SEISMIC VULNERABILITY ASSESSMENT OF SUBSTATIONS AND POWER TRANSMISSION NETWORK

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COMPLEX SYSTEM

"As complexity rises, precise statements lose meaning and meaningful statements lose precision."

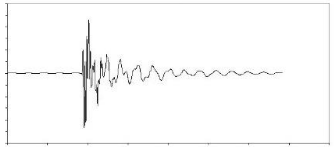
LOTFI ZADEH

- **Uncertainty**
  - **Vagueness**: The lack of definite or sharp distinctions
  - **Ambiguity**: One-to-many relationships
    - **Discord (conflict)**: Disagreement in choosing among several alternatives
    - **Non-specificity**: Two or more alternatives are left unspecified

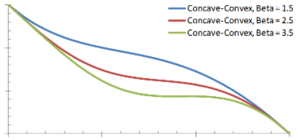
Klir and Yuan (1995)

Multi-Hazard

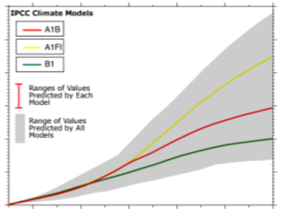
Earthquakes



Aging and deterioration

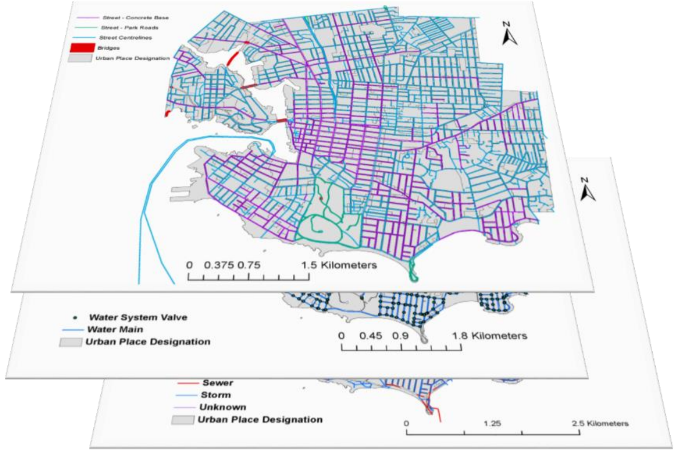


Climate change: Env. Canada

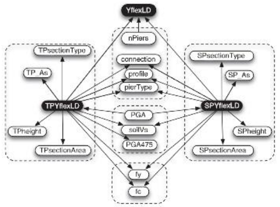


Complex Systems

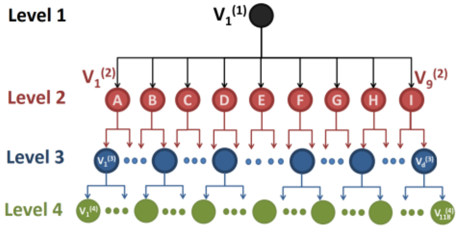
Spatially distributed system



System modelling

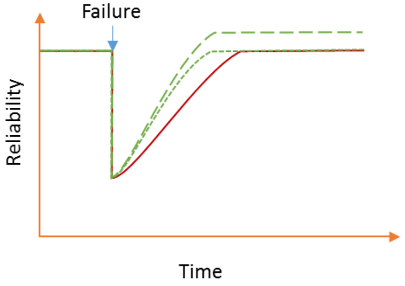


Hierarchical modelling of network



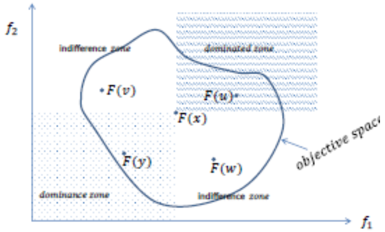
System Performance: Resiliency

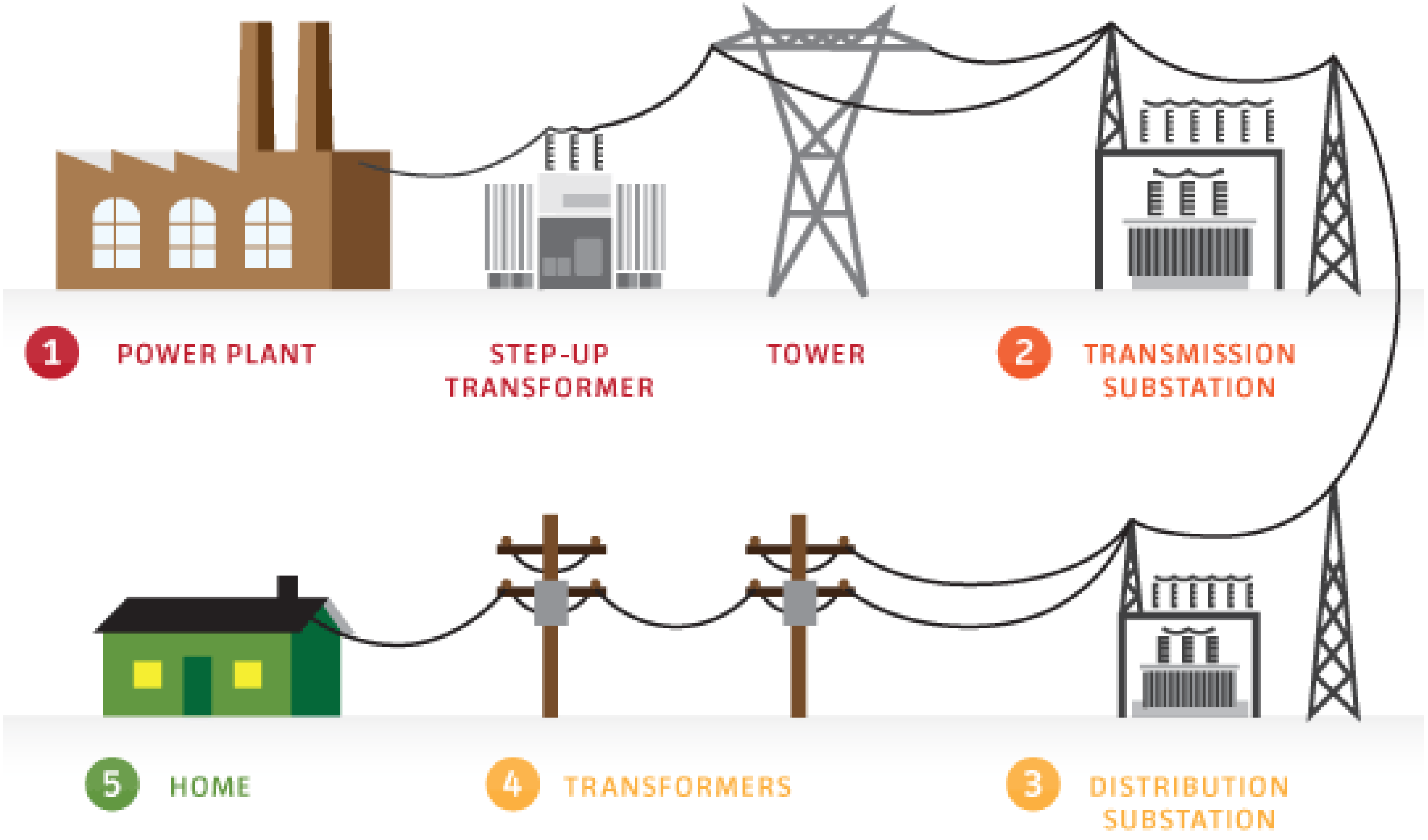
Resiliency



Decision making under uncertainty and risk

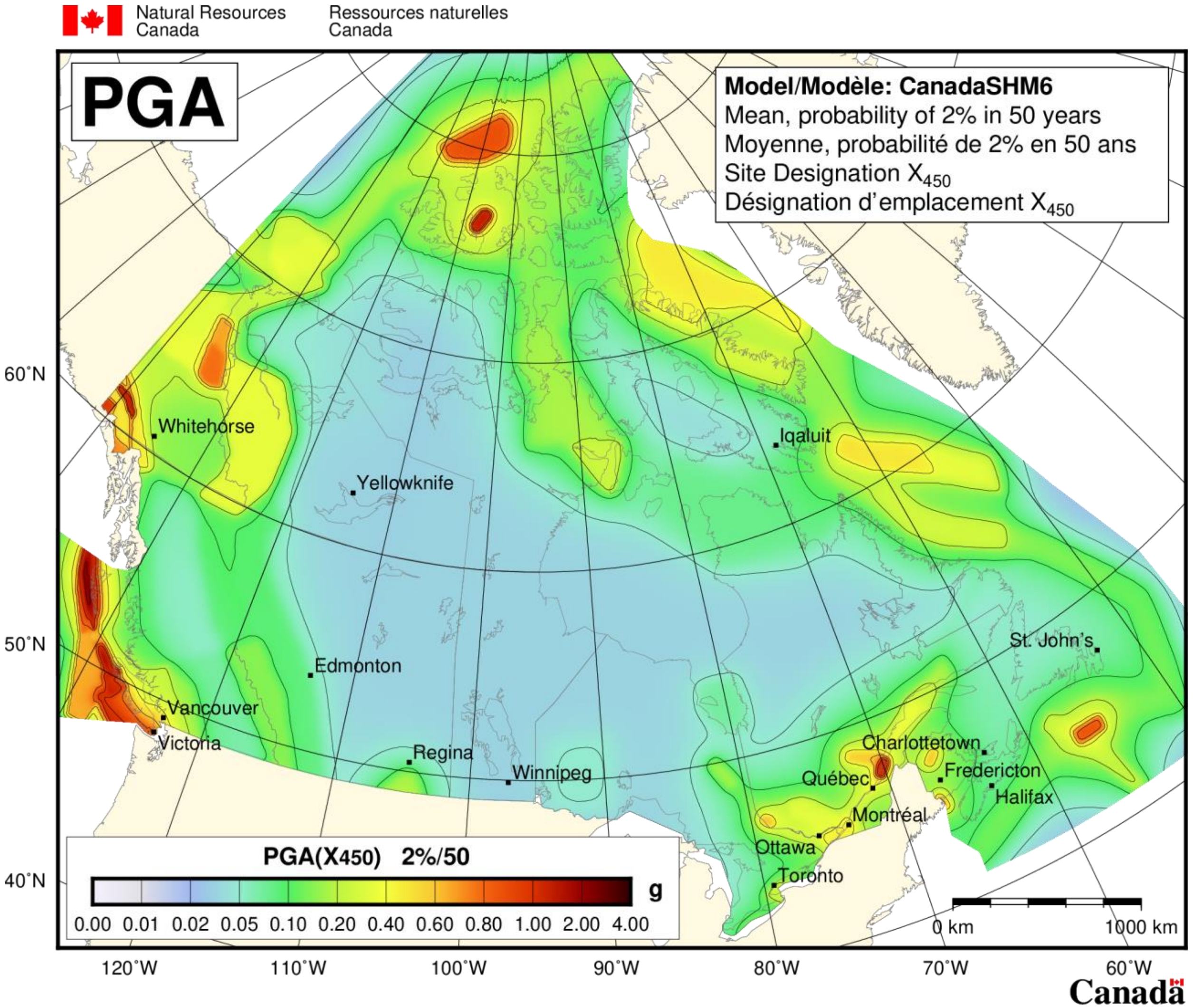
Multi-objective optimization





Source of figure: http://www.dpandl.com/education/electricity-information/how-electricity-gets-to-you/

Seismicity of Canada



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Seismicity of BC

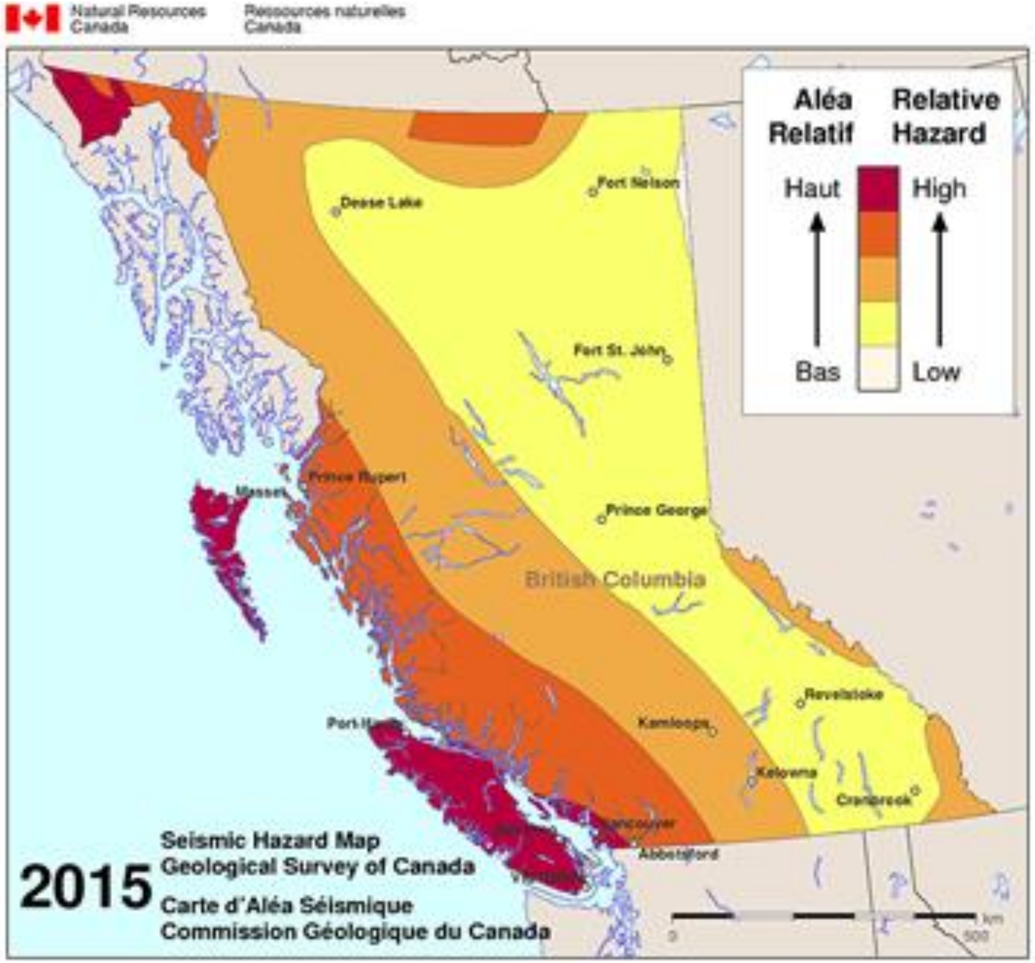
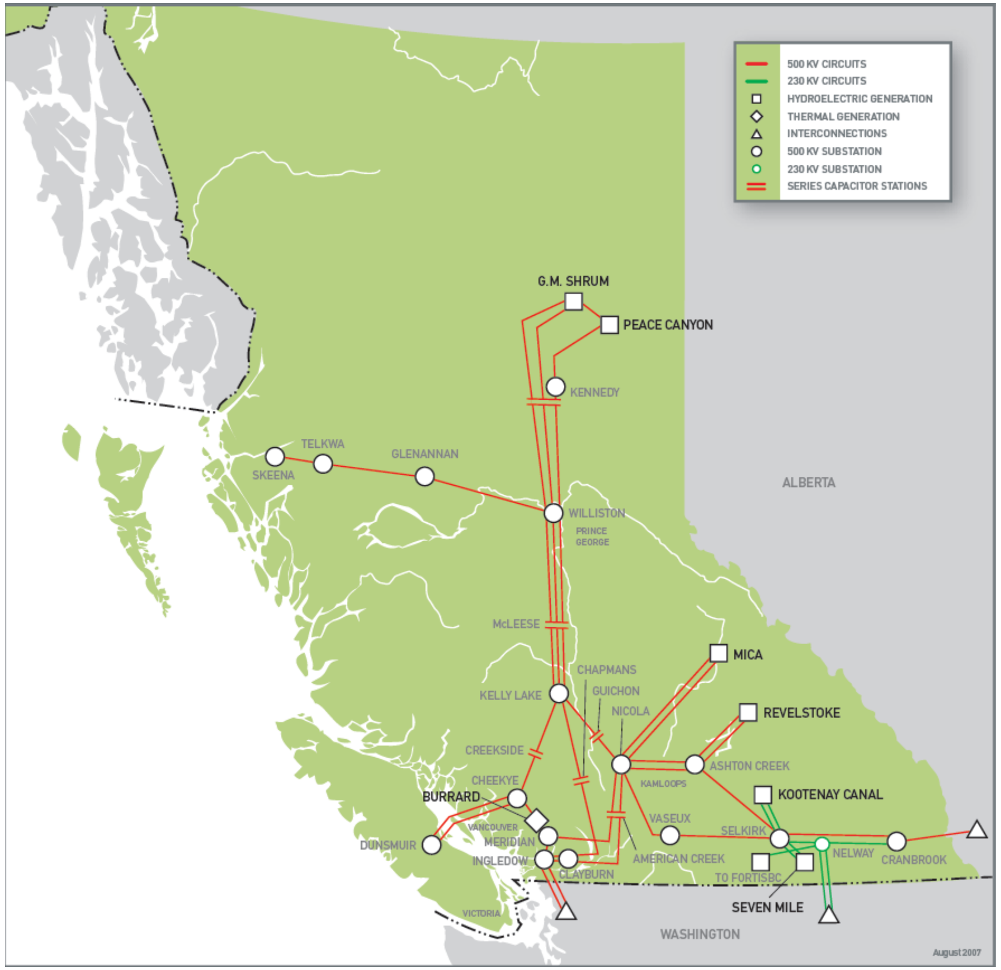
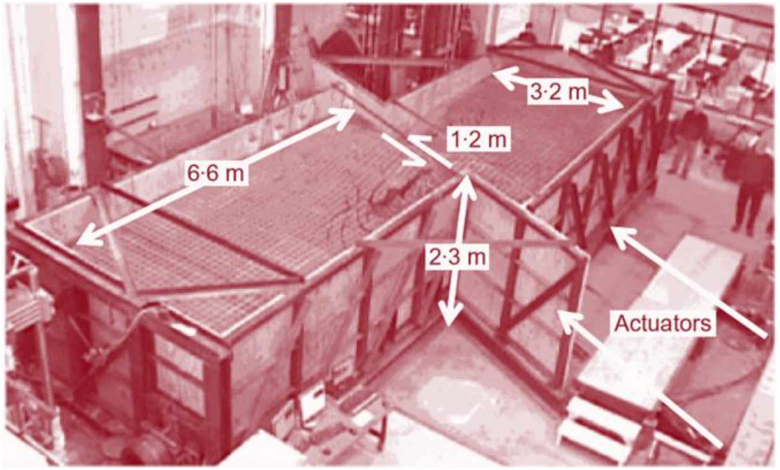


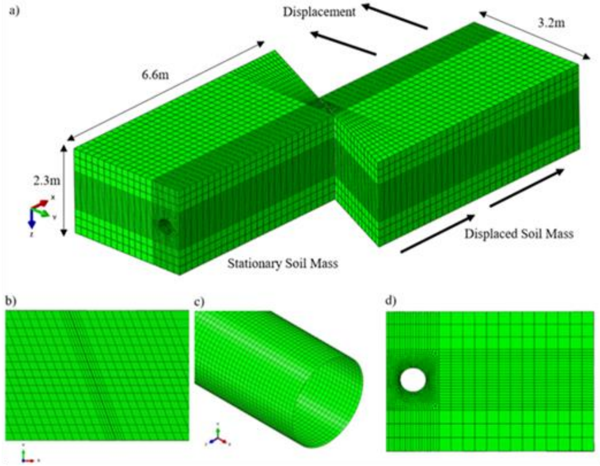
Figure taken from
http://www.bchydro.com/energy_in_bc/projects/substation.html



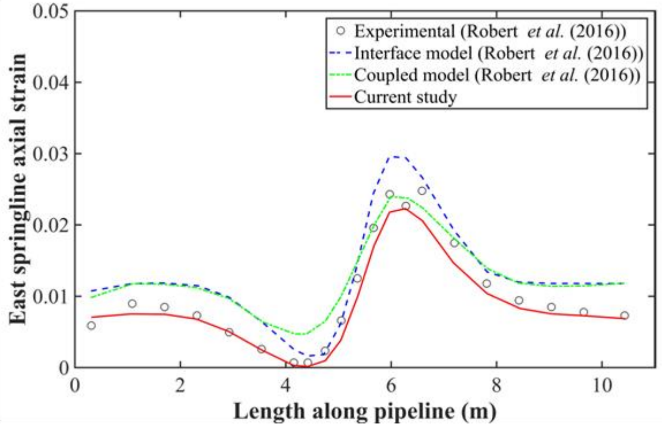
Multi-fidelity pipe vulnerability assessment



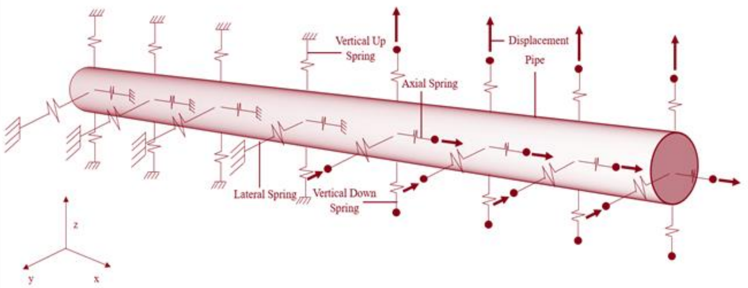
Cornell University Test Setup

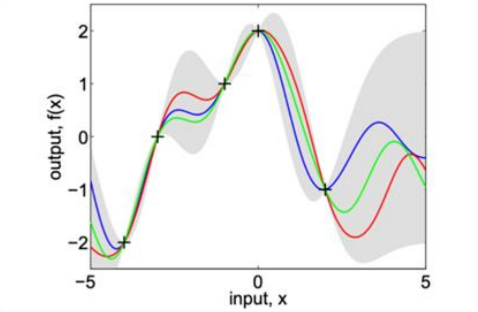


High-fidelity Model



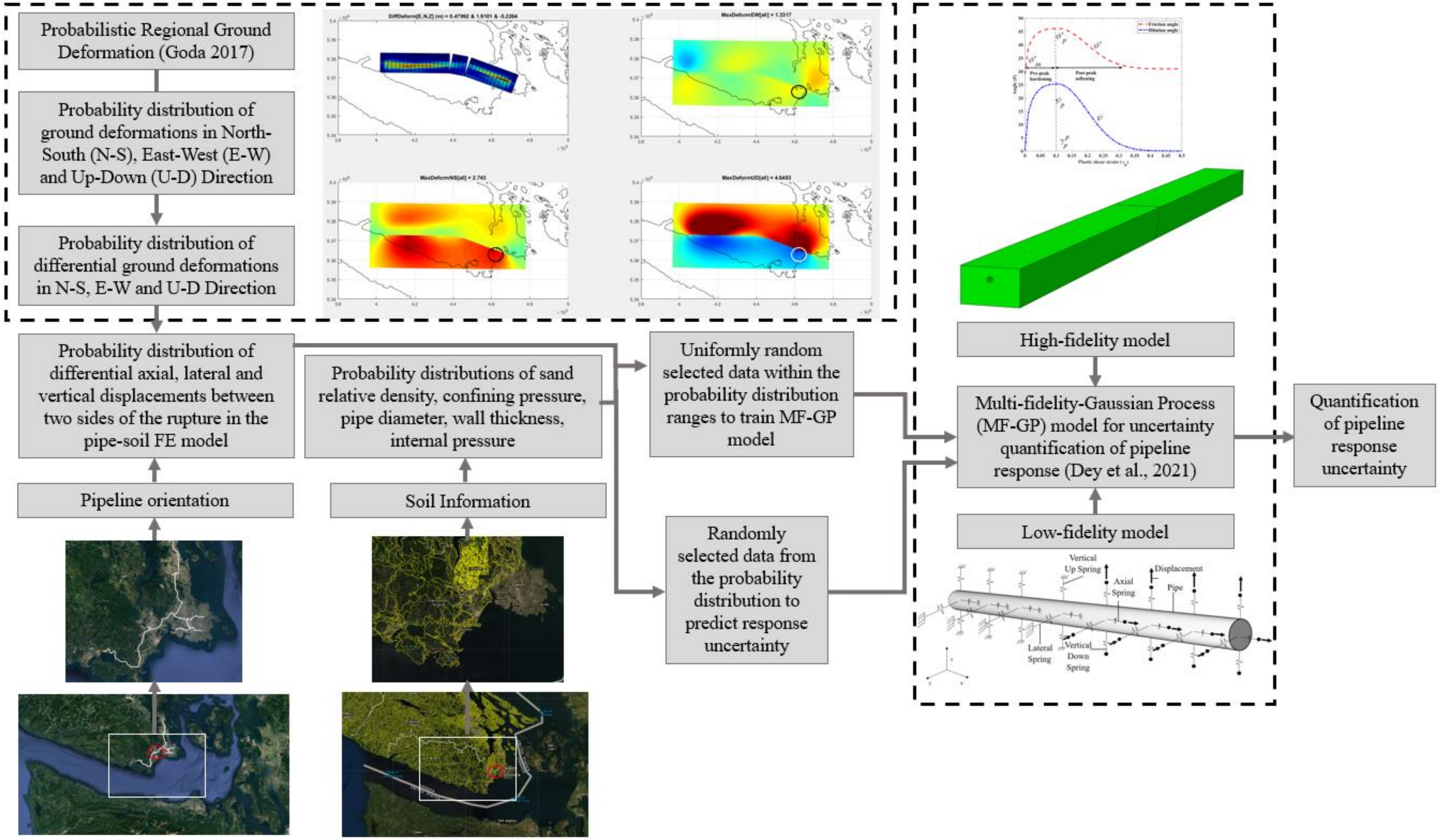
Dey, S., **Chakraborty**, S. and Tesfamariam, S. 2020. Structural performance of buried pipeline undergoing strike-slip fault rupture in 3D using a non-linear sand model. ***Soil Dynamics and Earthquake Engineering***, 135, 106180.





Dey, S., **Chakraborty**, S. and Tesfamariam, S. 2021. Multi-fidelity approach for uncertainty quantification of buried pipeline response undergoing fault rupture displacements in sand. ***Computers and Geotechnics***, 136, 104197.

Regional seismic vulnerability assessment of pipelines



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Motivation

Losses during Northridge EQ, 1994

- Power disruption lasted about 3 hours (max)
- Direct economic losses $138 million to Los Angeles department of water and power

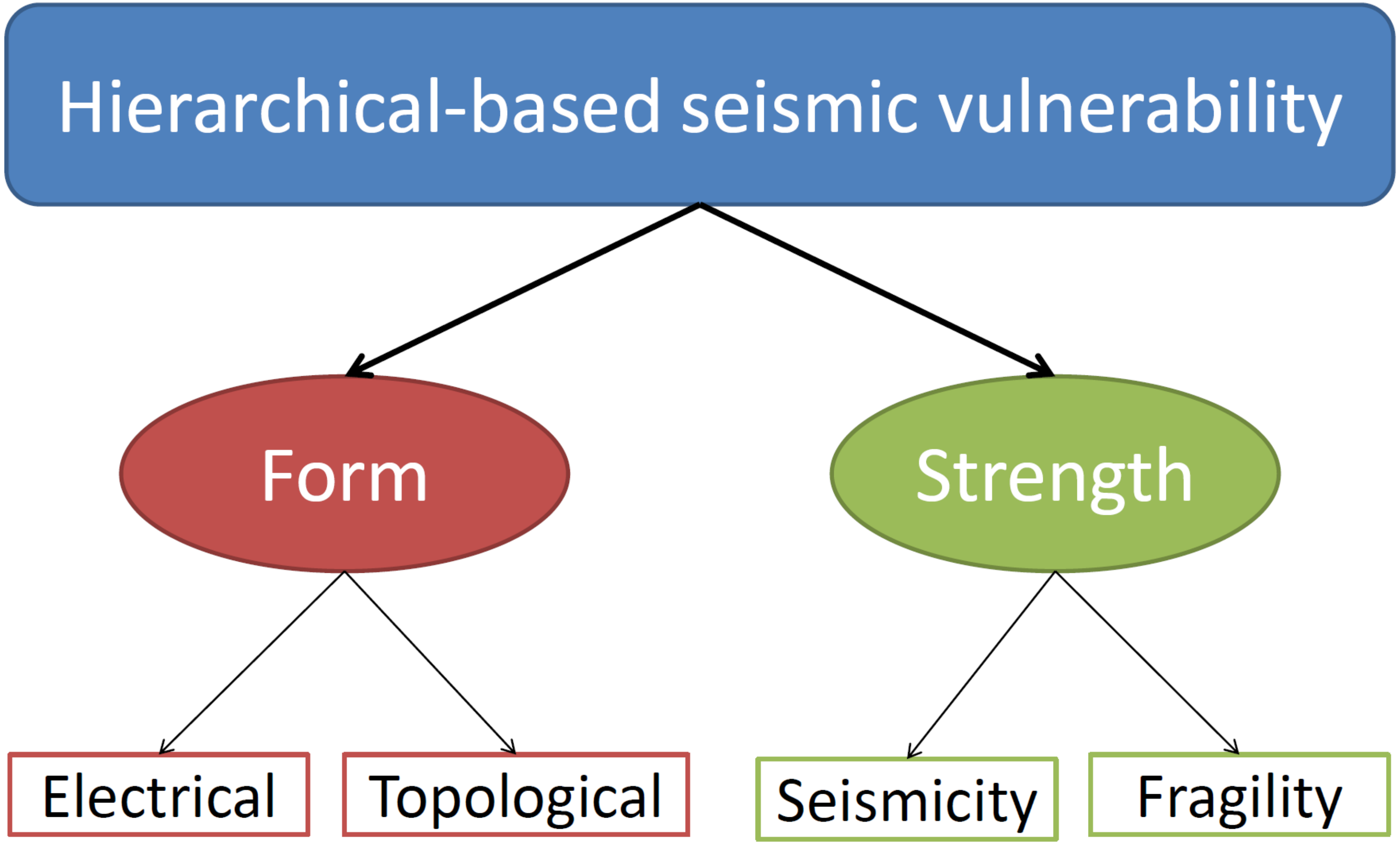
Motivation

- A key component of substations is the transformer (60% of the total investment)
- Methods that enable large transformer vulnerability assessment in a practical and rigorous way are scarce
- Study proposes risk assessment using BBN which combines most of the critical failure modes

Transformer failure

TOPOLOGICAL VULNERABILITY ASSESSMENT OF POWER TRANSMISSION NETWORK

Buriticá Cortés, J.A., Sánchez-Silva, M. and Tesfamariam, S., 2015. A hierarchy-based approach to seismic vulnerability assessment of bulk power systems. Structure and Infrastructure Engineering, 11(10), pp.1352-1368.



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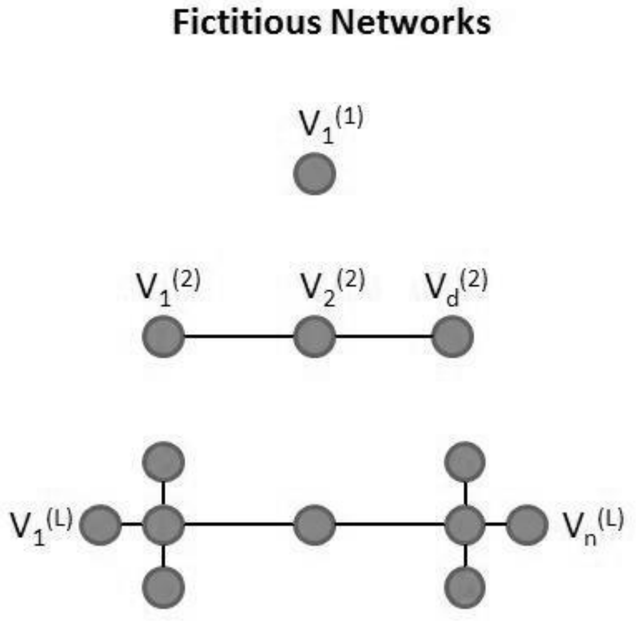
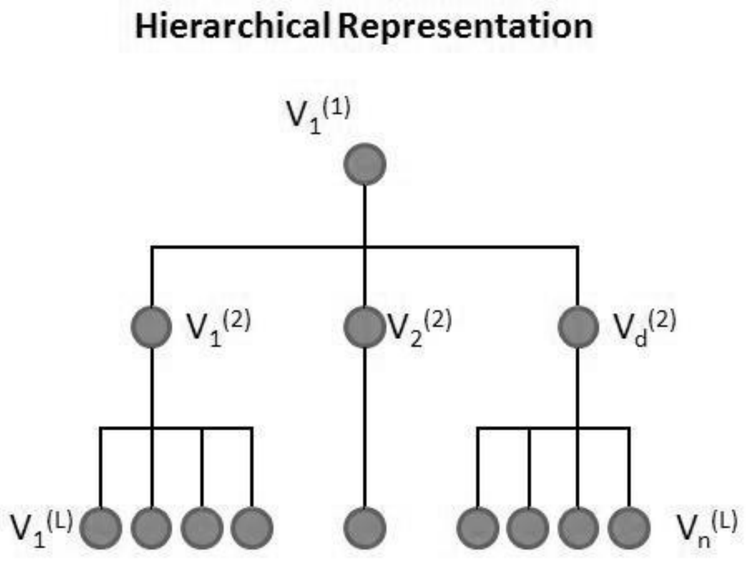
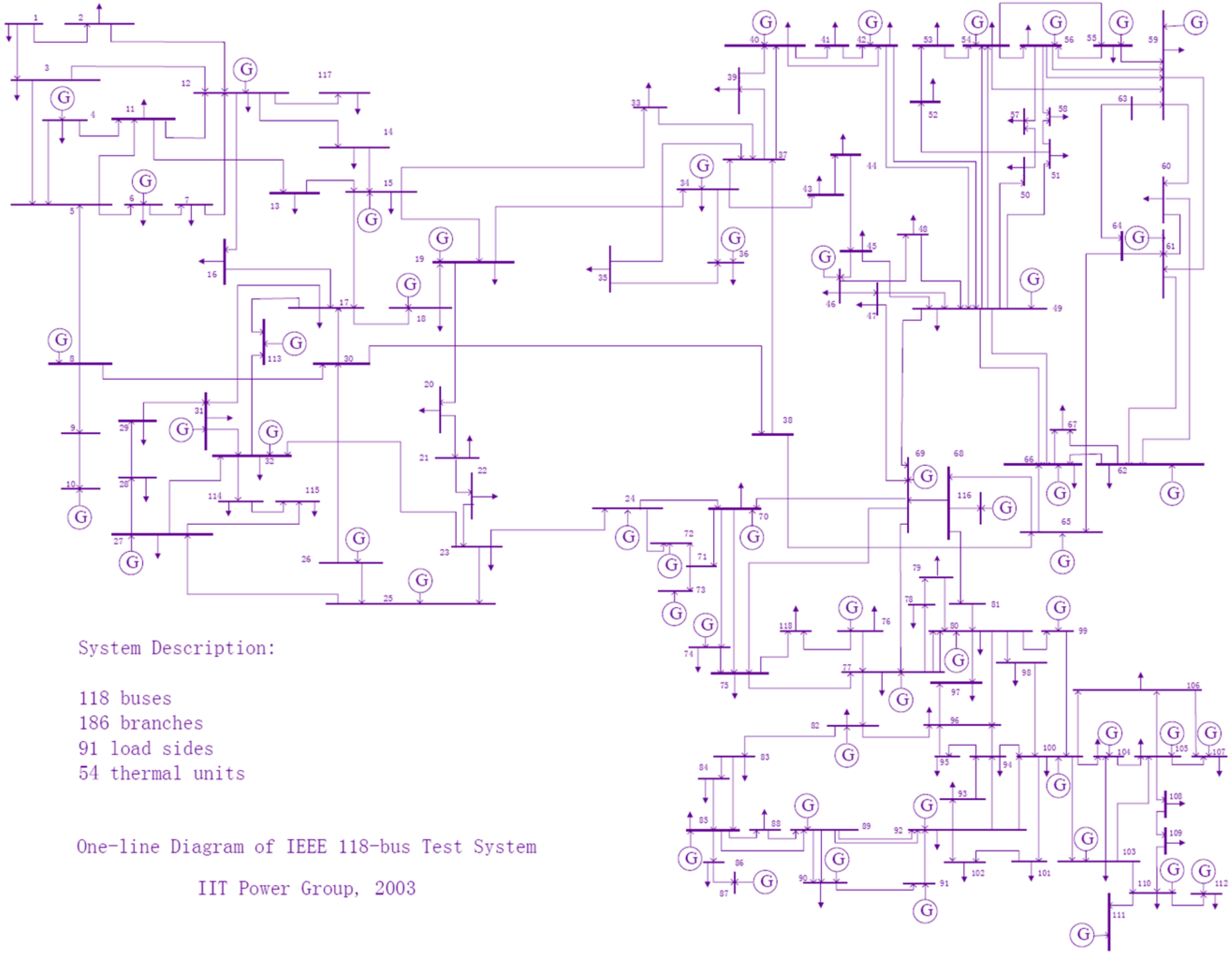
Topological importance: Hierarchical representation

- The use of recursive clustering is proposed to: detect Communities and Communities of communities until the network consists of a single unit.






System Description:
118 buses
186 branches
91 load sides
54 thermal units
One-line Diagram of IEEE 118-bus Test System
IIT Power Group, 2003

Electrical importance: Drop in net-ability

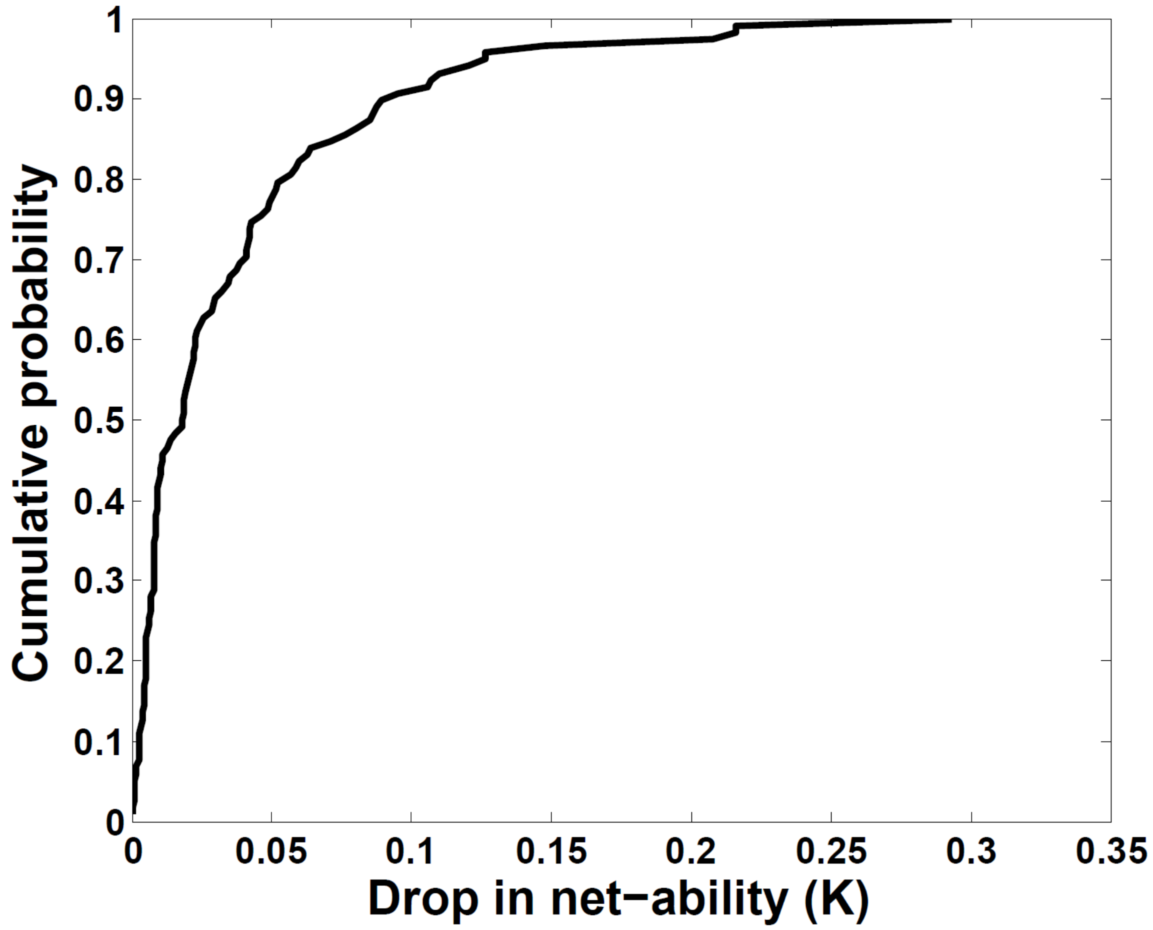
- Net-ability is a capacity measure of power flow in a power network. The drop in net-ability constitutes the relative electrical importance:

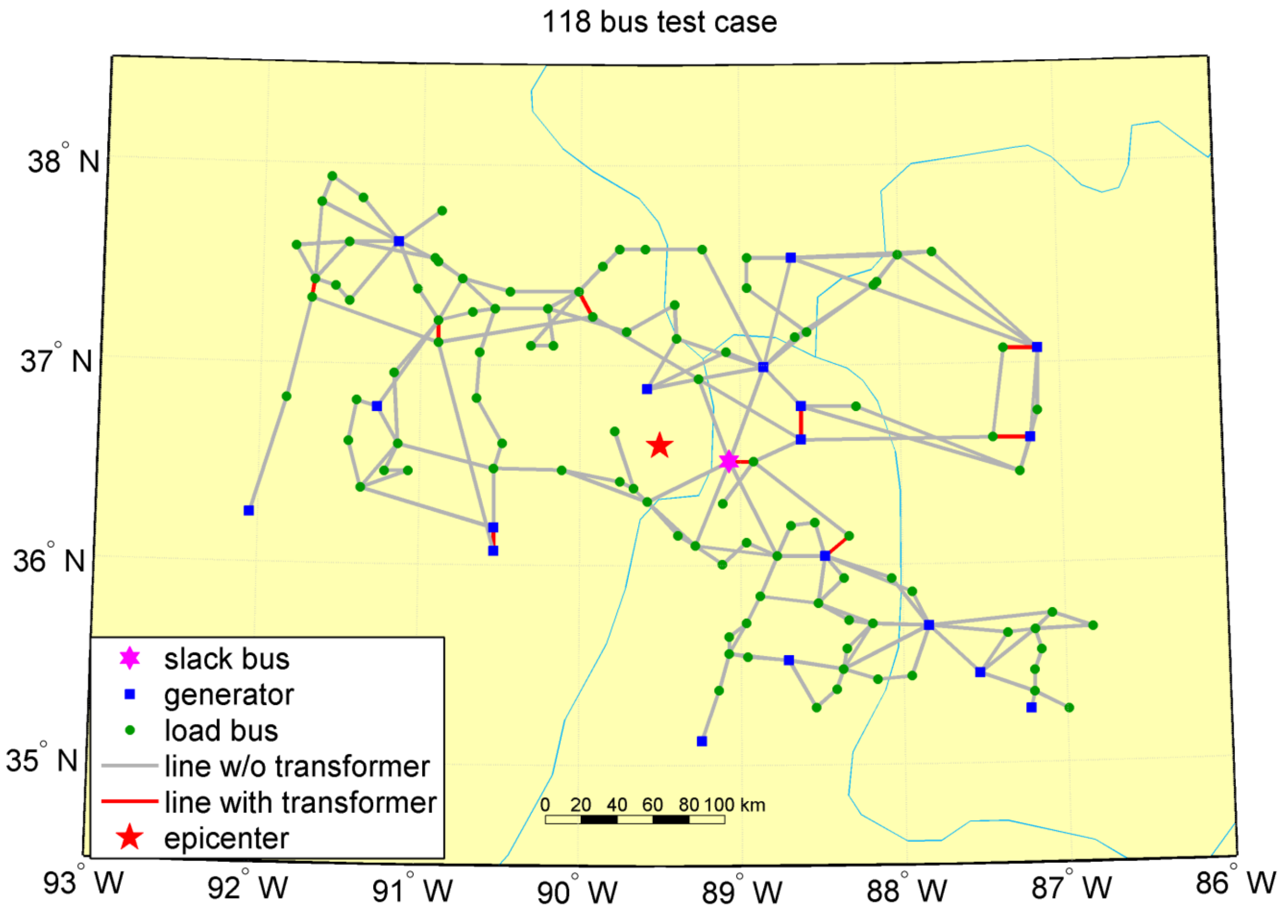
where
- K(j) = drop in net-ability
- A = global electrical efficiency (net-ability)
- A(j) = efficiency after the removal of element j
- NG = number of generation nodes
- ND = number of transmission and load nodes
- C_{ij} = power transmission capability
- Z_{ij} = equivalent impedance

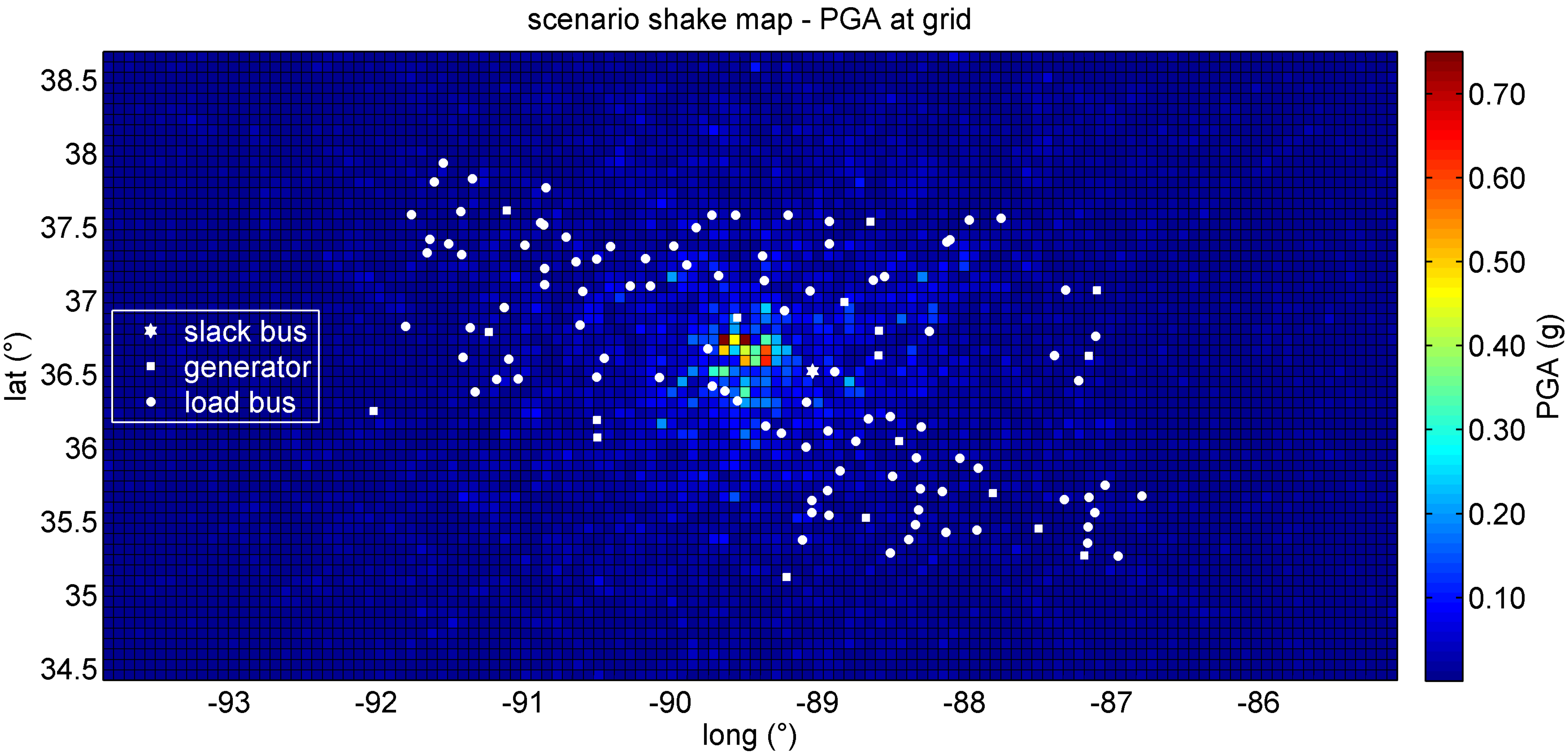
$$K(j) = \frac{A - A(j)}{A}$$

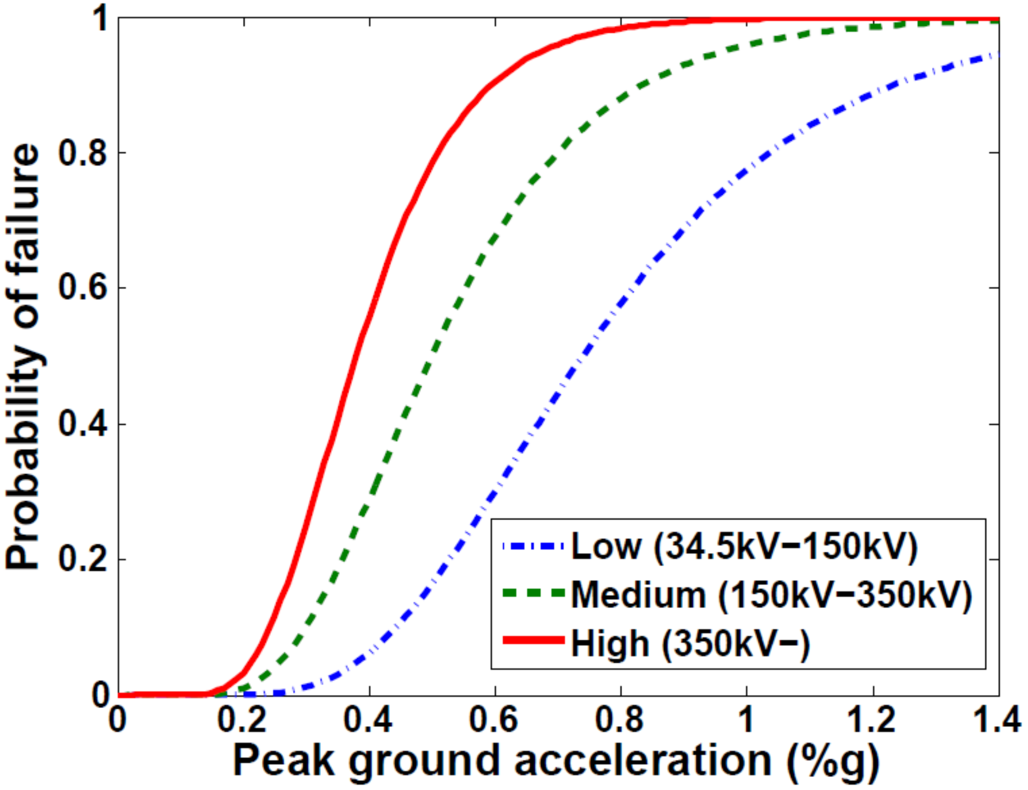
$$A = \frac{1}{N_G N_D} \sum_{i \in G} \sum_{j \in D} \frac{C_{ij}}{Z_{ij}}$$

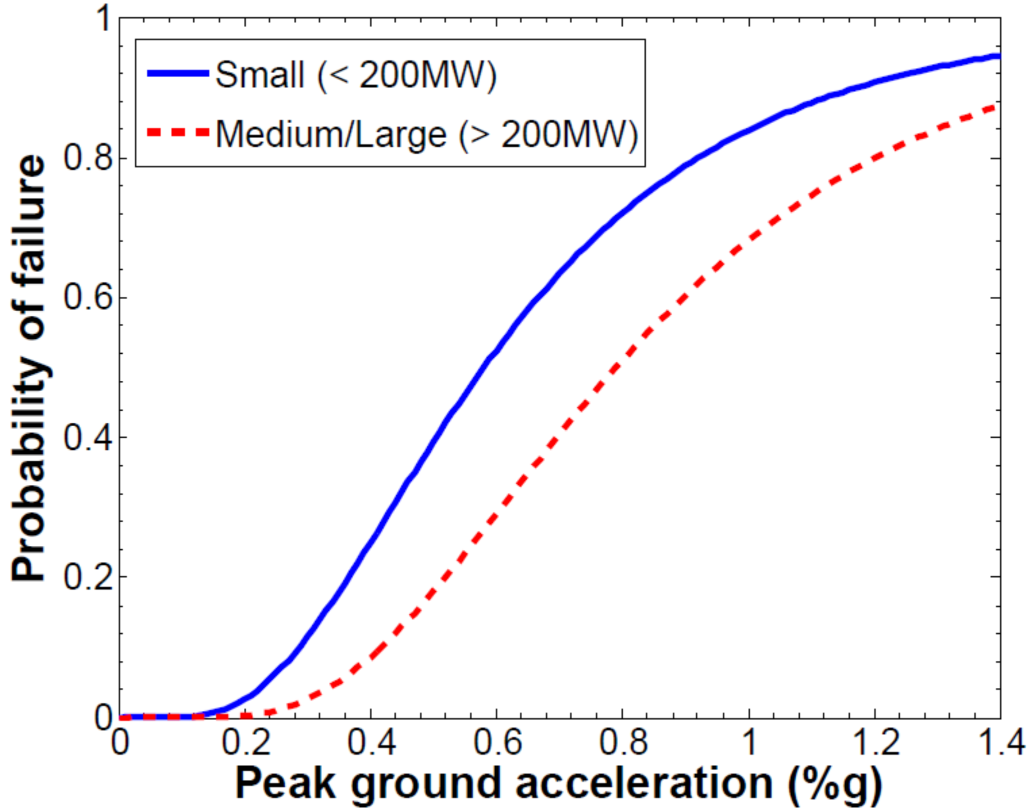
Electrical importance: Drop in net-ability




118 bus test case
38° N
37° N
36° N
35° N
93° W
92° W
91° W
90° W
89° W
88° W
87° W
86° W
slack bus
generator
load bus
line w/o transformer
line with transformer
epicenter
0 20 40 60 80 100 km


scenario shake map - PGA at grid
lat (°)
long (°)
PGA (g)
38.5
38
37.5
37
36.5
36
35.5
35
34.5
-93
-92
-91
-90
-89
-88
-87
-86
0.70
0.60
0.50
0.40
0.30
0.20
0.10
slack bus
generator
load bus





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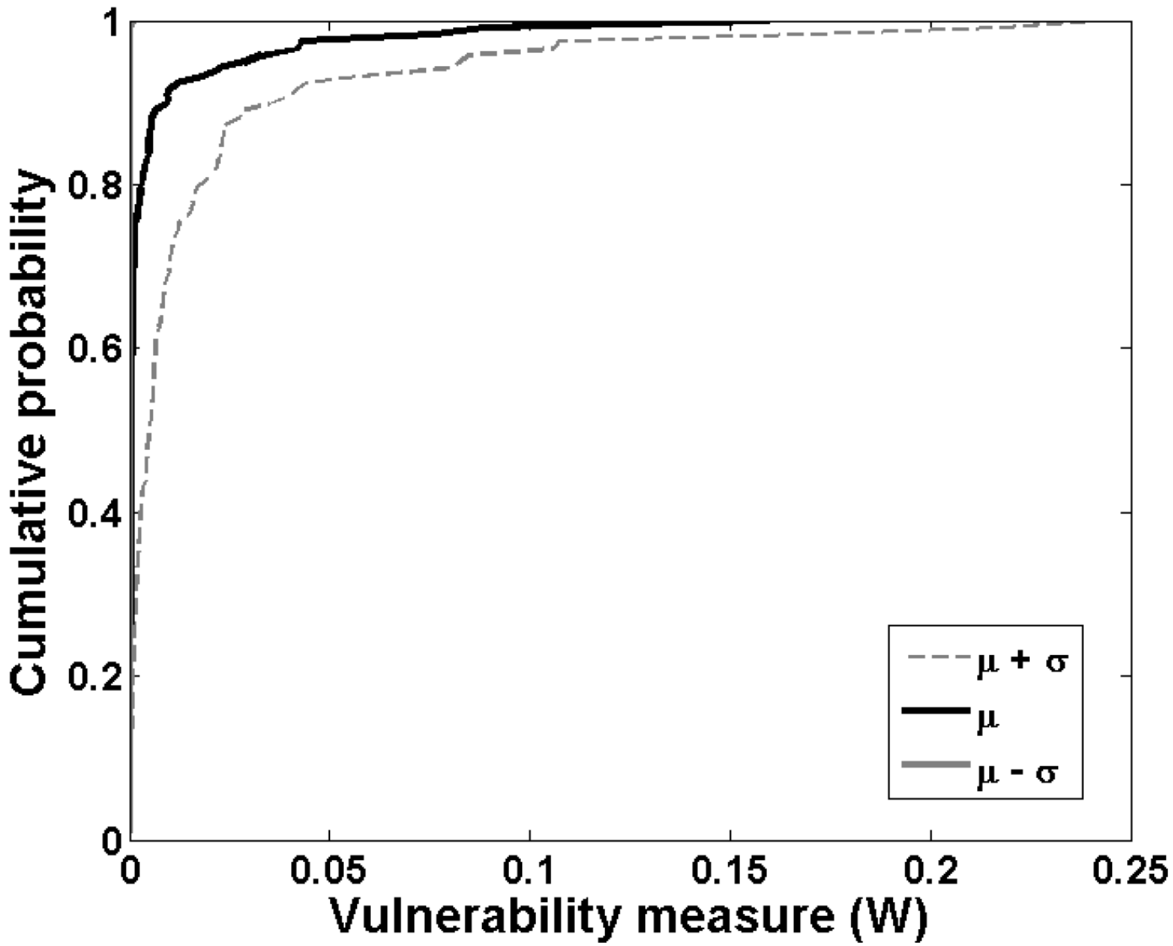
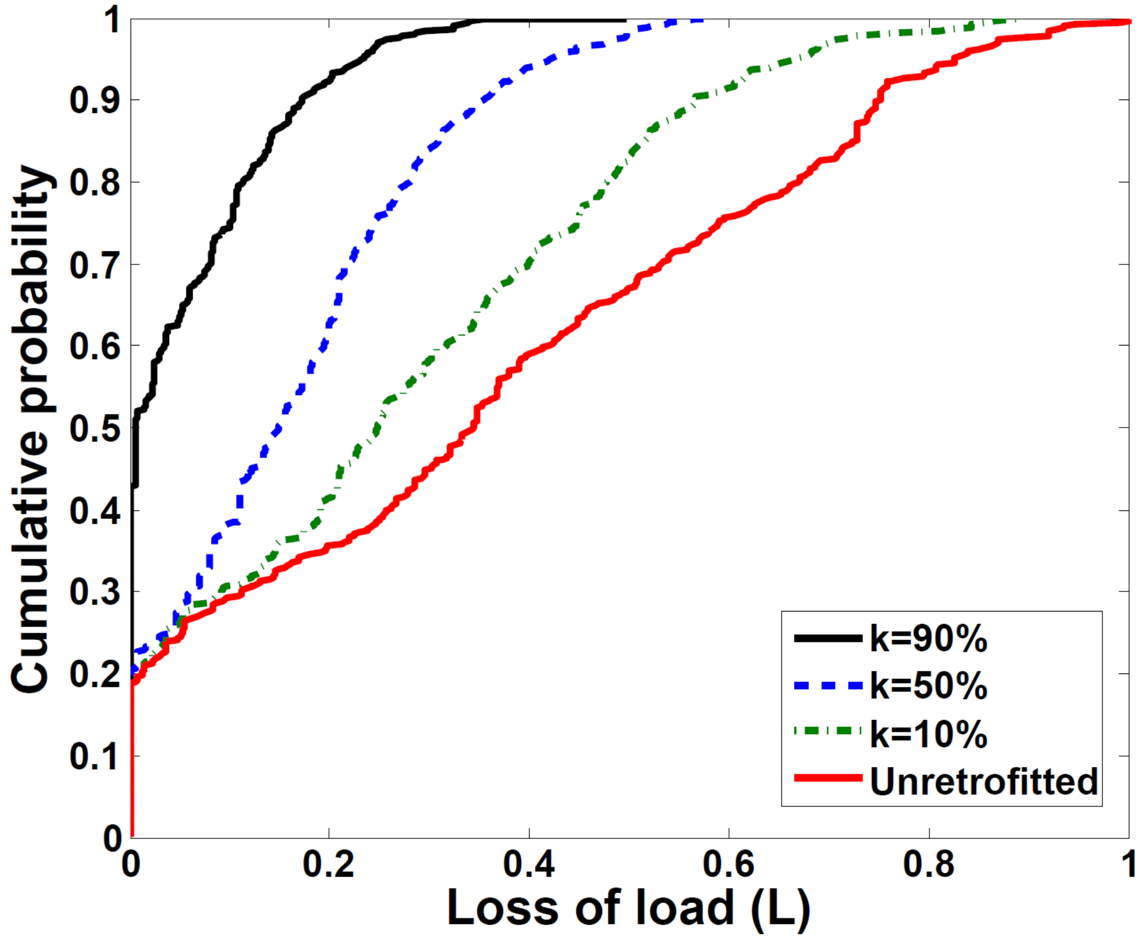
Vulnerability



Prioritization



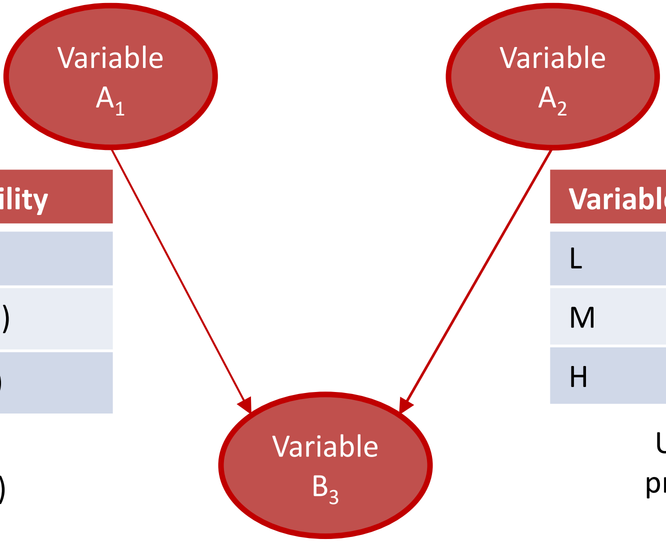
BAYESIAN BELIEF NETWORK (BBN)

Bayesian belief network

BBN is an acyclic directed graph composed by:

- A set of nodes (i.e., variables), with a finite set of states
- A set of directed edges between nodes, that represent probability relations

Design consideration and deterioration



Variable A_1	Probability
L	$P(A_1=L)$
M	$P(A_1=M)$
H	$P(A_1=H)$

Unconditional probability (UP)

Variable A_2	Probability
L	$P(A_2=L)$
M	$P(A_2=M)$
H	$P(A_2=H)$

Unconditional probability (UP)

Variable A_1	Variable A_2	Variable B_3		
		Probability		
		L	**M**	**H**
L	L	$P(B_3=L\|A_1=L, A_2=L)$	$P(B_3=M\|A_1=L, A_2=L)$	$P(B_3=H\|A_1=L, A_2=L)$
…	…	…	…	…
H	M	$P(B_3=L\|A_1=H, A_2=M)$	$P(B_3=M\|A_1=H, A_2=M)$	$P(B_3=H\|A_1=H, A_2=M)$
H	H	$P(B_3=L\|A_1=H, A_2=H)$	$P(B_3=M\|A_1=H, A_2=H)$	$P(B_3=H\|A_1=H, A_2=H)$

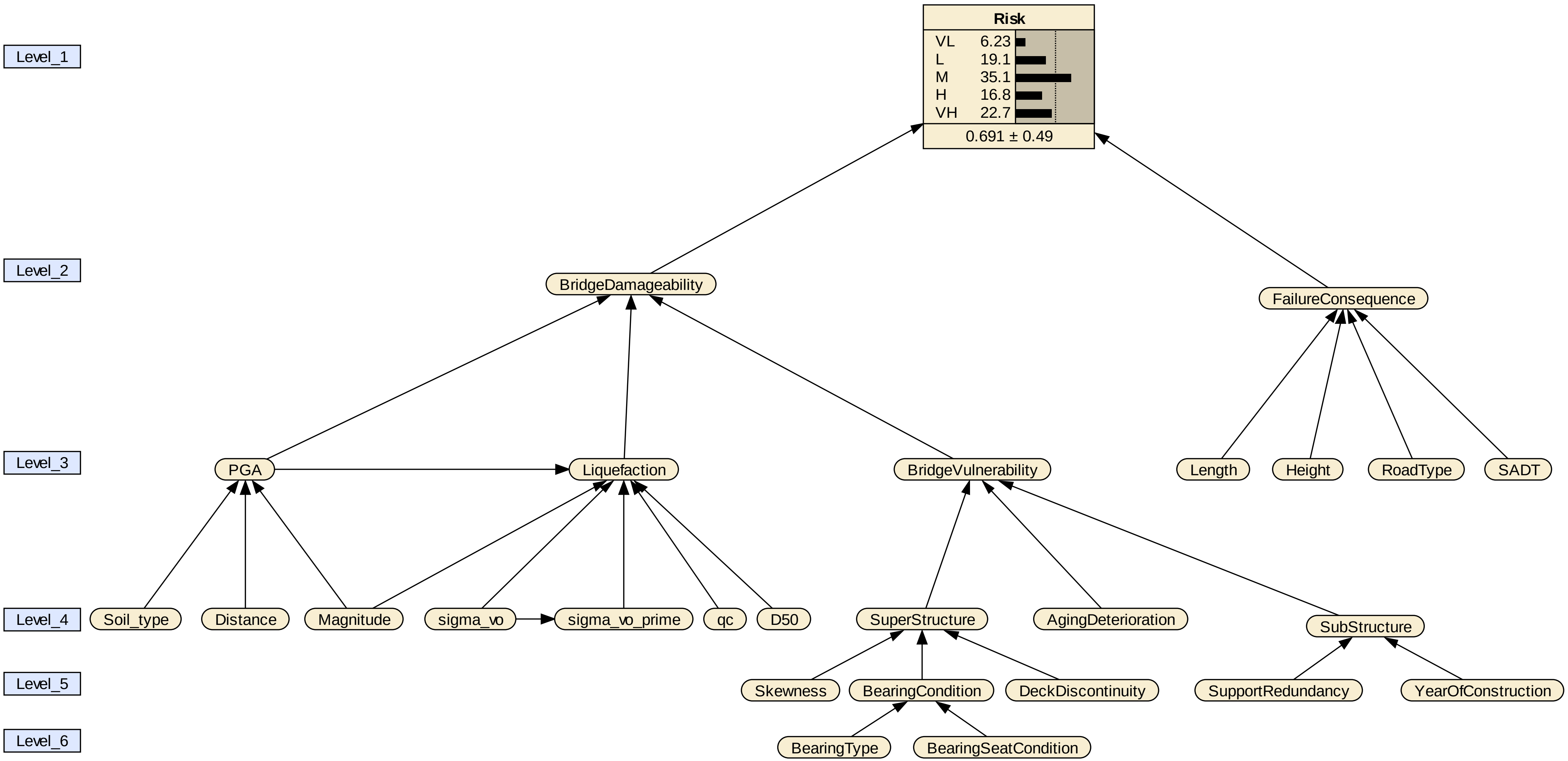
Conditional probability table (CPT)

Bayesian belief network

Employs Bayes' theorem:

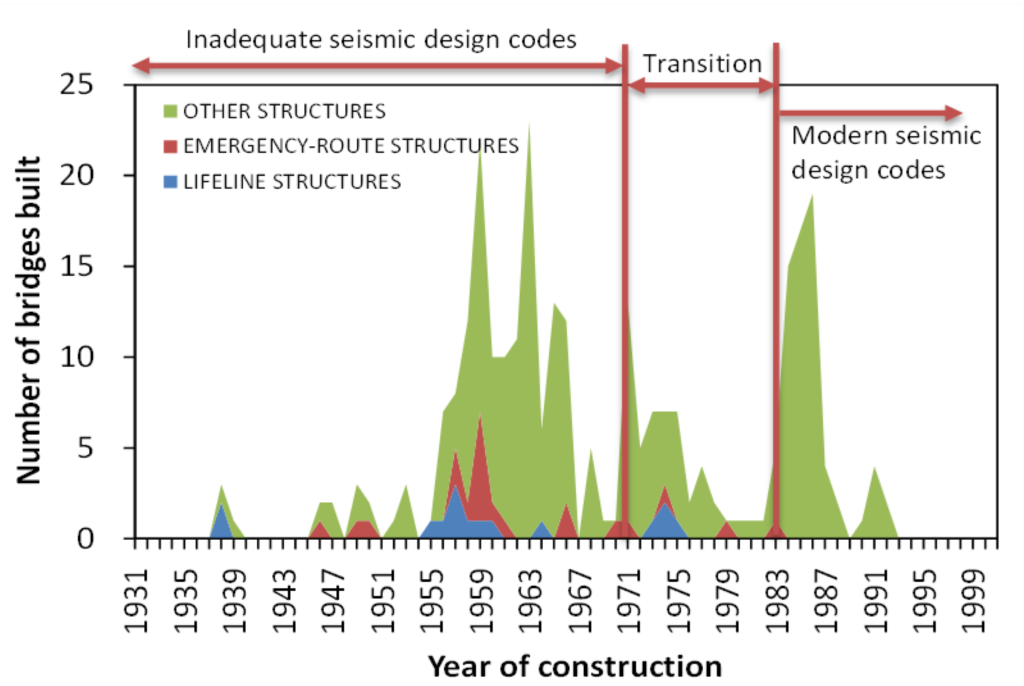
$$P(H_j|E) = \frac{P(E|H_j) \times P(H_j)}{\sum_{i=1}^{n} P(E|H_i) \times P(H_i)}$$

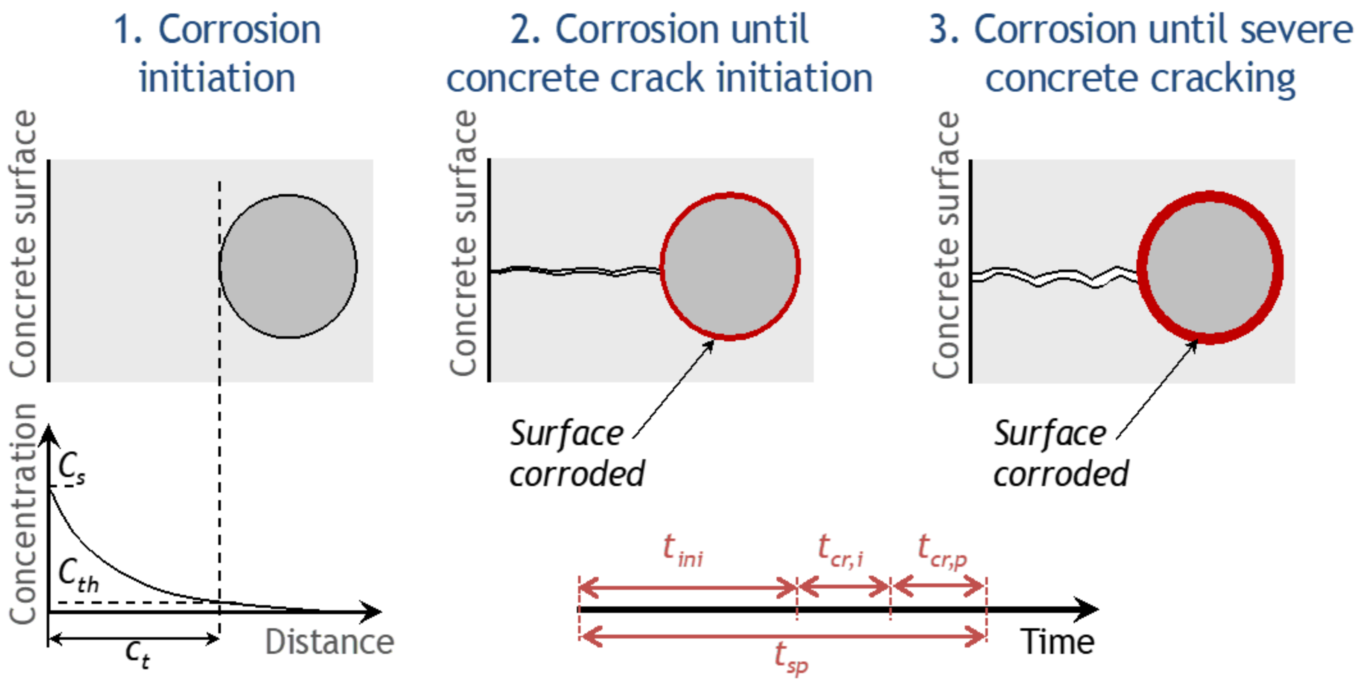
- H is a hypothesis, E is evidence and P() are probabilities



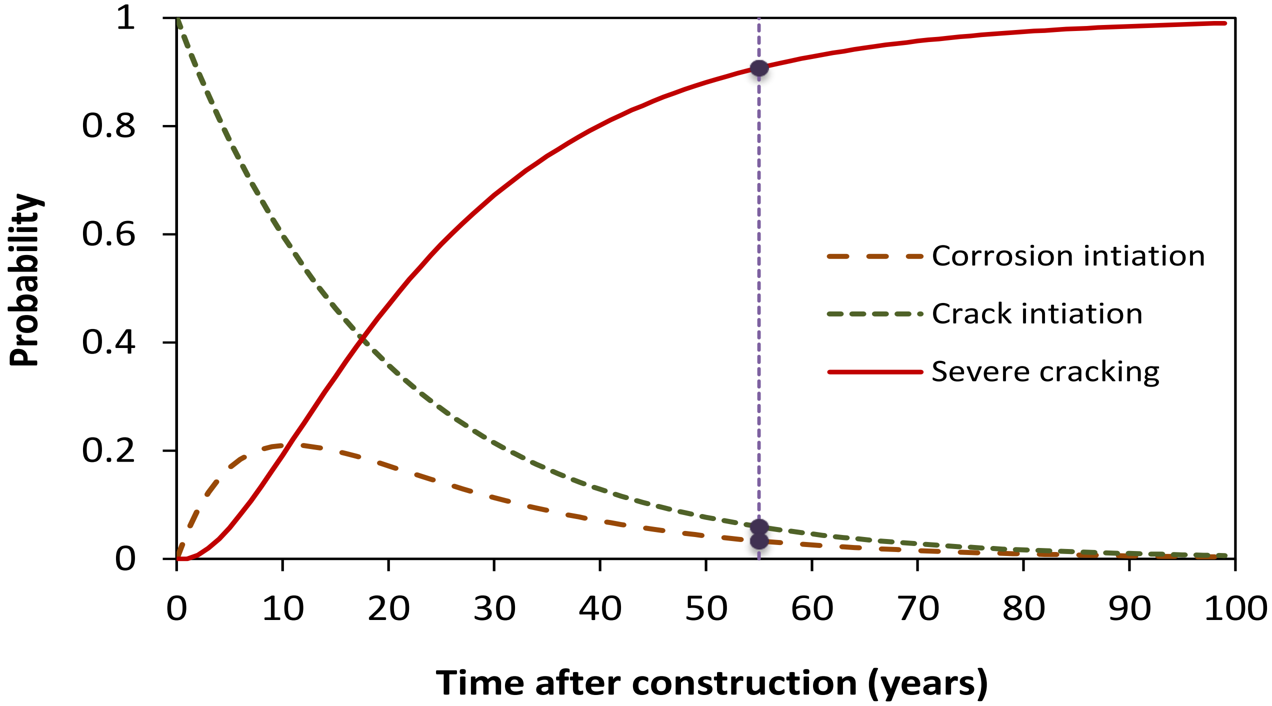
Tesfamariam, S., Bastidas-Arteaga, E. and Lounis, Z. 2018. Seismic retrofit screening of existing highway bridges with consideration of chloride-induced deterioration: A Bayesian belief network model. *Frontiers in Built Environment: Bridge Engineering*, 4(67), 1-11, doi: 10.3389/fbuil.2018.00067.

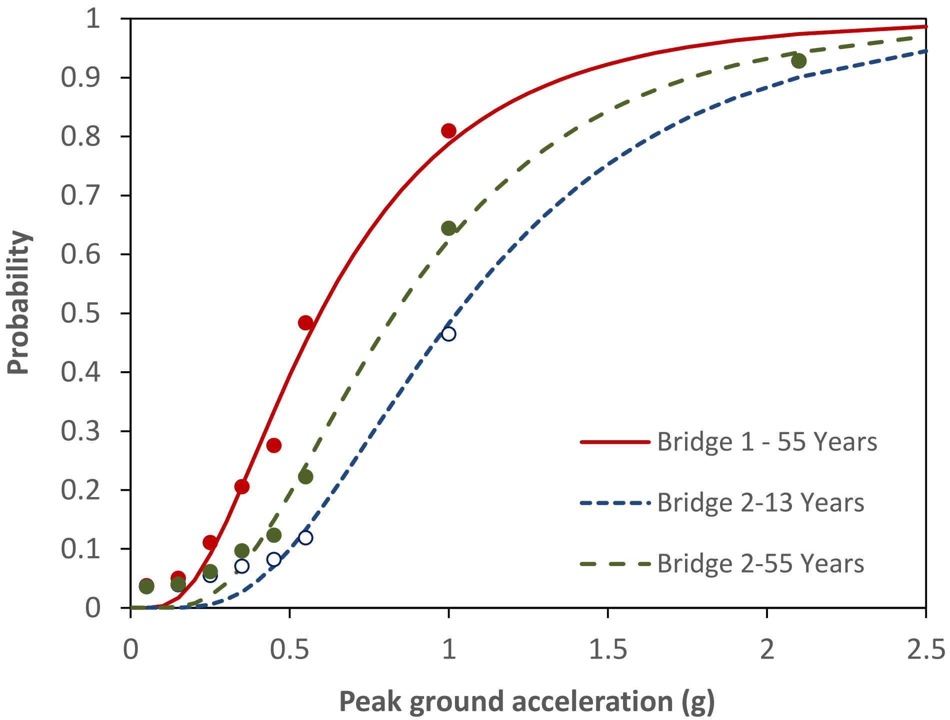
Design consideration and deterioration





Design consideration and deterioration





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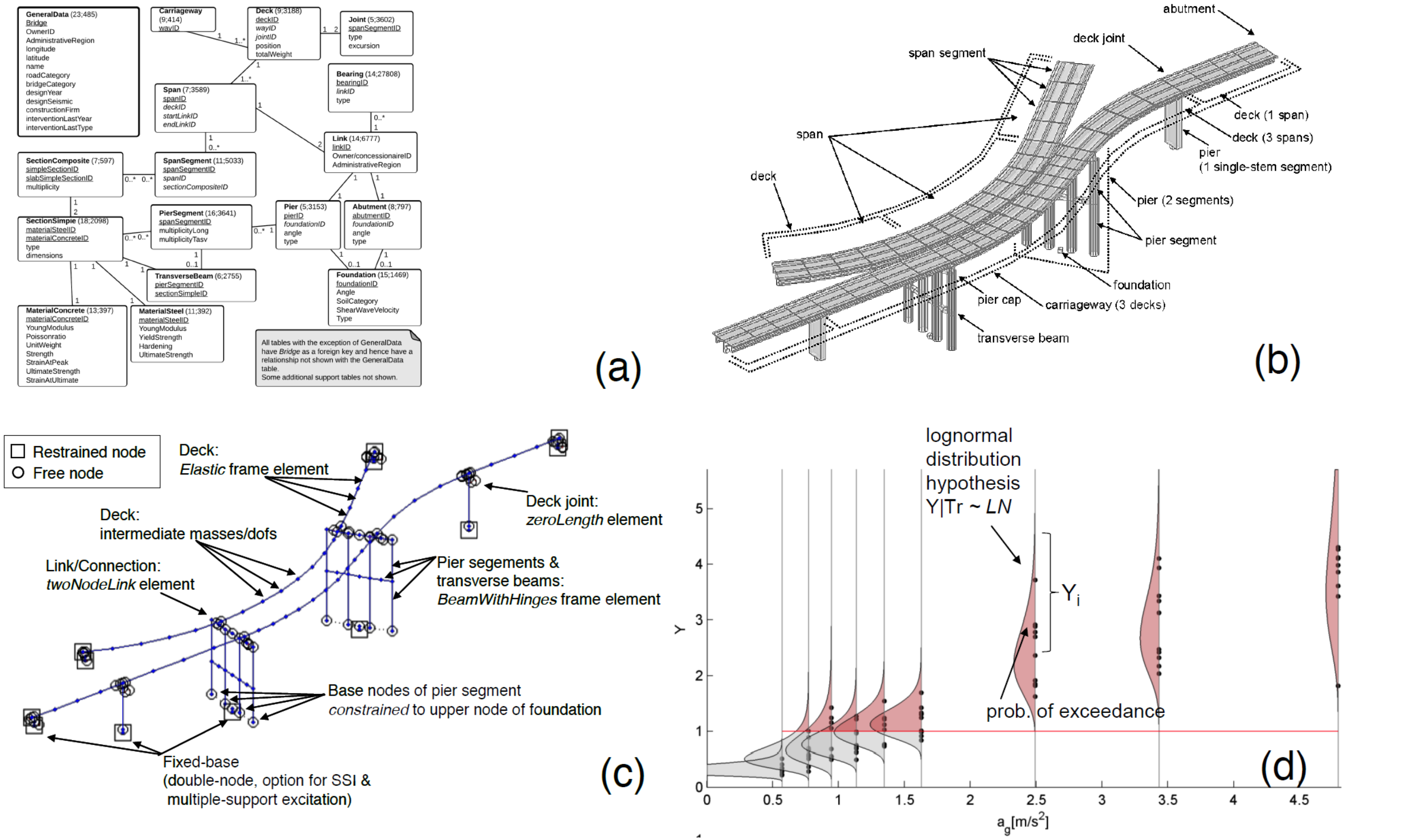
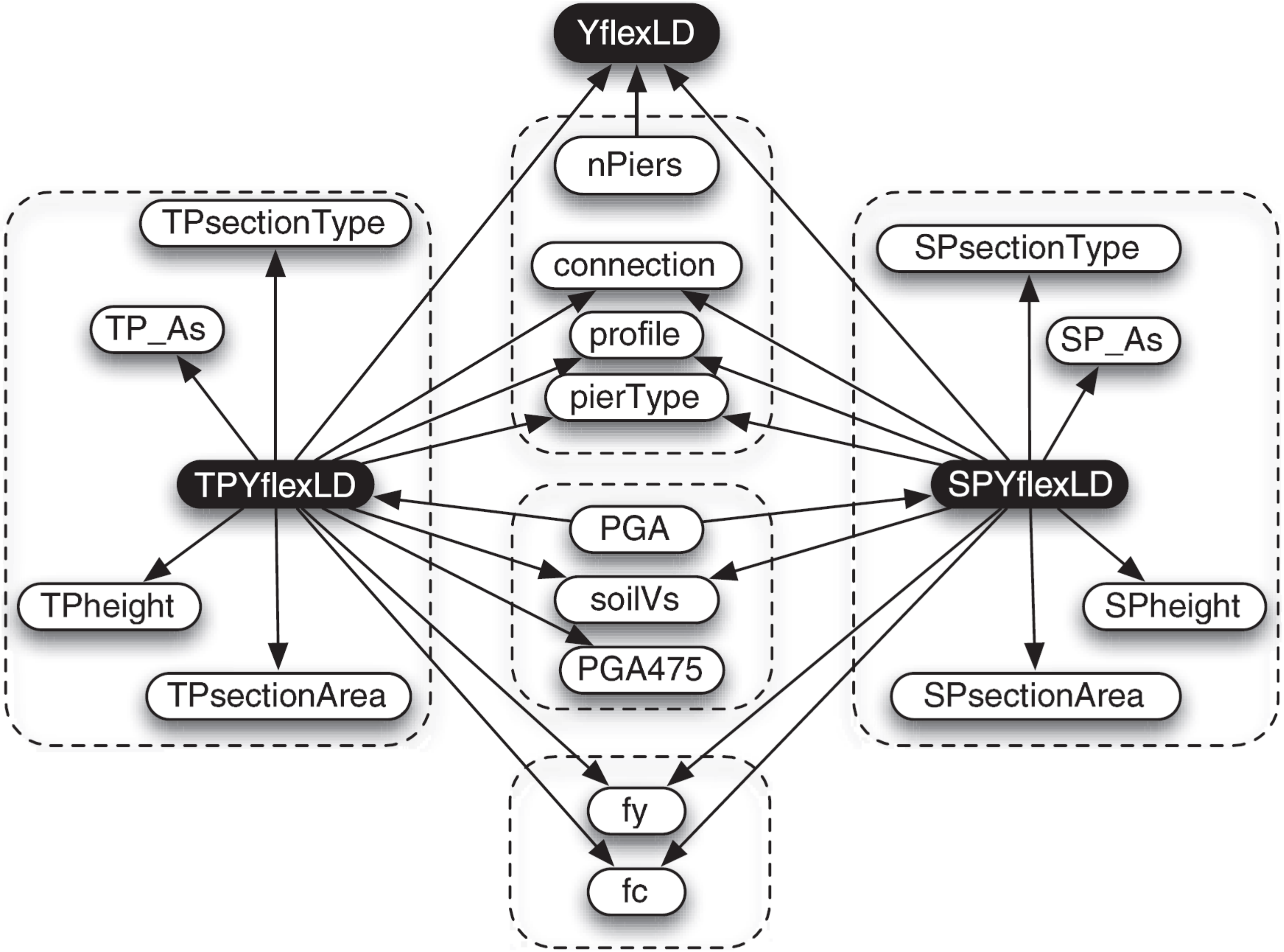
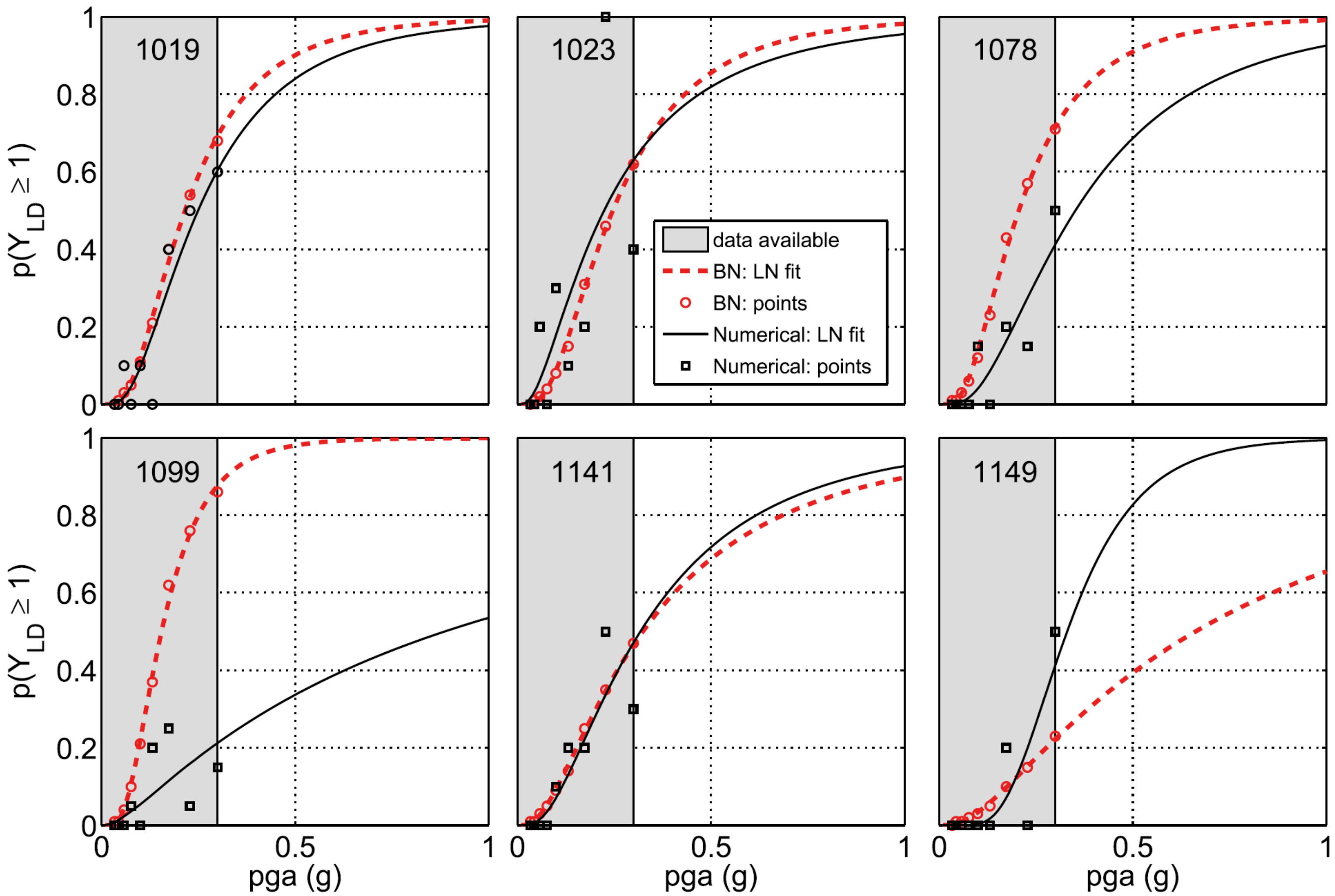


Franchin, P., Lupoi, A., Noto, F., and Tesfamariam, S. 2016. Seismic fragility of reinforced concrete girder bridges using Bayesian belief network. *Earthquake Engineering & Structural Dynamics*, 45(1), 29–44.

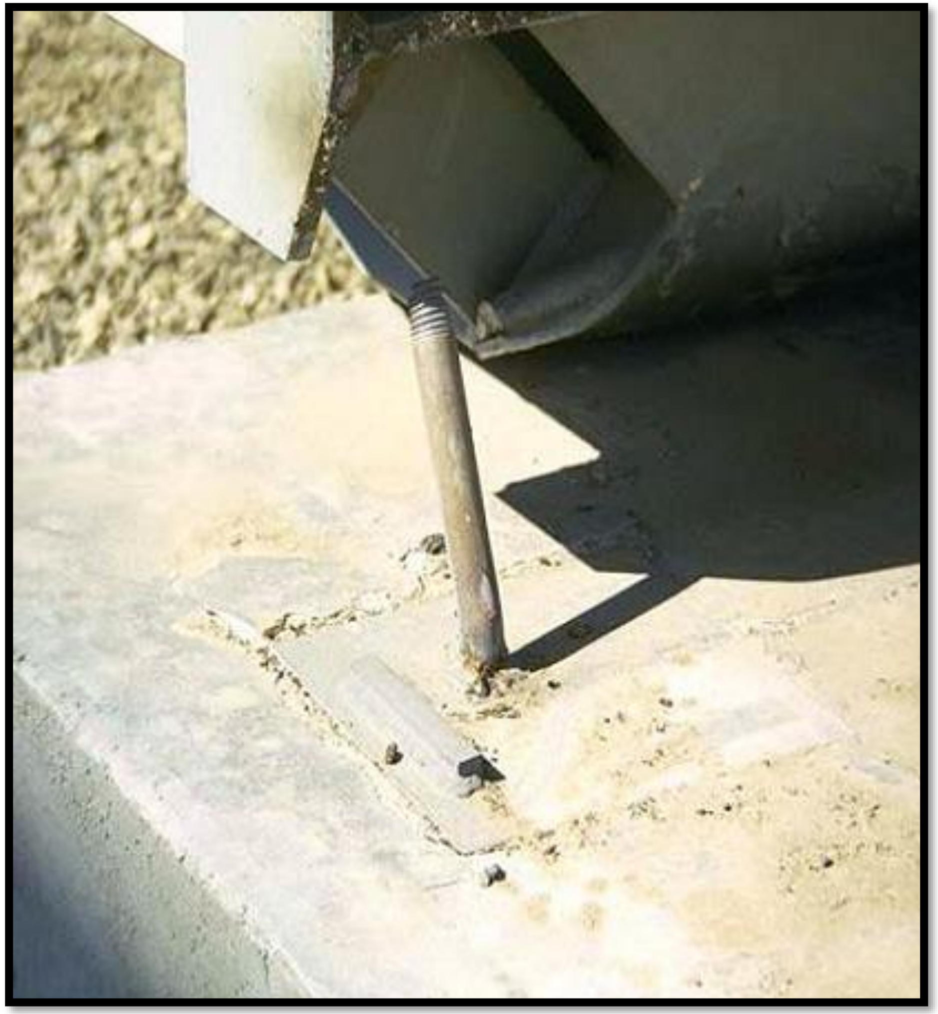

YflexLD
nPiers
connection
profile
pierType
TPsectionType
TP_As
TPYflexLD
TPheight
TPsectionArea
SPsectionType
SP_As
SPYflexLD
SPheight
SPsectionArea
PGA
soilVs
PGA475
fy
fc

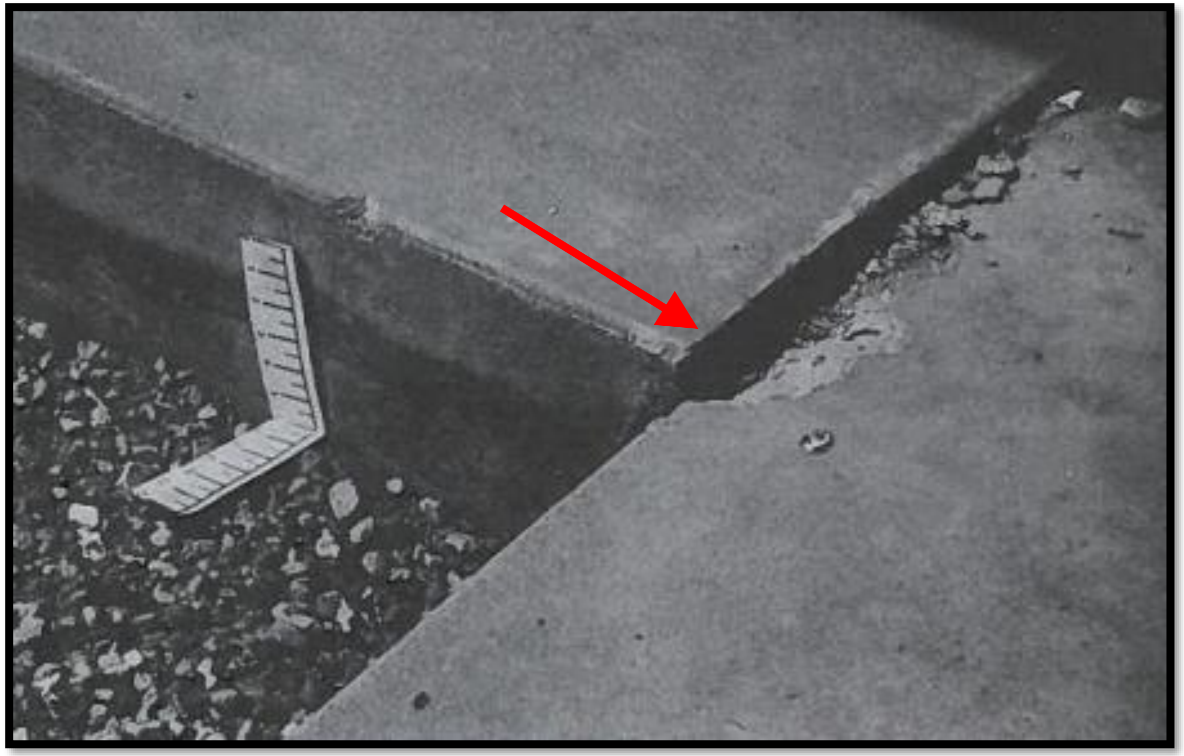

1019
1023
1078
1099
1141
1149
data available
BN: LN fit
BN: points
Numerical: LN fit
Numerical: points
$p(Y_{LD} \geq 1)$
pga (g)
0
0.2
0.4
0.6
0.8
1
0.5

BBN FOR SUBSTATION VULNERABILITY ASSESSMENT

Siraj, T., Tesfamariam, S. and Duenas-Osorio, L. 2015. Seismic risk assessment of high-voltage transformers using Bayesian belief networks. *Journal of Structure and Infrastructure Engineering*, 11(7), 929-943.

Causes	Effects
-Seismic vibration -Soil instability -Rocking response -Interaction coming from conductors	-Foundation failure -Anchorage failure -Component failure





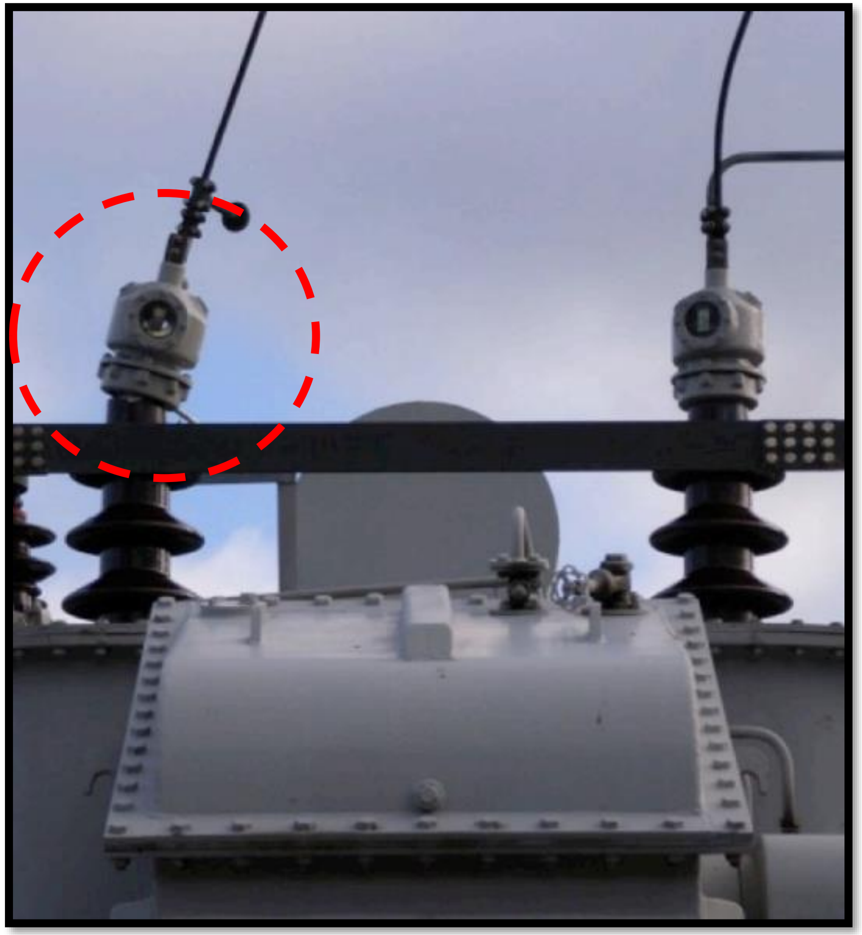
Foundation failure
Source：ASCE (1999)

Anchorage failure
Source：Markis and Black (2001)

Motivation

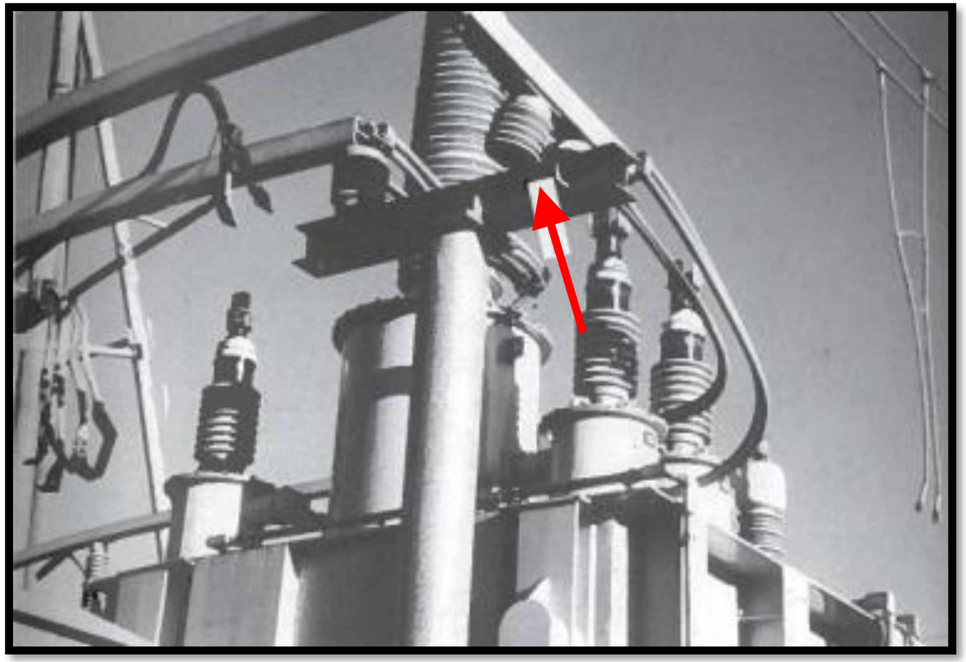
Component failure

- Radiator failure
- Internal parts malfunctioning
- Conservator failure
- Lightning arrester and tertiary bushing failure
- Porcelain bushing failure, etc.



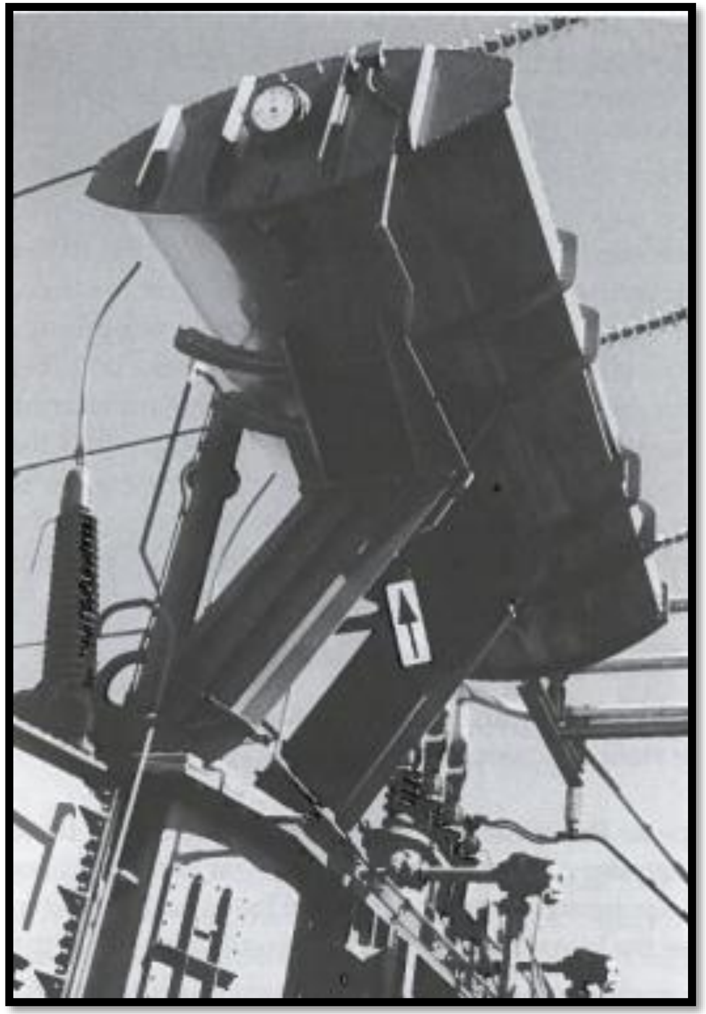
Component failure: Broken transformer bushing

Source: *Christchurch EQ damage report*

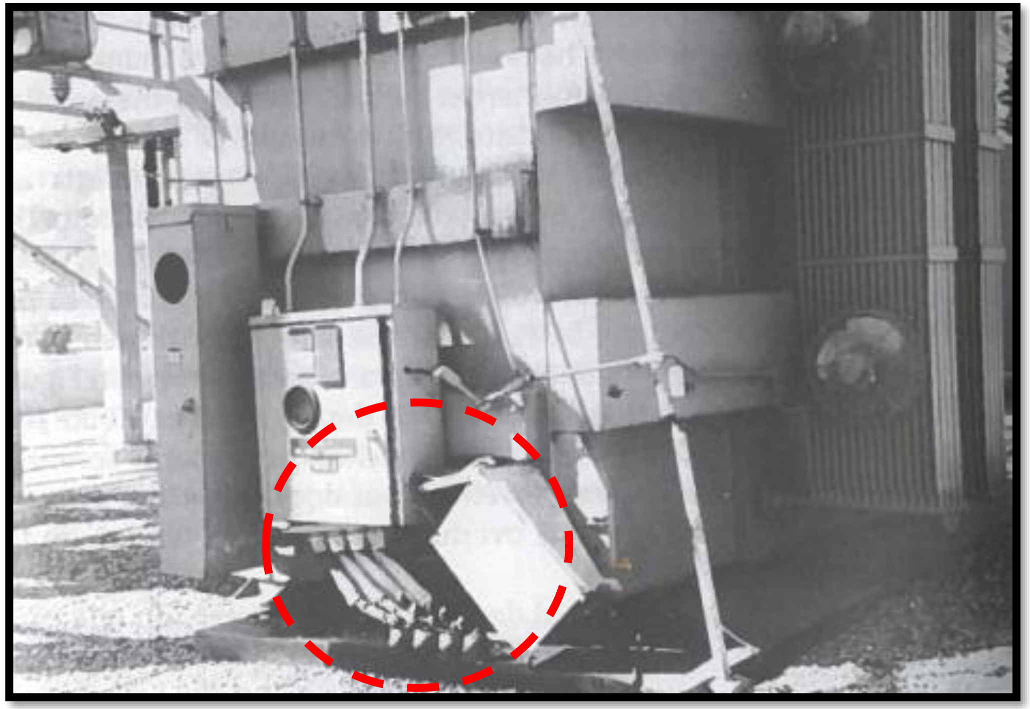


Component failure: Damaged tertiary bushing

Source: *ASCE (1999)*



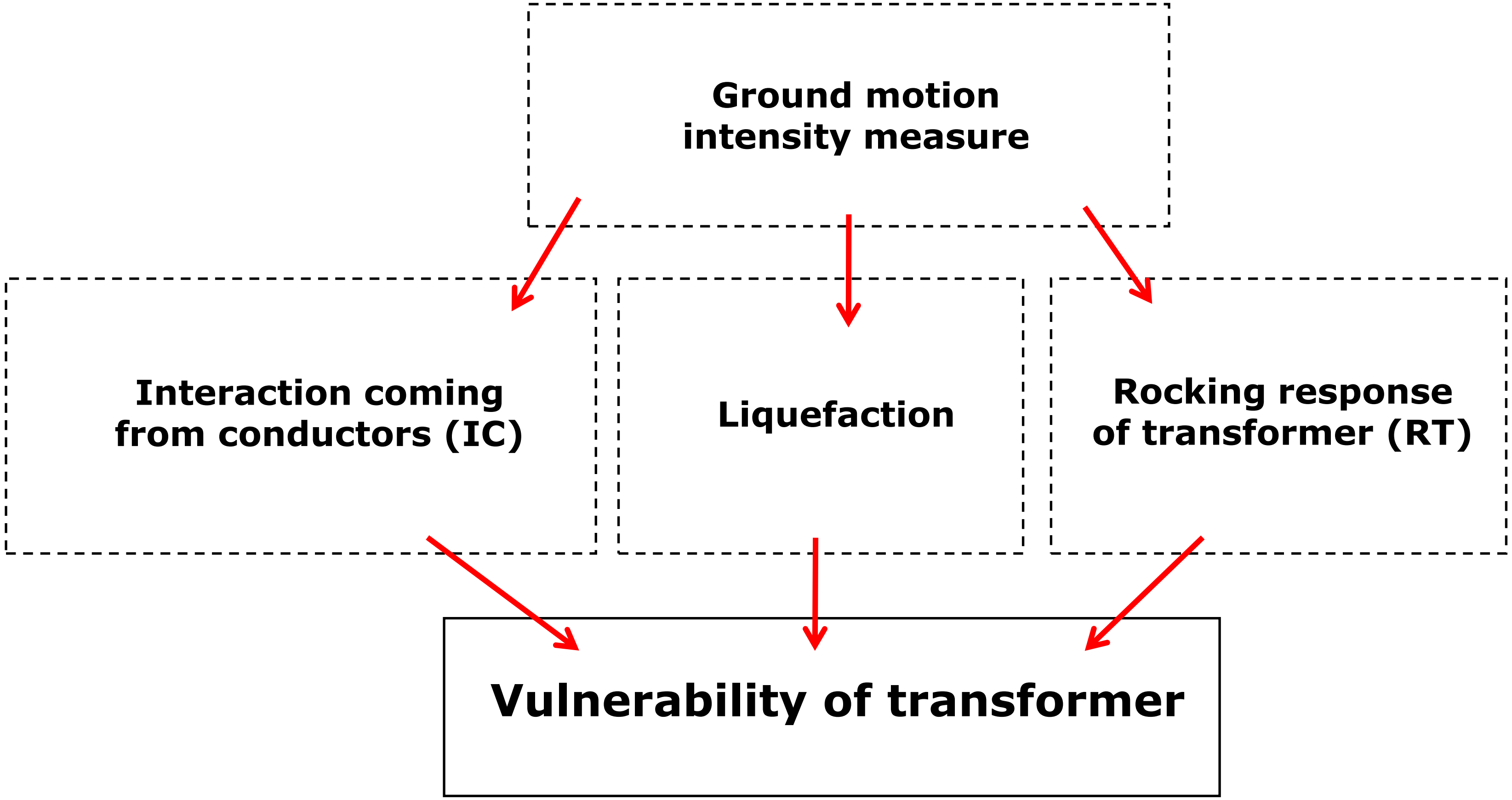
Component failure: Conservator support failure

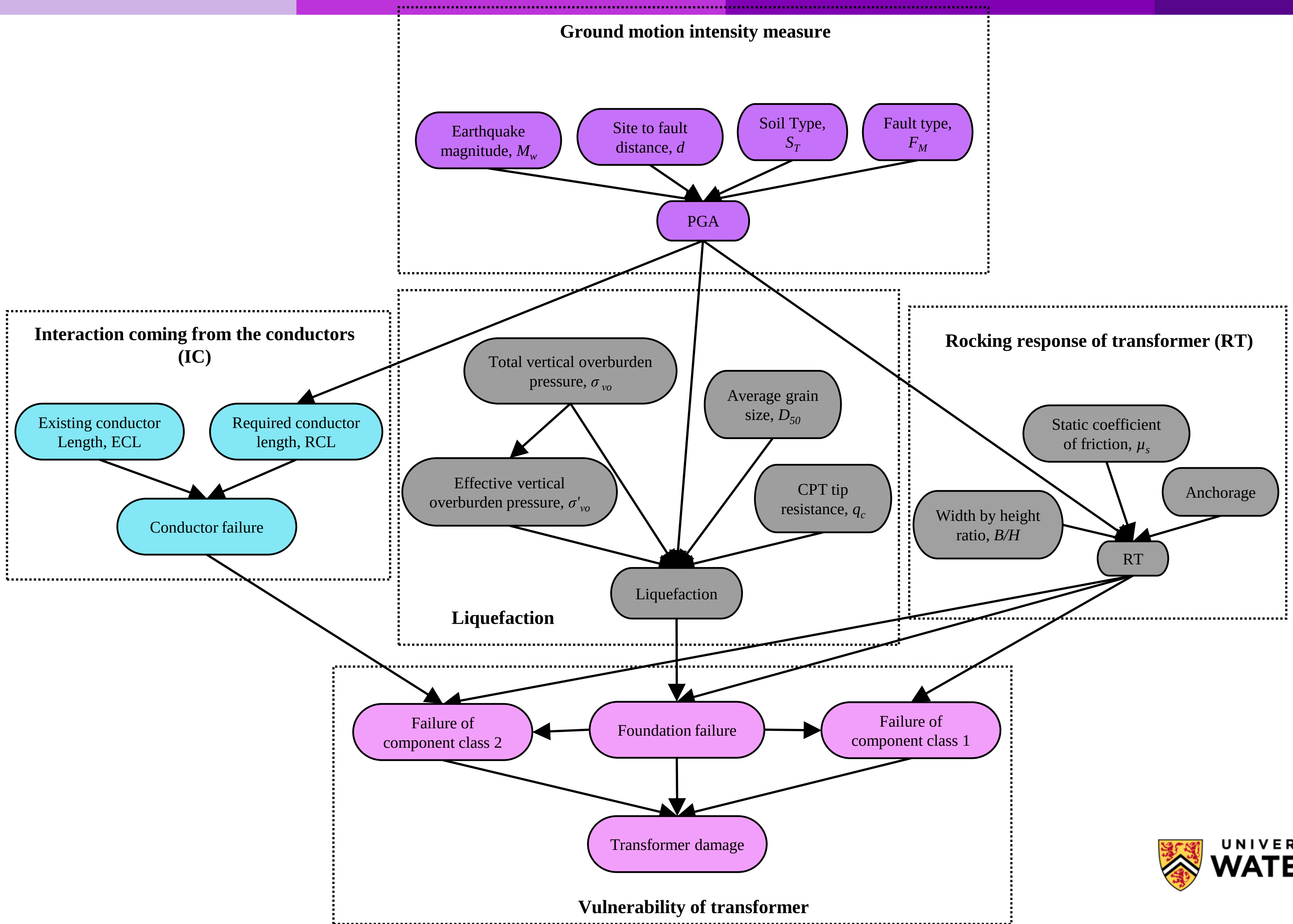


Component failure: Damaged control cables of a transformer

Source: *ASCE (1999)*

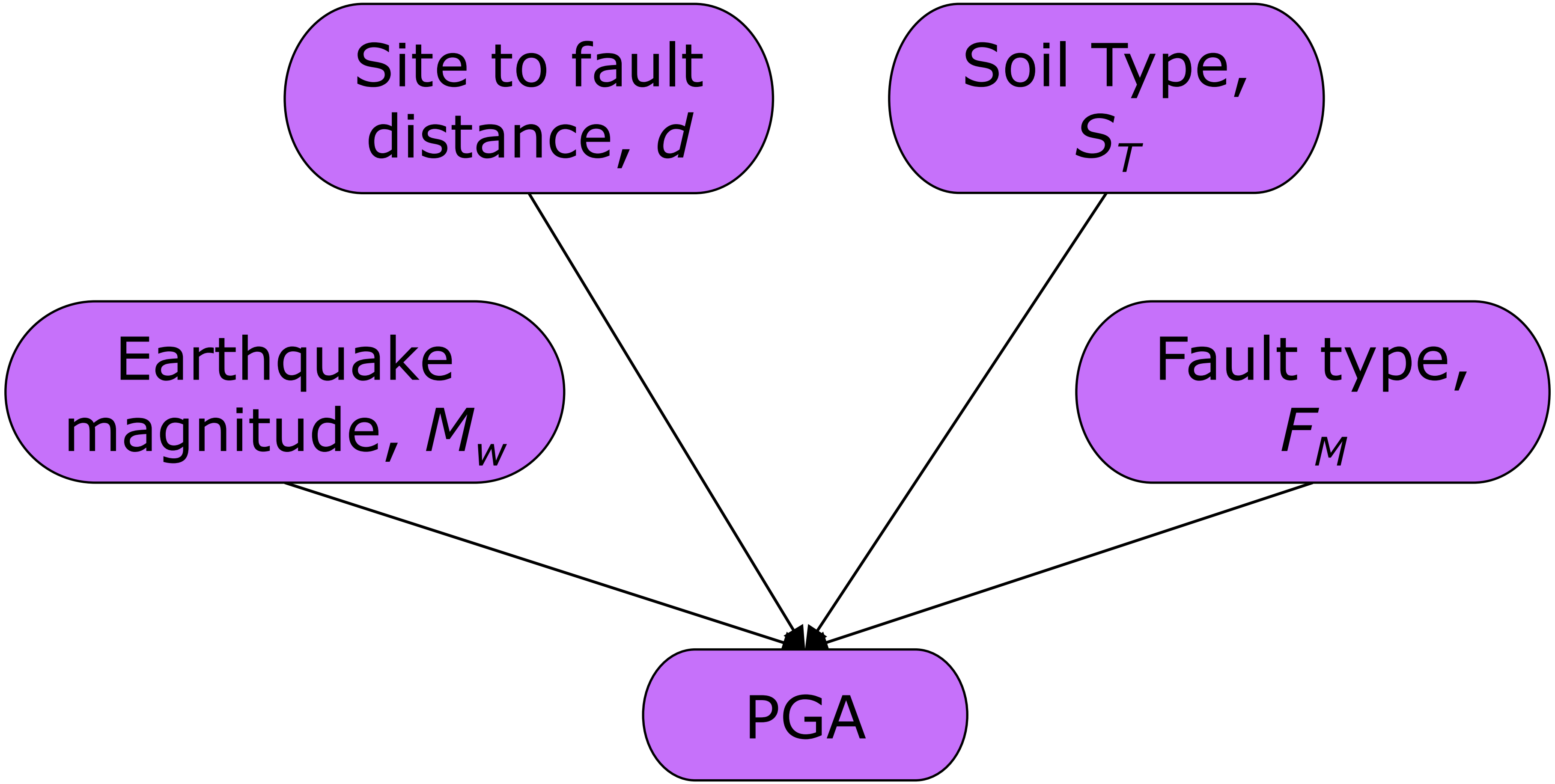
Proposed framework



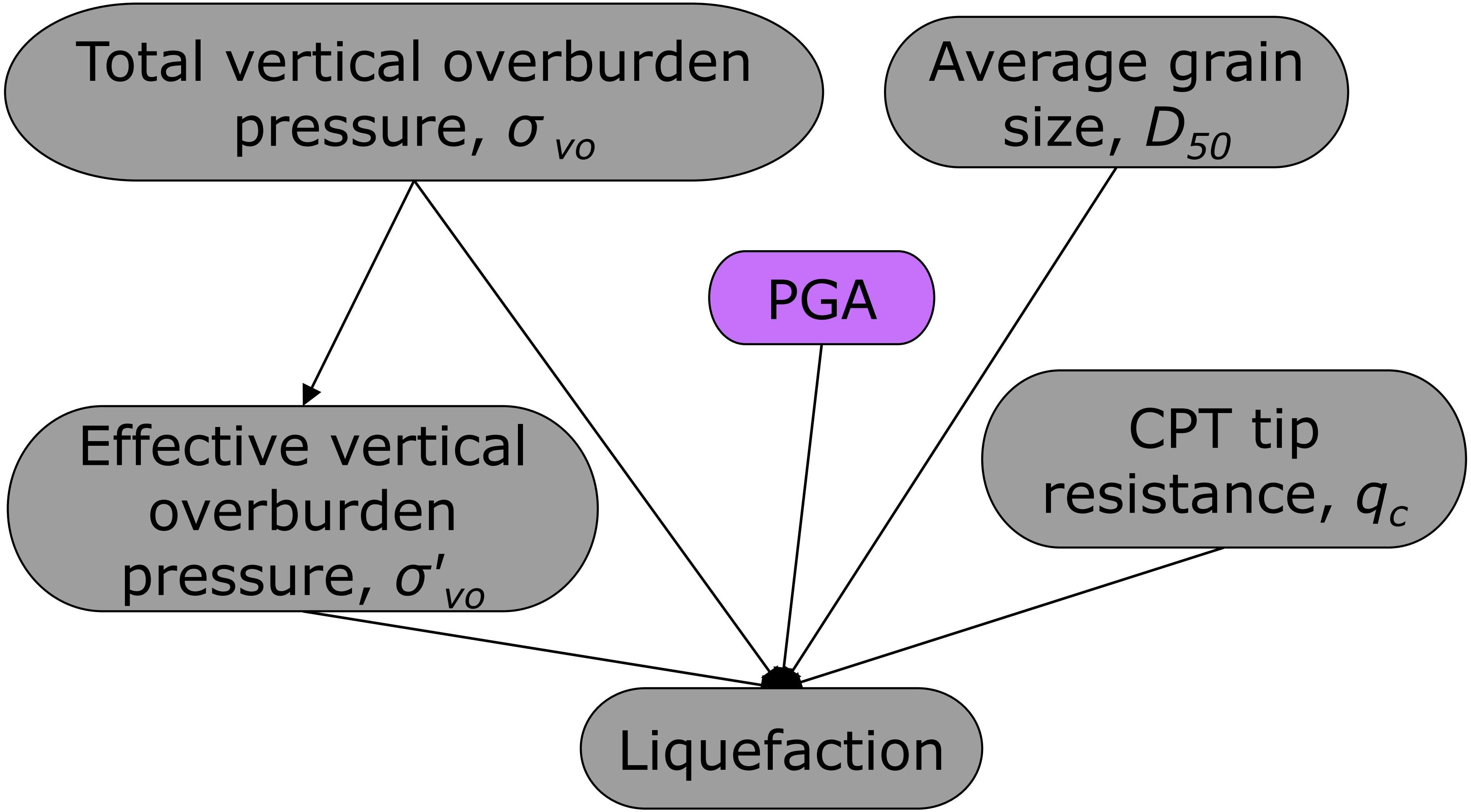


Ground motion intensity measure
Earthquake magnitude, M_w
Site to fault distance, d
Soil Type, S_T
Fault type, F_M
PGA
Interaction coming from the conductors (IC)
Existing conductor Length, ECL
Required conductor length, RCL
Conductor failure
Total vertical overburden pressure, σ_{vo}
Effective vertical overburden pressure, σ'_{vo}
Average grain size, D_{50}
CPT tip resistance, q_c
Liquefaction
Liquefaction
Rocking response of transformer (RT)
Static coefficient of friction, μ_s
Anchorage
Width by height ratio, B/H
RT
Failure of component class 2
Foundation failure
Failure of component class 1
Transformer damage
Vulnerability of transformer

Ground motion intensity measure



Liquefaction



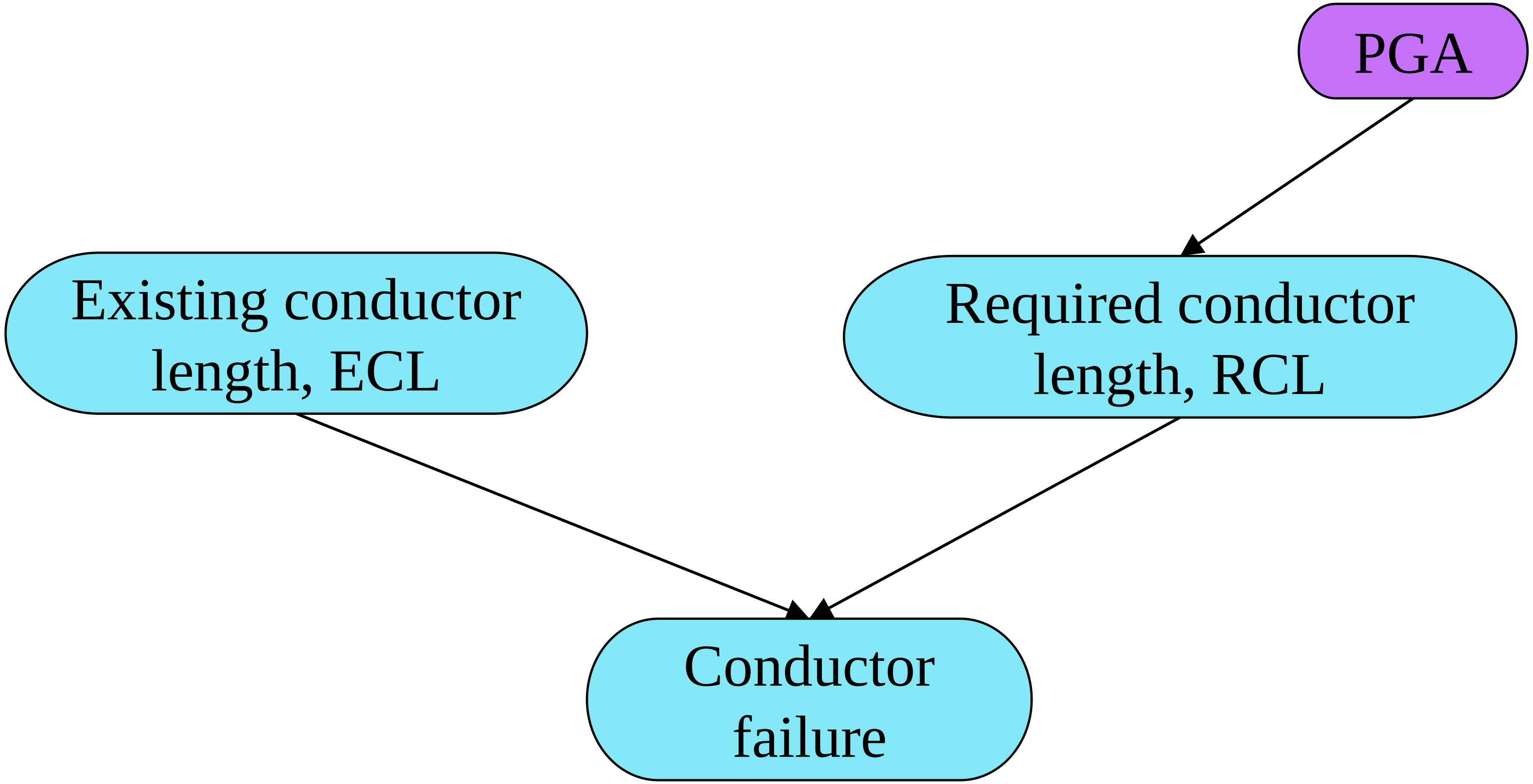
Interaction coming from conductors (IC)

Required conductor length

IEEE 1527

Existing conductor length

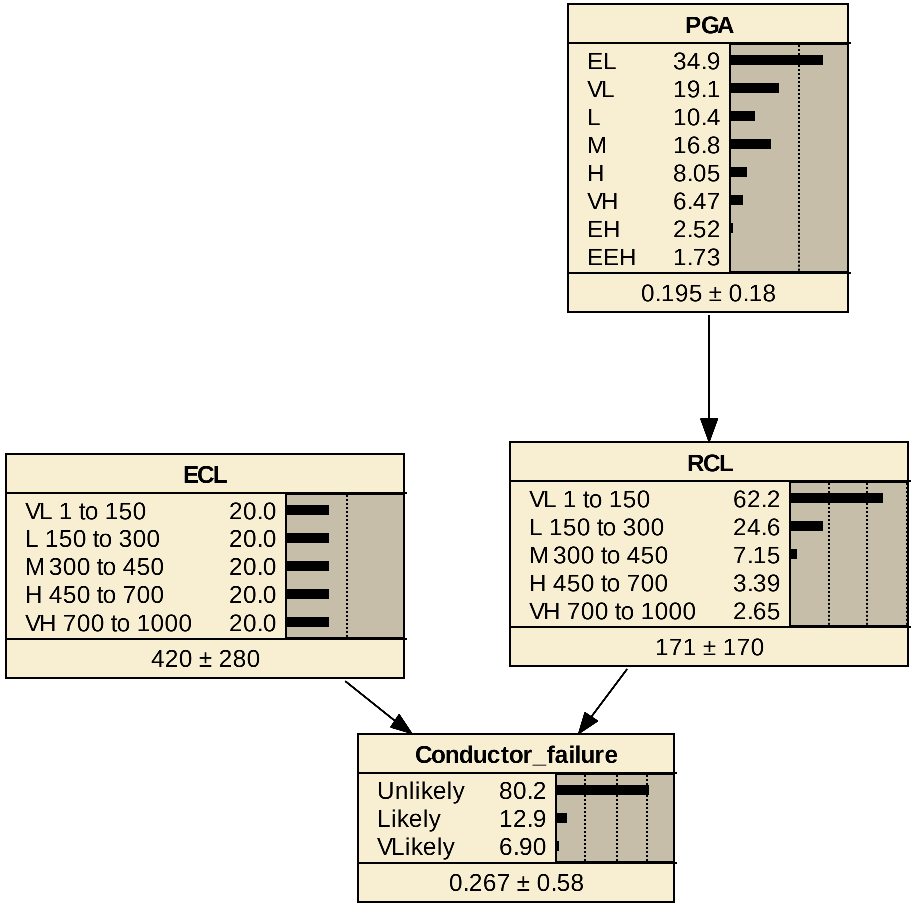
Interaction coming from conductors (IC)



Interaction coming from conductors (IC)

Conditional probability table

(EC, RC)	Conductor failure (Unlikely, Likely, Very likely)
($VL_{1\text{-}150}$, $VL_{1\text{-}150}$)	(80, 20, 0)
⋮	⋮
($M_{300\text{-}450}$, $L_{150\text{-}300}$)	(80, 15, 5)
($VH_{700\text{-}1000}$, $H_{450\text{-}700}$)	(75, 20, 5)



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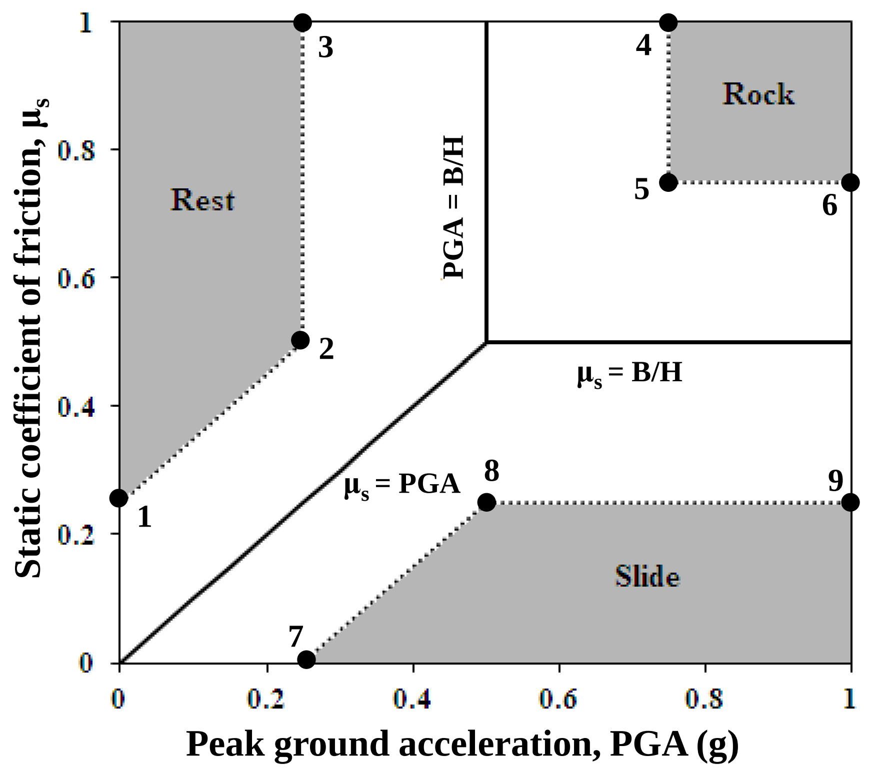
Rocking response of transformer (RT)



Co-ordinates of the points:
1 = [0.5 B/H, 0], **2** = [0.5 B/H, B/H], **3** = [0.5 B/H, 1], **4** = [0.5 (1+B/H), 1]
5 = [0.5 (1+B/H), 0.5 (1+B/H)], **6** =[1, 0.5 (1+B/H)], **7** =[0.5 B/H, 0]
8 = [B/H, 0.5 B/H], **9** = [1, 0.5 B/H]

Boundaries of rest, slide, and rock modes, for H/B=2 (based on Shenton (1996))

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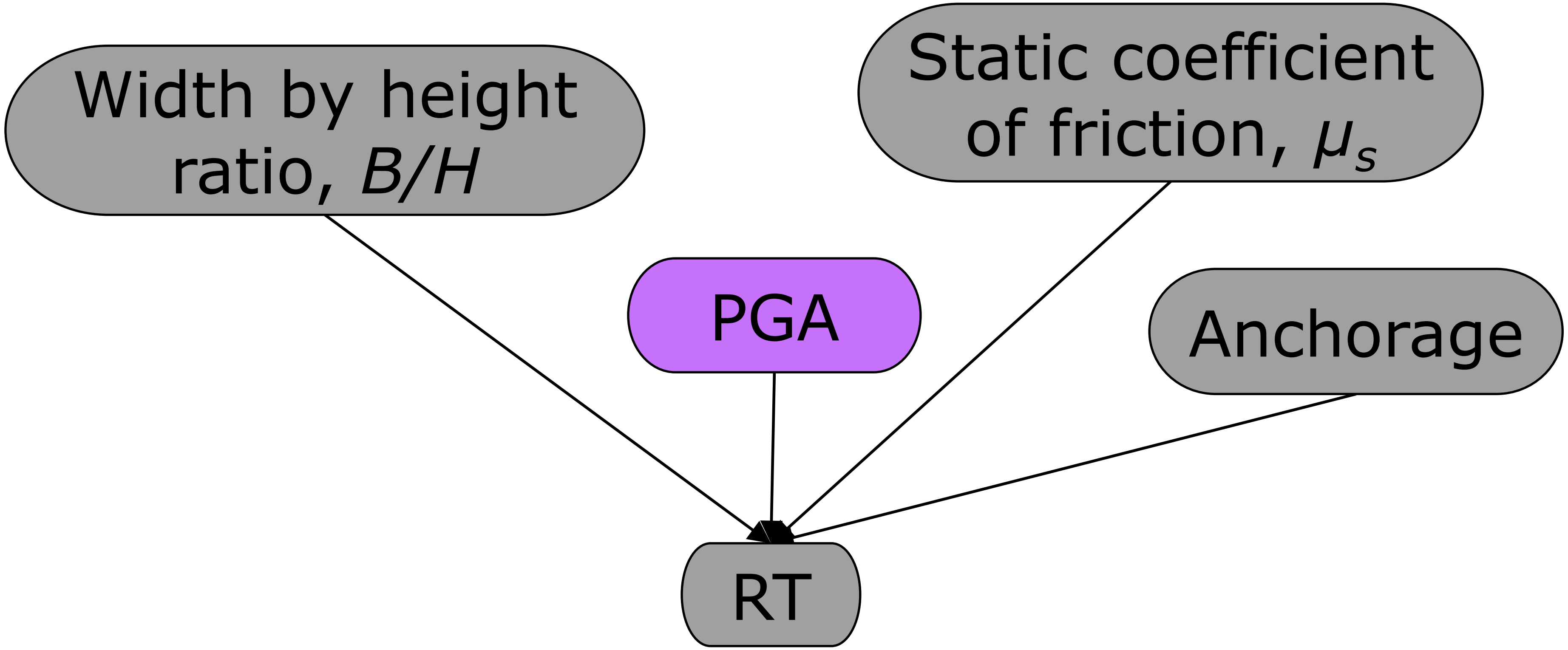
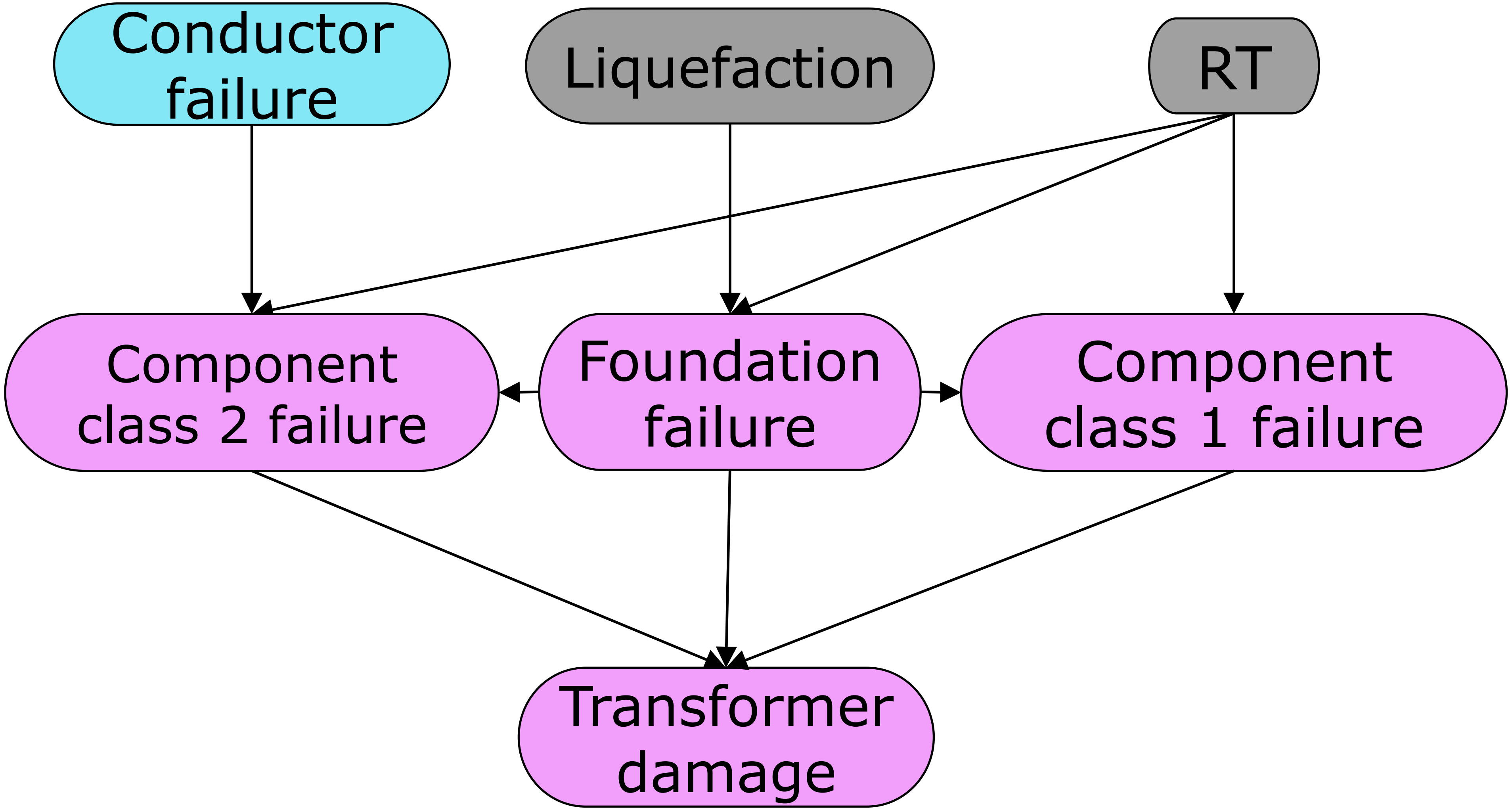
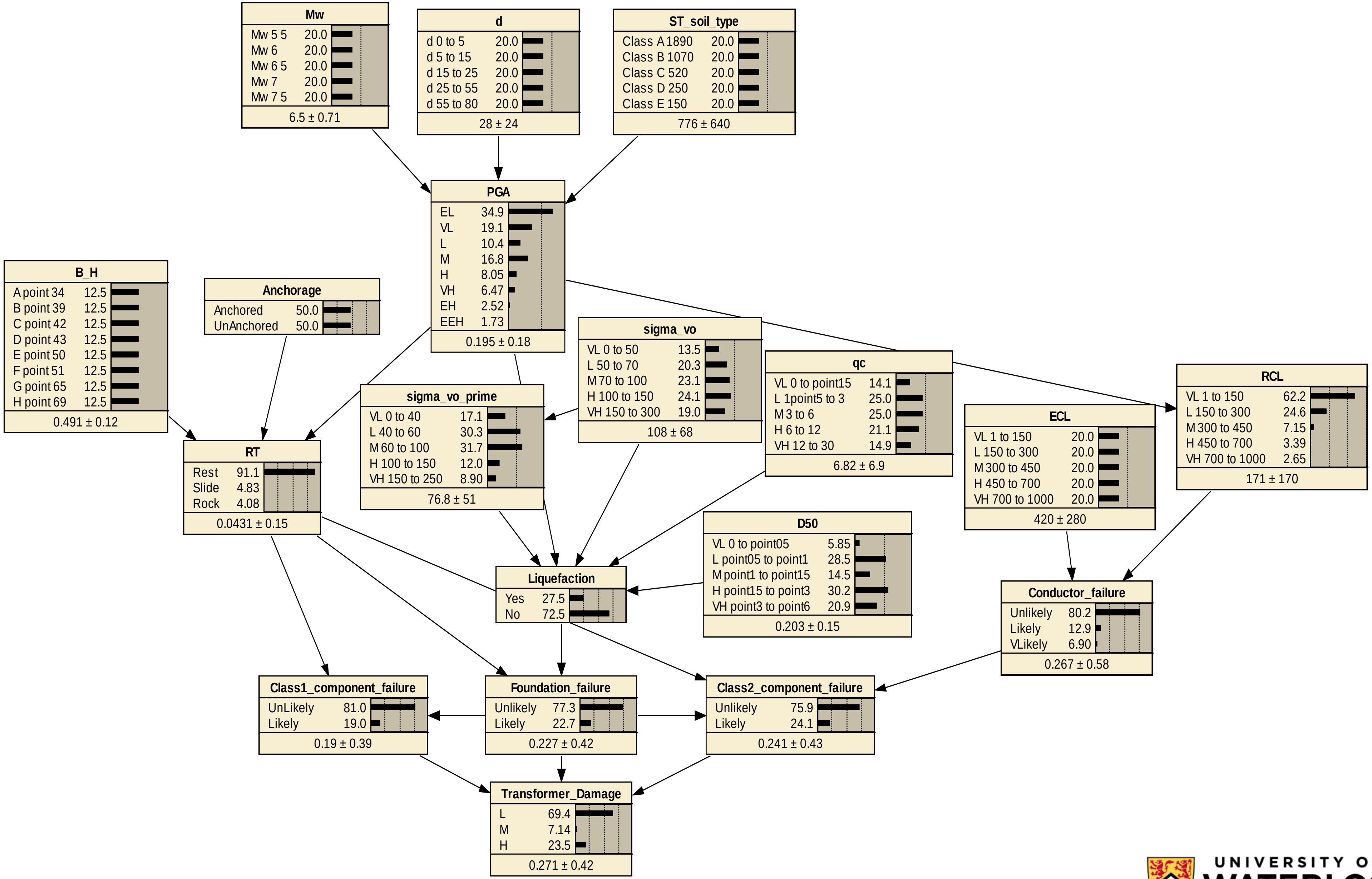


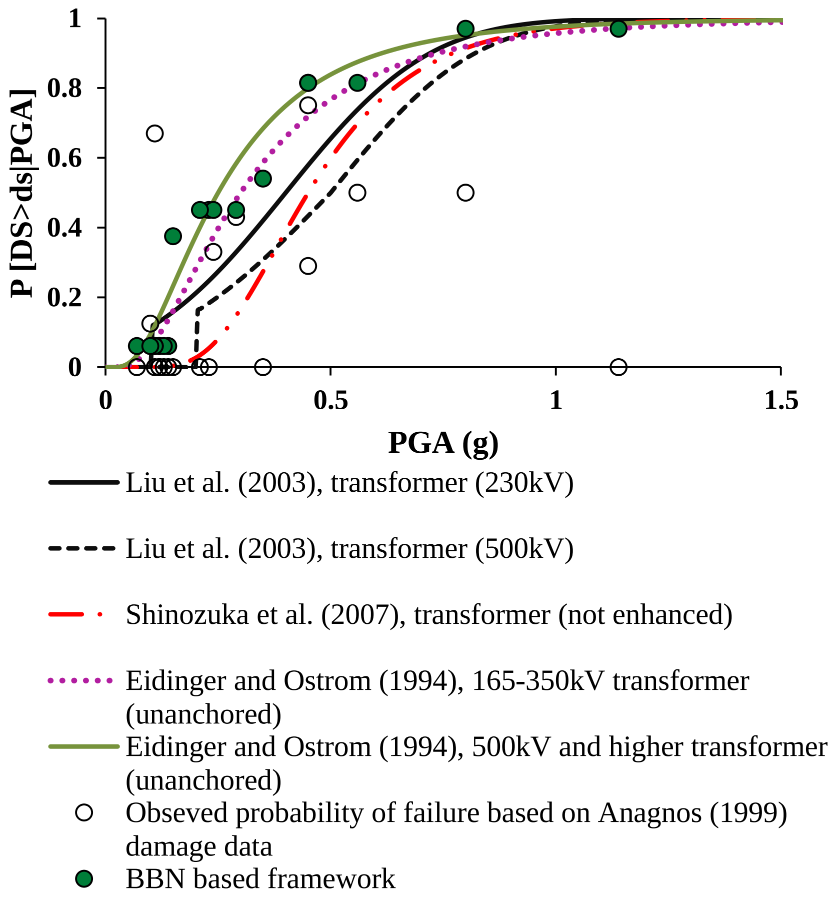
Vulnerability of transformer



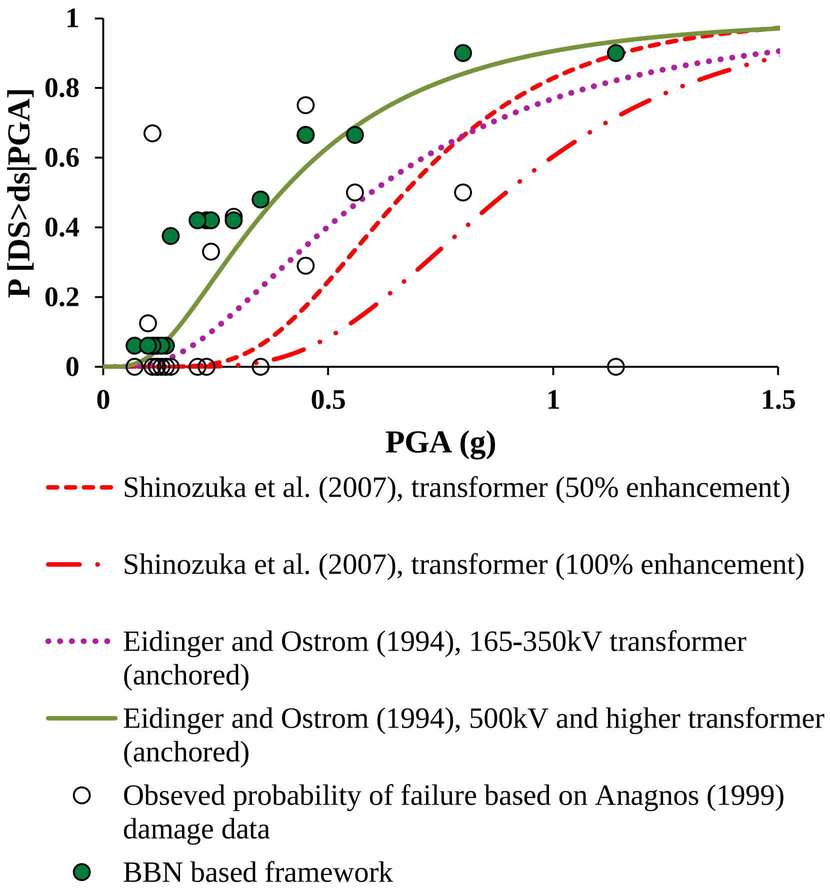

Mw
Mw 5 5 20.0
Mw 6 20.0
Mw 6 5 20.0
Mw 7 20.0
Mw 7 5 20.0
6.5 ± 0.71
d
d 0 to 5 20.0
d 5 to 15 20.0
d 15 to 25 20.0
d 25 to 55 20.0
d 55 to 80 20.0
28 ± 24
ST_soil_type
Class A 1890 20.0
Class B 1070 20.0
Class C 520 20.0
Class D 250 20.0
Class E 150 20.0
776 ± 640
PGA
EL 34.9
VL 19.1
L 10.4
M 16.8
H 8.05
VH 6.47
EH 2.52
EEH 1.73
0.195 ± 0.18
B_H
A point 34 12.5
B point 39 12.5
C point 42 12.5
D point 43 12.5
E point 50 12.5
F point 51 12.5
G point 65 12.5
H point 69 12.5
0.491 ± 0.12
Anchorage
Anchored 50.0
UnAnchored 50.0
sigma_vo
VL 0 to 50 13.5
L 50 to 70 20.3
M 70 to 100 23.1
H 100 to 150 24.1
VH 150 to 300 19.0
108 ± 68
qc
VL 0 to point15 14.1
L 1point5 to 3 25.0
M 3 to 6 25.0
H 6 to 12 21.1
VH 12 to 30 14.9
6.82 ± 6.9
RCL
VL 1 to 150 62.2
L 150 to 300 24.6
M 300 to 450 7.15
H 450 to 700 3.39
VH 700 to 1000 2.65
171 ± 170
sigma_vo_prime
VL 0 to 40 17.1
L 40 to 60 30.3
M 60 to 100 31.7
H 100 to 150 12.0
VH 150 to 250 8.90
76.8 ± 51
ECL
VL 1 to 150 20.0
L 150 to 300 20.0
M 300 to 450 20.0
H 450 to 700 20.0
VH 700 to 1000 20.0
420 ± 280
RT
Rest 91.1
Slide 4.83
Rock 4.08
0.0431 ± 0.15
D50
VL 0 to point05 5.85
L point05 to point1 28.5
M point1 to point15 14.5
H point15 to point3 30.2
VH point3 to point6 20.9
0.203 ± 0.15
Liquefaction
Yes 27.5
No 72.5
Conductor_failure
Unlikely 80.2
Likely 12.9
VLikely 6.90
0.267 ± 0.58
Class1_component_failure
UnLikely 81.0
Likely 19.0
0.19 ± 0.39
Foundation_failure
Unlikely 77.3
Likely 22.7
0.227 ± 0.42
Class2_component_failure
Unlikely 75.9
Likely 24.1
0.241 ± 0.43
Transformer_Damage
L 69.4
M 7.14
H 23.5
0.271 ± 0.42

Sensitivity analysis

Node	Normalized percent contribution
Site to fault distance, *d*	**67.00%**
Earthquake magnitude, M_w	**16.12%**
Soil type, S_T	**15.12%**
Existing conductor length, ECL	**0.76%**
Total vertical overburden pressure, σ_{vo}	**0.44%**
CPT tip resistance, q_c	**0.24%**
Anchorage	**0.22%**
Width to height ratio of transformer, B/H	**0.11%**
Average grain size, D_{50}	**0.007%**



1
0.8
0.6
0.4
0.2
0
P [DS>ds|PGA]
0
0.5
1
1.5
PGA (g)
Liu et al. (2003), transformer (230kV)
Liu et al. (2003), transformer (500kV)
Shinozuka et al. (2007), transformer (not enhanced)
Eidinger and Ostrom (1994), 165-350kV transformer (unanchored)
Eidinger and Ostrom (1994), 500kV and higher transformer (unanchored)
Obseved probability of failure based on Anagnos (1999) damage data
BBN based framework



1
0.8
0.6
0.4
0.2
0
P [DS>ds|PGA]
0
0.5
1
1.5
PGA (g)
Shinozuka et al. (2007), transformer (50% enhancement)
Shinozuka et al. (2007), transformer (100% enhancement)
Eidinger and Ostrom (1994), 165-350kV transformer (anchored)
Eidinger and Ostrom (1994), 500kV and higher transformer (anchored)
Obseved probability of failure based on Anagnos (1999) damage data
BBN based framework

PARADOX OF RISK MANAGEMENT

"You always got to be prepared, but you never know for what."

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Our greatest impact happens together.