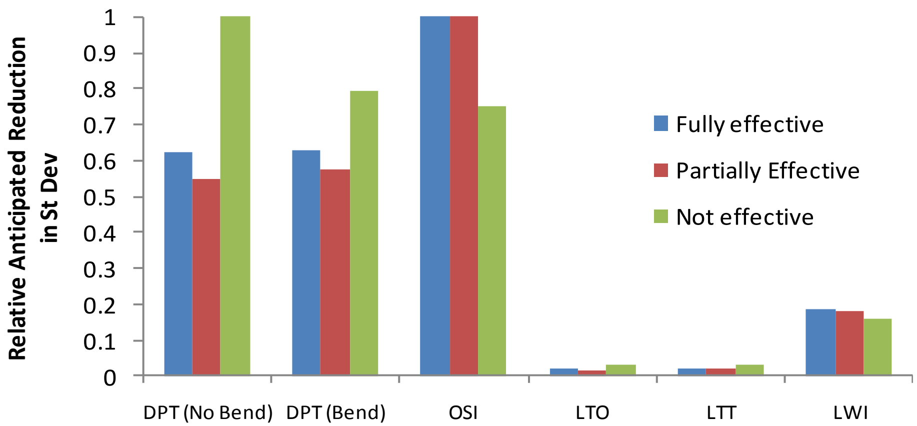
Minimise

Maximise

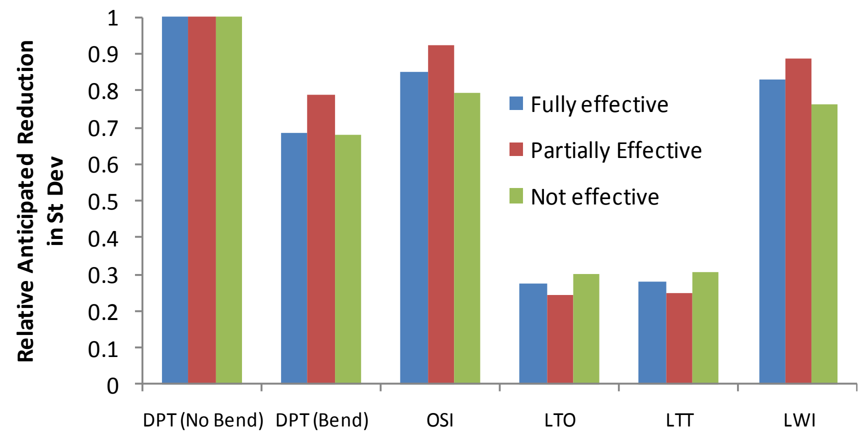
Test Comparison By Expert

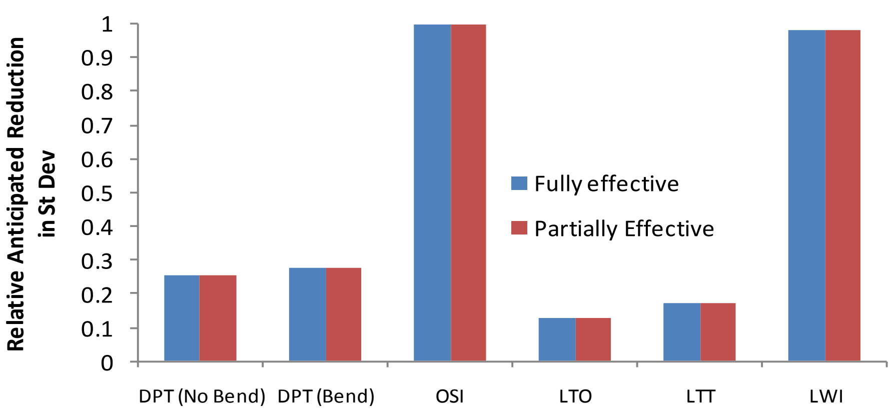
$$\frac{Var\left[E\left(p|data\right)\right]}{Var\left(p\right)}$$

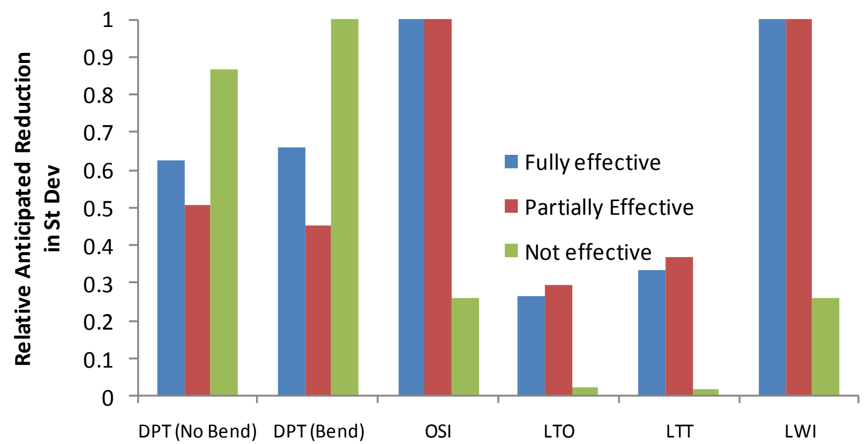
Expert 1



Expert 2







Expert 3

Expert 4

Summary and Conclusions

- Managed to elicit a BBN that is meaningful and is, in principle, able to provide estimates that can be used to inform decisions
  - Non-trivial to structure & quantify BBN due to e.g. novelty of methods & complexity of problem
  - Social and technical methods to reconcile judgements of different experts

- Further work?
  - Analyse outcomes of test to update estimates and review predictions

Working Group 1
Processes and Procedures

- develop and evaluate less labour intensive elicitation methods
- aggregation of expert judgment
- support model parameter uncertainty assessment
- develop graphical and interactive methods
- stakeholder preferences.