Towards more Resilient Infrastructure Systems: Methods and Tools

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Dr Francesco Cavalieri (Sapienza University of Rome)
Indranil Kongar (University College London)
Towards more Resilient Infrastructure Systems

Our Aim: Create scientifically-sound, end-user oriented methods and tools:

- to support resilience assessments for status-quo infrastructure systems, and
- to inform decision making processes towards more resilient infrastructure systems
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![Diagram showing levels of service and time]
- Robustness
- Redundancy
- Interdependencies
- Rapidity
- Resourcefulness
- Awareness of, & adaptability to, modified ‘Levels of Service’
Towards more Resilient Infrastructure Systems

- Resilience to multi-hazards (& shocks) & cascading effects

![Diagram showing levels of service and resilience over time](image-url)

- Robustness
- Redundancy
- Interdependencies
- Resourcefulness
- Rapidity
- Awareness of, & adaptability to, modified ‘Levels of Service’
Towards more Resilient Infrastructure Systems

• Resilience to multi-hazards (and shocks) and cascading effects
• Integrating ‘technical’ dimensions of resilience with ‘social’, ‘organisational’, ‘economic’ dimensions toward an holistic resilience assessment.

Integrated approach:
• ‘observation-based’ - from evidence & learning to transferable models
• ‘analysis-based’ - cross-calibration with analytical models
• ‘expert-based’ - ‘reality check’ with end-users

✓ Robustness
✓ Redundancy
✓ Interdependencies
✓ Resourcefulness
✓ Rapidity
‘Levels of Service’
Towards more Resilient Infrastructure Systems

On-going Projects and International Collaborations:

• *Earthquake-Flood Multi-hazard Impacts on Lifeline Systems following the Canterbury Earthquake Sequence 2010-2011*

  Su Young Ko (PhD)

  A multi-hazard framework for assessing and managing flooding hazard in a seismically active low-lying urban environment

  David Holland (MSc)

• *Projecting Damage and Losses for Buildings and Infrastructures from the Canterbury Earthquake Sequence*

  Melanie Liu (PhD)

  Decision support system for post-earthquake rehabilitation of sewerage systems: A project management perspective

  Adnan Rais (PhD)

• Integrated *bridge-utility systems: performance based assessment and mitigation of earthquake-induced physical and functional impacts*

  Website under construction
Multi-hazards are?

*e.g. coastal & river quakes*

0.1% likelihood in 21st C

- tsunami; sea level rise; erosion;
  - coastal, estuary, & river flood risks altered

0.01% likelihood in 21st C

- subsidence & surface crust ‘rafting’, sediment & other pollutants released

0.01% likelihood in 21st C

- coastal plain & riverside shallow water table

0.1% likelihood in 21st C

- old coastal plain & river beds

Lateral spreading, bank & shoreline failure

River banks & coastal cliffs

Surfaced rupture

Faulting

Tsunamis

Seismic energy release

Landslides

Liquefaction

Topographic relief

Strong ground motion

Soil deposits

Amplified ground shaking

(Black: Bird & Bommer 2004)
Multi-hazard prone infrastructure?

*e.g. coastal settlements*

- Holocene coast ~6500 y BP
- Inland extent of heavy lifelines network damage
- Inland limit of increased flooding vulnerability
- Post-sea level rise liquefaction vulnerability zone

21st century population concentration in megacities vulnerable to coastal quake multi-hazards

Cities on seismically-active recent coastal plains
- Charleston 1886
- Napier 1931
- Anchorage 1964
- Tokyo ???

Line demarcates?

- 5 km
Multi-hazards link the ‘un-linkable’

Lifelines & Increased Flooding Vulnerability (IFV) Project

– terrain deformation (river & land profile changes, runoff, swales, pipe strain)
– liquefaction
– river channel capacity loss via constriction from rafting & bed uplift
– relative sea level rise: land levels, estuary/ river drainage, groundwater depths
– pipe network damage (breaks, sediment load & deposits, connection failures)
– domino effects of subterranean erosion (roads), waste water interactions

• 2013-15 IFV research by Holland (MSc) & Ko (PhD) drainage network & stormwater foci: http://www.civil.canterbury.ac.nz/postgrads/sko.shtml
• 2015-16 TCLEE monograph
Object-Oriented Framework for Infrastructure Modelling and Simulation (OOFIMS)

The software (in Matlab language) was developed in Rome within SYNER-G
https://sites.google.com/a/uniroma1.it/oofims/home
Christchurch stormwater network
Prediction of physical damage and overflow

Network topology
Christchurch stormwater network
Prediction of physical damage and overflow

Network subcatchments
Christchurch stormwater network
Prediction of physical damage and overflow

Analysis of a portion of the network enclosed within one CBD subcatchment
Christchurch stormwater network
Prediction of physical damage and overflow

Physical damage indicators: maximum expected number of leaks and breakage probability

Original materials

All pipes made of ductile iron
Christchurch stormwater network
Prediction of physical damage and overflow

Overflow probability

Expected overflow during a given rain event
Christchurch stormwater network
Prediction of physical damage and overflow

Flood height before and after the earthquake, to assess the Increased Flooding Vulnerability (IFV)
Electric power network case studies
Prediction of physical damage, connectivity and serviceability indicators

Case study #1: Sicily power network

Network nodes and lines
Electric power network case studies

Prediction of physical damage, connectivity and serviceability indicators

Case study #1: Sicily power network

Faults affecting Sicily and simulated PGA shake map

Power flow analysis,
Mean Voltage Ratio (VR),
Voronoi diagram
Electric power network case studies
Prediction of physical damage, connectivity and serviceability indicators

Case study #2: IEEE-118 bus power network
Electric power network case studies
Prediction of physical damage, connectivity and serviceability indicators

Case study #2: IEEE-118 bus power network

Simulated PGA shake map

Power flow analysis,
Mean Voltage Ratio (VR),
Voronoi diagram
Christchurch electric power network
Prediction of physical damage, connectivity and serviceability indicators
Orion network with PGA shake map, Feb 2011 event

Transpower grid exit point (GXP)
Orion zone substation
Lifelines data management

- **Pre-disaster:** classify or ‘inventorise’ system into hierarchy of elements with locations and attributes
  - **Substations**
  - **Cables**
    - **Transformer**
    - **Distribution**
    - **Overhead**
    - **Buried**

- **Post-disaster:** document damage occurrences and recovery activities
  - Attributes:
    - Voltage, power rating, age, usage statistics
    - **Damage:**
      - Where? What? How bad?
  - Attributes:
    - Materials, size, phasing, age
    - **Damage:**
      - Where?
Lifelines data management

Why is it important?
Vulnerability of elements
Risk assessment of system
Risk-based investment
Insurance
Emergency management
Learn lessons

What can improve?
Lack of standardisation
Post-disaster data collection
Interdependencies
Resilience aspects
  • robustness, redundancy, resourcefulness, rapidity
  • technical, organisational, social
## Lifelines data management

<table>
<thead>
<tr>
<th>Infrastructure system</th>
<th>Components</th>
<th>Component attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric power</td>
<td>Generation plants</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Substations</td>
<td>Voltage, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Cables</td>
<td>Material, size</td>
</tr>
<tr>
<td>Potable water</td>
<td>Wells</td>
<td>Seismic design level</td>
</tr>
<tr>
<td></td>
<td>Water treatment plants</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Pumping stations</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Storage tanks</td>
<td>Elevation, material, geometry, quantity of contents, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Pipelines</td>
<td>Material, joint type, age, diameter</td>
</tr>
<tr>
<td>Waste water</td>
<td>Lift stations</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Treatment plants</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Pipelines</td>
<td>Material, joint type, age, diameter</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Pipelines</td>
<td>Material, joint type, age, diameter</td>
</tr>
<tr>
<td></td>
<td>Compressor stations</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td>Fuel</td>
<td>Refineries</td>
<td>Capacity, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Pumping stations</td>
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<td>Elevation, material, geometry, quantity of contents, seismic design level</td>
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<tr>
<td></td>
<td>Pipelines</td>
<td>Material, joint type, age, diameter</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>Central offices</td>
<td>Seismic design level</td>
</tr>
<tr>
<td></td>
<td>Cables</td>
<td>Material, size</td>
</tr>
<tr>
<td>Highways</td>
<td>Roadways</td>
<td>Importance level</td>
</tr>
<tr>
<td></td>
<td>Bridges</td>
<td>Structural system, material, age, geometry, seismic design level</td>
</tr>
<tr>
<td></td>
<td>Tunnels</td>
<td>Construction method, geometry, local geology</td>
</tr>
<tr>
<td></td>
<td>Embankments</td>
<td>Height, soil type</td>
</tr>
</tbody>
</table>
Thank you for your attention

• Speaker contact details
  ▪ Dr Sonia Giovinazzi (sonia.giovinazzi@canterbury.ac.nz)
  ▪ Dr Deirdre Hart (deirdre.hart@canterbury.ac.nz)
  ▪ Dr Francesco Cavalieri (francesco.cavalieri@uniroma1.it)
  ▪ Indranil Kongar (indranil.kongar.10@ucl.ac.uk)

• Acknowledgements

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NHRP
Natural Hazards Research Platform

EMERGENCY MANAGEMENT CANTERBURY

Chorus

Christchurch City Council

Waimakariri District Council

Selwyn District Council

Environment Canterbury Regional Council

EQC

Orion yournetwork

Contact

UCQUAKE CENTRE
Tom Wilson and volcanic impacts team
Volcanic Impacts Study Group – Auckland Lifelines Group
University of Canterbury, New Zealand
GNS Science, New Zealand
Massey University, New Zealand
University of Cambridge, United Kingdom
USGS, United States of America
Volcanic Ash Research -- Lifelines

- Why worry?
- Current activities
- Case-study:
  - Volcanic risk to electricity systems
- International Contributions
- Resources Available
Why worry?
Ashfall characteristics are variable:
- Loading (thickness) – kg/m²
- Grainsize
- Highly abrasive
- Surface chemistry
Why worry?

- Volcanic ash is the most likely volcanic hazard to affect the most people during an explosive eruption.

- Volcanic eruptions can cause a range of impacts.
  - Exotic impacts. Mitigation options??
  - Potentially long duration, multi-stage, multi-hazard

- Infrequent eruptions
  - Limited opportunities to develop experience
  - So how do we learn?

- Limited knowledge base of impacts + mitigation compared to other perils
  - dominated by only several eruptions
Volcanic Impact Study Group

- Hosted by Auckland Lifelines Group
  - Subcommittee
  - National Focus
  - Researcher + practitioner membership

- Strong user-researcher partnership
  - strong culture of supporting research to practise
  - Multi-disciplinary

- Funding support for applied research project
  - Leveraging off larger Natural Hazard Research Platform + DEVORA funding
Research Context – Ash Impact Research

- Over the past 20 years our New Zealand research group (and collaborators) have aimed to undertake a sustained and systematic approach to volcanic impact assessment
  - critical infrastructure: electricity, water supplies, wastewater, land and air transport, telecommunications
  - ash cleanup and disposal
  - primary industries, e.g. agriculture
  - social impacts
  - emergency management
Addressing Knowledge Gap: Recon Trips

- Redoubt 1996; 2010
- Eldfell (Heimaey) 2008
- Shinmoedake 2011
- Sakurajima 2001
- Pinatubo 2007
- Merapi 2006
- Kelut 2014
- Lapevi 2003-05
- Ruapehu 1995-96
- Puyehue Cordon-Caulle 2012
- Hudson 2008
- Chaiten 2009
- Etna 2003
- Pacaya 2010
- Tungurahua 2005; 2010
Addressing Knowledge Gap

- Volcanic Ash Testing Lab (VATLab)

- Empirical experiments of components and systems which are vulnerable
  - Laboratory testing in controlled environment
  - Engineering College
  - UC re-development – investment
Fostering Research Partnerships

- **2009**: AELG-19: Impact of Ash on Electricity, Telecommunications, Broadcasting Networks
  - Electricity systems susceptible to ash fall induced outage
  - Identified knowledge gaps
    - Threshold for insulator flash-over?
    - What factors influenced resistivity of volcanic ash?
    - Resilient insulator design?

*2008-2009*
Case Study: Electricity Systems

The main impacts are:

- Supply outages from insulator flashover caused by ash contamination
- Disruption of generation facilities
- Controlled outages during tephra cleaning
- Abrasion and corrosion of exposed equipment
- Line breakage due to tephra loading
- Flashover and voltage fluctuation
- Exposed surfaces coated in 3mm of ash
Fostering Research Partnerships

2010-2013: PhD Project: Johnny Wardman
- Vulnerability of HV Transmission Systems to Volcanic Ashfall Hazards
- Sponsor: Transpower Ltd.
  - $140,000 + consumables
  - co-funding from NHRP
• Aided Transpower volcanic risk management planning
Fostering Research Partnerships

- Volcanic Ashfall Risk on Critical Infrastructure
  - Probabilistic ash fall modelling
  - Refined impact thresholds for:
    - Transmission circuits
    - Grid Exit Points (GXP) – substations
    - Power Stations

2014-2015
• **2014: PhD Research Project: Grant Wilson**

• **Risk Reduction**
  - E.g. locations for preventative mitigation
  - Compare against other perils + account for uncertainty (probabilistic)

• **Readiness**
  - E.g. prioritisation of cleaning

• **Response**
  - E.g. deterministic scenario
- UNISDR – Global Assessment Report (GAR-15)
  - Global ashfall hazard and risk modelling
  - Impact thresholds...scenario planning

- International partnership
  - South Korea (national scale assessment)
  - UK nuclear generator (site assessment)

- NZ Defence Technology – Aircraft Volcanic Ash Identification Protocol
  - UK + US civilian and military linkages
- Medium term Research Strategy
  - Co-development of applied research projects

- Impact/risk planning + response resources

- Natalia Deligne
  - Presenting tomorrow

Thank you
Questions?

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Resilience research

Resilient cities are safer, more attractive to investors and new residents, and more able to recover quickly and with less loss of life and assets in the event of crises. UNISDR
Research initiatives

- Measuring the resilience of transport infrastructure (NZTA)

- Paper: Review of key terminology: risk, resilience, vulnerability, sustainability

- Canterbury lifelines: ongoing discussion around measurement / benchmark approaches.

- Internationally:
  - Rockefeller 100RC
  - UNISDR Resilient Cities Scorecard (MCR Campaign)
  - World Bank R!SE
  - UN Habitat CRPP
Reasons to Focus on Resilience

By 2050 over 70% of the World’s population will live in Cities

Loss of life have decreased from Natural Disasters but...capital losses have exceeded $2.5 T since 2000
Reasons to Focus on Resilience

Direct disaster losses are 50% higher than reported figures.

Kobe port before the earthquake in 2005 was 6th busiest port in the world; By 2010 it had fallen to 47th despite massive investment.

Toyota lost $1.2B in product revenue after the 2011 earthquake & tsunami.
Reasons to Focus on Resilience

“Economic losses from disasters are out of control and can only be reduced with collaboration with the private sector”

Ban Ki-Moon
Secretary General of the United Nations
Measuring transport resilience
Resilience framework

- Consists of *Dimensions*, *Principles* and specific *Measures* which can map to the NIP attributes if required.
## How did we categorise resilience of infrastructure?

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical / Asset</td>
<td>The ability of the physical system(s) to perform to an acceptable/desired level when subject to a hazard event.</td>
</tr>
<tr>
<td>Organisational</td>
<td>The capacity of an organisation to make decisions and take actions to plan, manage and respond to a hazard event.</td>
</tr>
</tbody>
</table>
How did we categorise resilience of infrastructure?

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Principle</th>
<th>Categories</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technical / Asset</td>
<td>Robustness</td>
<td>Measures</td>
</tr>
<tr>
<td></td>
<td>Redundancy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Safe-to-fail</td>
<td></td>
</tr>
<tr>
<td>Organisational*</td>
<td>Change readiness</td>
<td>Measures</td>
</tr>
<tr>
<td></td>
<td>Networks</td>
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<tr>
<td></td>
<td>Leadership &amp; Culture</td>
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</tr>
</tbody>
</table>

*Refer work by Resorgs
The measurement framework
## Measures

### ROBUSTNESS

<table>
<thead>
<tr>
<th>Category</th>
<th>Measure</th>
<th>Measurement</th>
<th>Measurement Scale</th>
</tr>
</thead>
</table>
| Maintenance | Processes exist to maintain critical infrastructure and ensure integrity and operability - as per documented standards, policies & asset management plans (e.g. – roads maintained, flood banks maintained, stormwater systems are not blocked). Should prioritise critical assets as identified. | Individual Score | 4 – Audited annual inspection process for critical assets and corrective maintenance completed when required.  
3 – Non-audited annual inspection process for critical assets and corrective maintenance completed when required.  
2 – Ad hoc inspections or corrective maintenance completed, but with delays/backlog.  
1 – No inspections or corrective maintenance not completed. |
| Renovation | Evidence that planning for asset renewal and upgrades to improve resilience into system networks exist and are implemented. | Individual Score | 4 – Renewal and upgrade plans exist for critical assets, are linked to resilience, and are reviewed, updated and implemented.  
3 – Renewal and upgrade plans exist for critical assets and are linked to resilience, however no evidence that they are followed  
2 – Plan is not linked to resilience, and an adhoc approach is undertaken  
1 – No plan exists and no proactive renewal or upgrades of assets. |
| Structural | Percentage of assets that are at or below current codes | Individual Score | 4 – >80% are at or above current codes  
3 – 50-80% are at or above current codes  
2 - 20-50% are at or above current codes  
1 - nearly all are below current codes |
| Design | Assessment of general condition of critical assets across region. | Individual Score | 4 – >80% are considered good condition  
3 – 50-80% are considered good condition  
2 - 20-50% are considered good condition  
1 - nearly all poor condition |
| | Percentage of assets that are in zones/areas known to have exposure to hazards | Individual Score | 4 – <20% have some exposure to known hazards  
3 – 20-50% are highly exposed, or >50% are moderately exposed  
2 - 50-80% are highly exposed  
1 - >80% are highly exposed to a hazard |
| | Percentage of critical assets with additional capacity over and above normal demand capacity | Individual Score | 4 – >80% of critical assets have >50% spare capacity available  
3 – 50-80% of critical assets have >50% spare capacity  
2 - 20-50% of critical assets have >50% spare capacity  
1 - 0-20% have spare capacity |

**Weighted Robustness Score**: 2.3

<table>
<thead>
<tr>
<th>Category</th>
<th>Weighting (%)</th>
<th>Weighted Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintenance</td>
<td>33.33%</td>
<td>94.4</td>
</tr>
</tbody>
</table>

November 6, 2014
Research paper: hazard, risk, resilience, vulnerability
We investigated

- Consistency across risk management approaches?
- Confusion in terminology - and suggestions for simplification
- Risk approaches vs resilience approaches. What are differences? When to use?
- Recommendations for asset management field and implications for other fields
Range of fields

- Disaster Risk Management (DRM)
- Climate Change
- Sustainable Development
- Social Science
- Civil Defence Emergency Management (CDEM)
- Asset Management
- Risk Management
- Resilience
Range of terms

- Hazard
- Risk
- Consequence
- Likelihood
- Exposure
- Robustness
- Redundancy
- Sustainability
- Vulnerability
- Sensitivity
- Resilience
- Adaptive Capacity
Links

- NZTA Research:

  http://www.nzta.govt.nz/resources/research/reports/546/

- Paper on risk, resilience and terminology: Come and see me: james.hughes@aecom.com
“Whilst systems have commonly been designed to be robust (designed to prevent failure), increasing complexity and the difficulty it poses to fail-proof planning have made a shift to "resilience" strategically imperative.

A resilient system on the other hand accepts that failure is inevitable and focuses instead on early discovery and fast recovery from failure”.

David Snowden