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Earthquakes & Cascading Risks: Lessons from Japan and the UK

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Content

- 2011 Tohoku earthquake and tsunami
- Tsunami casualty mitigation through effective evacuation strategies
- Fukushima Daiichi nuclear power plant crisis
- Research challenges: cascading multi-hazards and risks due to mega-thrust subduction earthquakes

Key words:
- **Cascading multi-hazards and risks**
- **Disaster risk reduction**
- **Critical infrastructure**

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2011 Tohoku Earthquake & Tsunami

Earthquake Facts

- Very large earthquake: $M_w 9.0$
- Catastrophic tsunami damage
- 19,000+ death/missing
- Direct loss: 300-400 billion US dollars
- Infrastructure damage – levees, roads, bridges, railways, water treatment plants, industrial facilities, etc.
- Widespread shaking damage and liquefaction
- Fukushima Daiichi nuclear power plant crisis (on-going, as severe as the direct loss)

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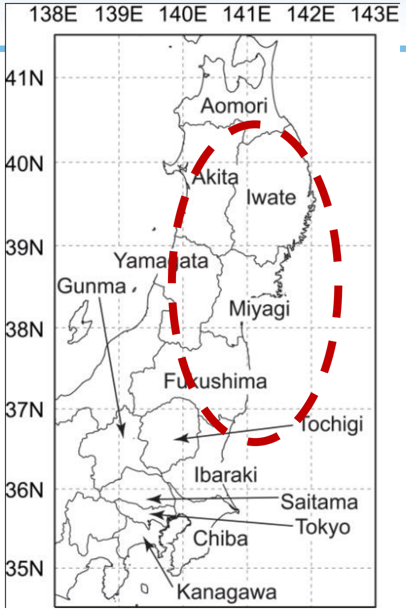
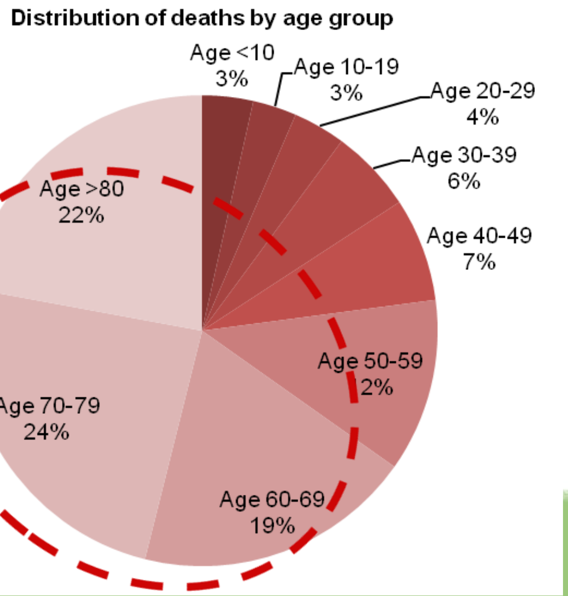
Damage Statistics

- Widespread damage to buildings – concentrated in Iwate/Miyagi/Fukushima.
- This includes both tsunami-affected and shaking-affected cases.



Damage statistics from National Police Agency

Prefecture	Total collapse	Half collapse	Partial damage	Non-residential damage	Road
Iwate	**20998**	**3174**	**2668**	**1538**	**30**
Miyagi	**65462**	**48684**	**76785**	**17826**	**390**
Fukushima	**15885**	**29125**	**92455**	**1015**	**19**
Ibaraki	2179	14873	132921	8551	307
Tochigi	257	2074	56799	295	257
Gunma	0	6	16145	195	7
Saitama	0	5	1800	33	160
Chiba	771	8056	27714	708	2343
Tokyo	0	11	257	20	13
Kanagawa	0	7	279	1	0
Others	343	959	110	1673	33
Total	**105895**	**106974**	**407933**	**31855**	**3559**



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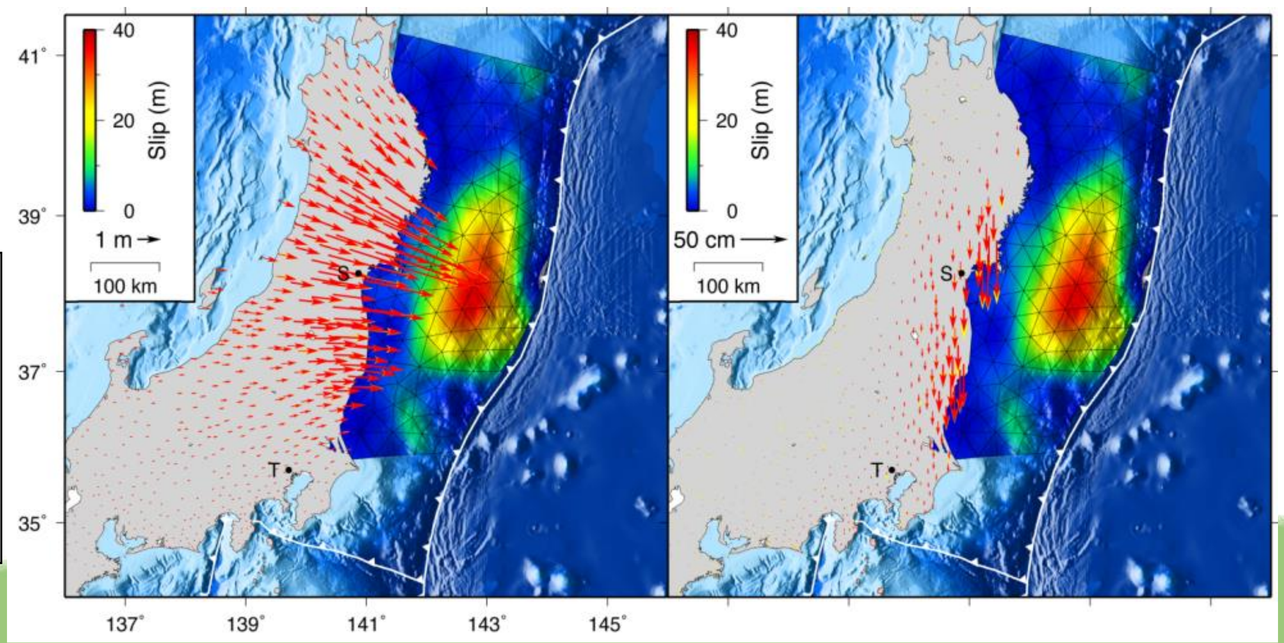
Earthquake & Tsunami

- A M_w9.0 mega-thrust earthquake at the plate boundary (2:46:23 pm, 11 March 2011) triggered tsunamis of 10+ m high, causing devastating damage.
- Large offshore deformation (up to +40m)
- Significant co-seismic deformation on land (up to 1 m subsidence).

Colour contour: slip
Vector: ground deformation
(Simons et al. 2011)

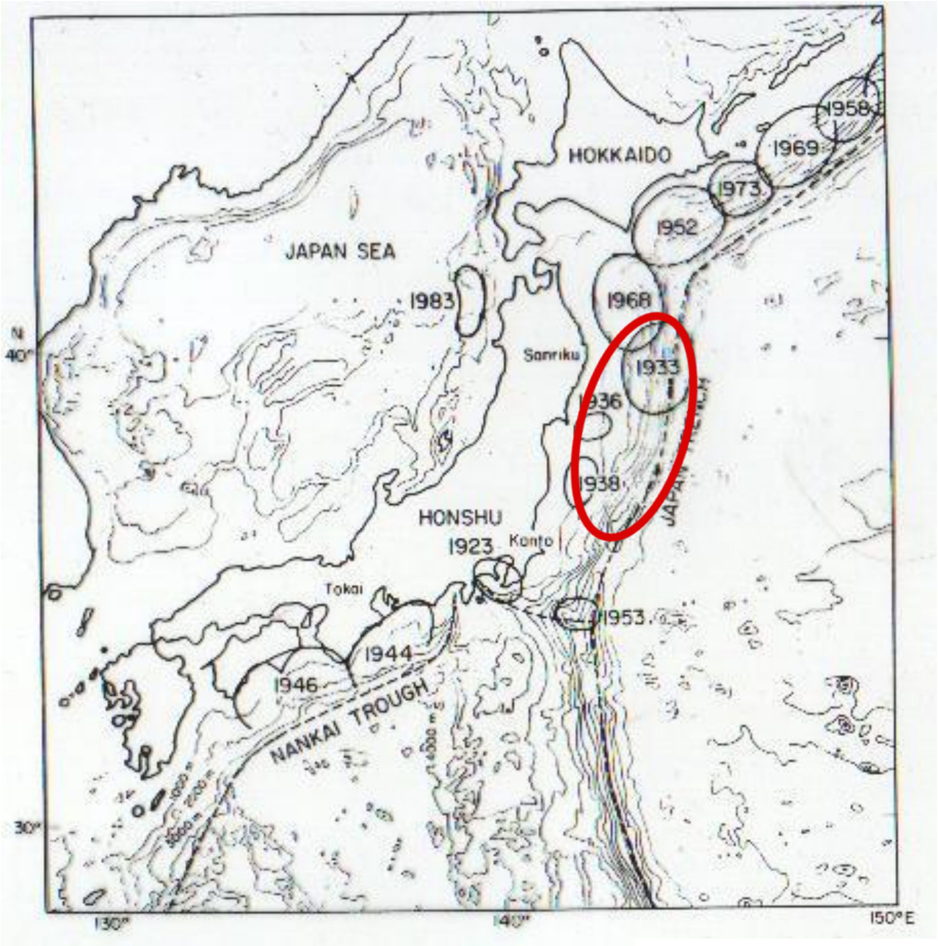
Viewpoints:
•The mainshock might have triggered marine landslides – generating local tsunamis.



Was This Earthquake Forecasted?

- Earthquakes expected in the Tohoku region were M_w7.4 to M_w8.2 due to six smaller fault segments based on historical seismicity.
- All six segments ruptured in a single event (M_w9.0) during the 2011 earthquake!

Perspectives:
•What are the implications of underestimating design-critical scenarios on earthquake and tsunami risk management?



Mogi (1977)

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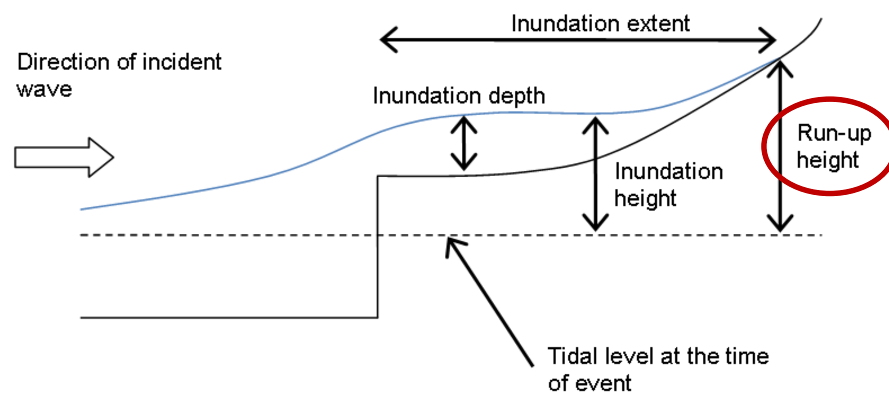
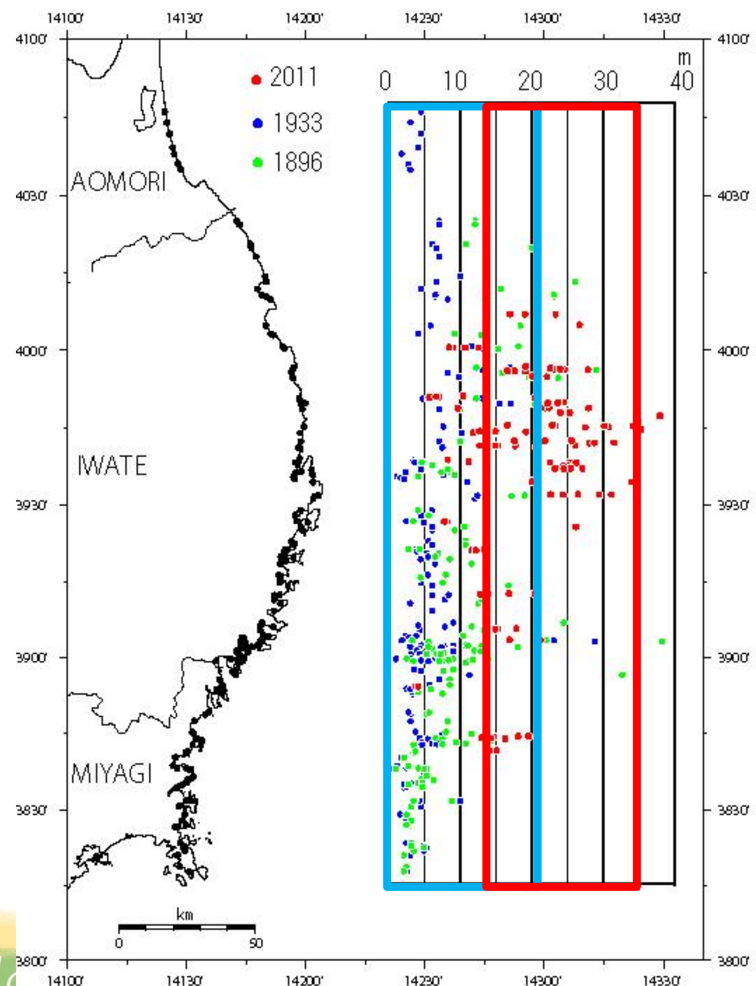
Was This Tsunami Forecasted?

- The Sanriku coast suffered tsunamis in 1896, 1933, and 1960 earthquakes repeatedly.
- The 2011 event generated much larger tsunami waves. Such high tsunami waves were not expected.
- However, historical records indicate such massive tsunamis did occur in the past – e.g. 1611 Keicho tsunami and 869 Jogan tsunami.



Run-up measurements for three events at Sanriku coast



Effects of Topography

- The Tohoku coastal line varies significantly from North to South.
- Northern Tohoku: ria coast – submerged valleys.
- Southern Tohoku: coastal plain – alluvial flat terrains.

Question:
•What are the effects of terrain features on tsunami waves?

Ria coast (northern Tohoku)

Plain coast (southern Tohoku)

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Taro (2011)

- 10-m high walls (above MSL) over 2 km – a well-protected town against tsunami – did not protect the town completely (about 200 fatalities) – but significantly reduced the damage.

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Taro (2012)

- Fishing is resumed, and some facilities (offices and markets) are reconstructed.
- Clearing/incineration of debris is on-going and is a major issue.

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Minami Sanriku (2011)

- Severe damage.
- High fatality rate (7% of the population).

Crisis management headquarters

Vertical evacuation building

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Minami Sanriku (2012)

- Local communities try to open several market places, which are run by local people.
- The adopted strategy is to sell local and fresh products directly (visible producer).

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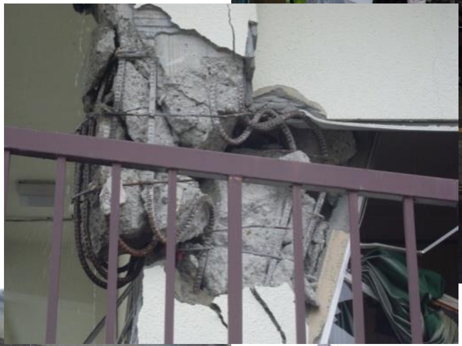
Shaking Damage

- Very large acceleration (> 2.5*g*) and long duration.
- Damage due to landslide/ slope failure.



Liquefaction Damage

- Loss of effective strength of soils due to rapidly increased pore pressure.
- Widespread liquefaction damage in reclaimed lands (Tokyo Bay area).
- This is due to a combination of susceptible soil (loose saturated sand) and long-duration ground shaking (up to 3 min).

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Tsunami Casualty Reduction Through Vertical Evacuation Buildings

Tsunami Casualty Reduction

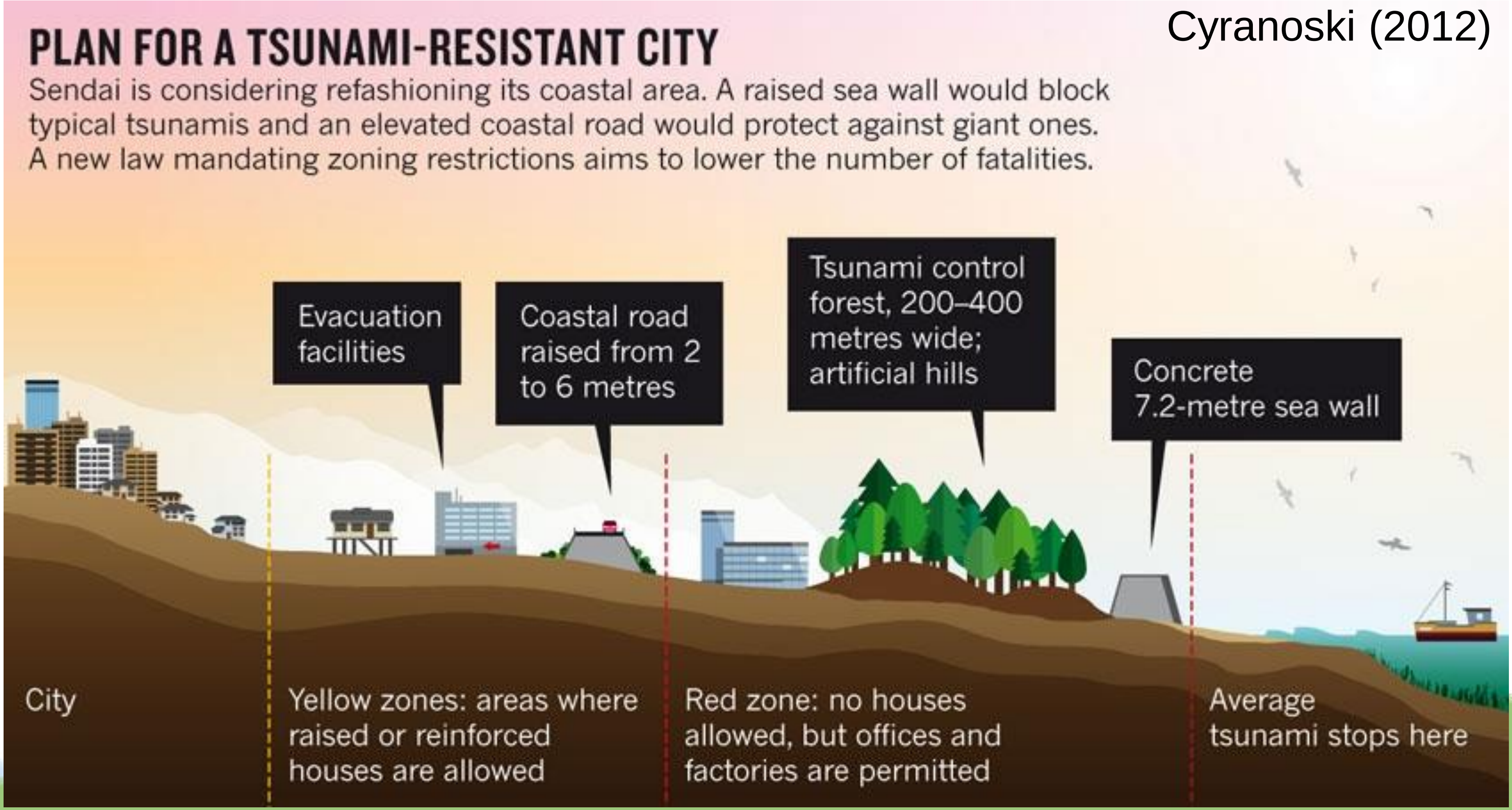
- What is the best strategy to reduce the number of fatalities in the future catastrophic tsunami?
- Option 1: As it is; sufficient tsunami protection – Fudai.

Tsunami Casualty Reduction

- Option 2: Rebuild the protection structures with higher capacity – Taro.

Tsunami Casualty Reduction

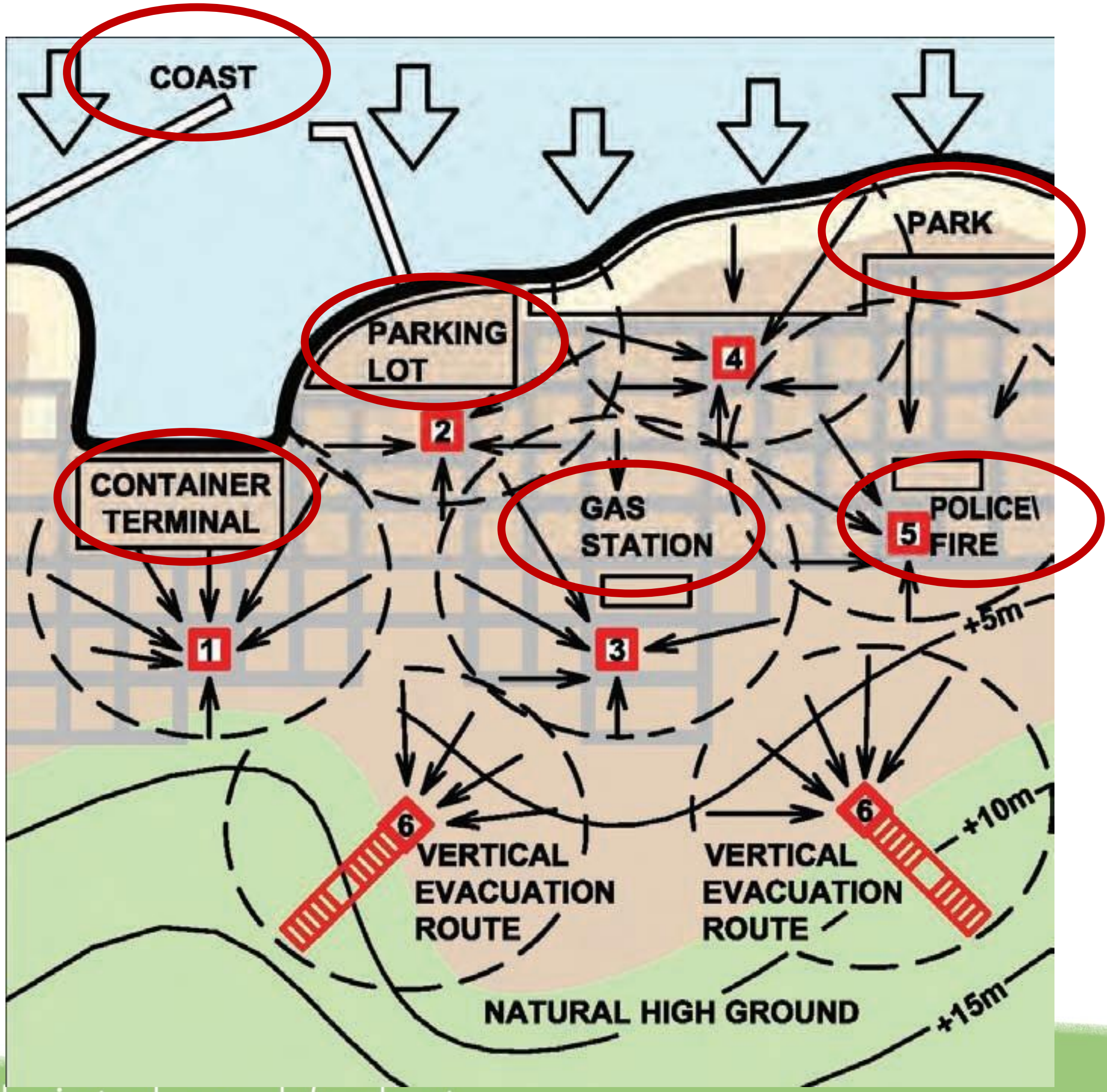
- Option 3: Relocation of an entire town/city to high grounds – Noda.
- Option 4: Combination of horizontal and vertical evacuation structures.



Cyranoski (2012)

Horizontal & Vertical Evacuation

- 19,000+ death - disproportionate risks for elderly (75% of deaths for age 50+).
- Both horizontal and vertical evacuations must be improved.
- Different strategies for different communities (land use/feature, sea defence, tsunami hazard, demography, etc).

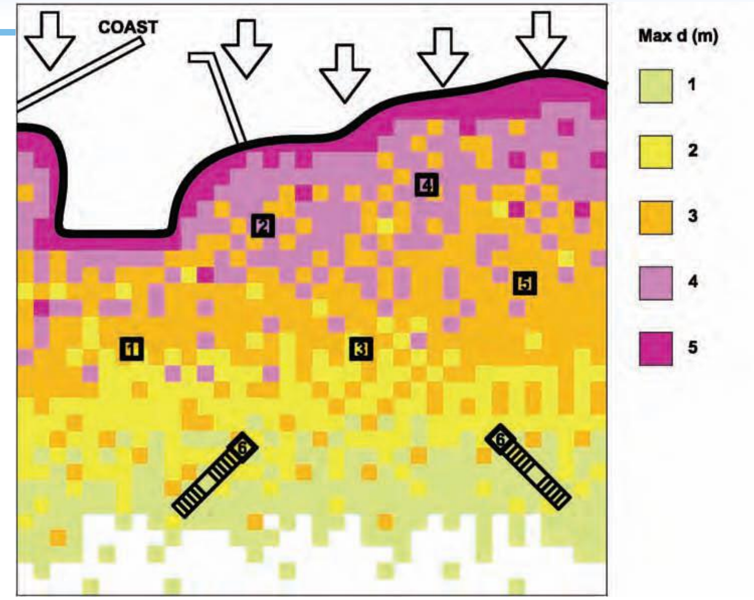


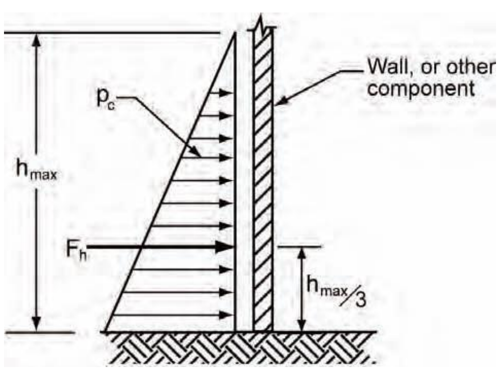
FEMA (2008)

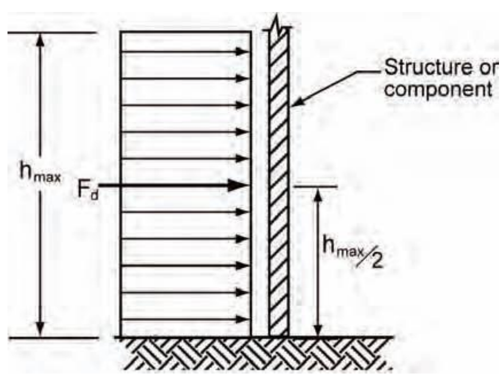
Question:
•What aspects should designers/planners consider for evacuation?

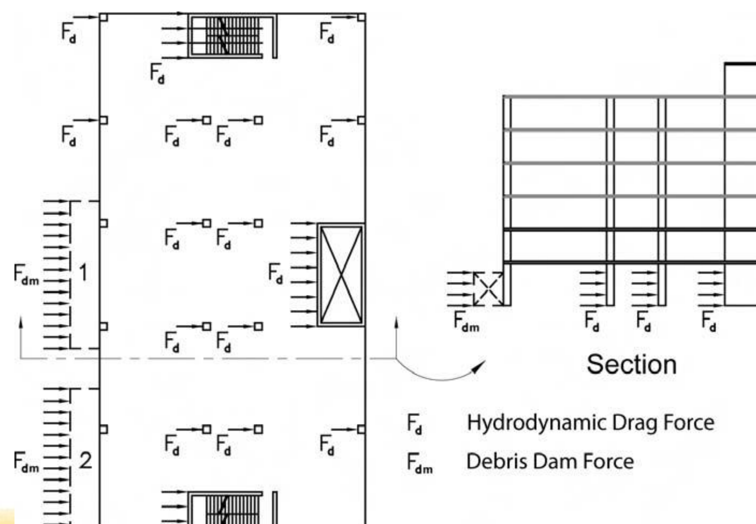
Design of Vertical Evacuation Buildings

- Input information – tsunami height and velocity at a location
- Various forces act on buildings subjected to tsunami: hydrostatic force, hydrodynamic force, debris, buoyant force, etc.







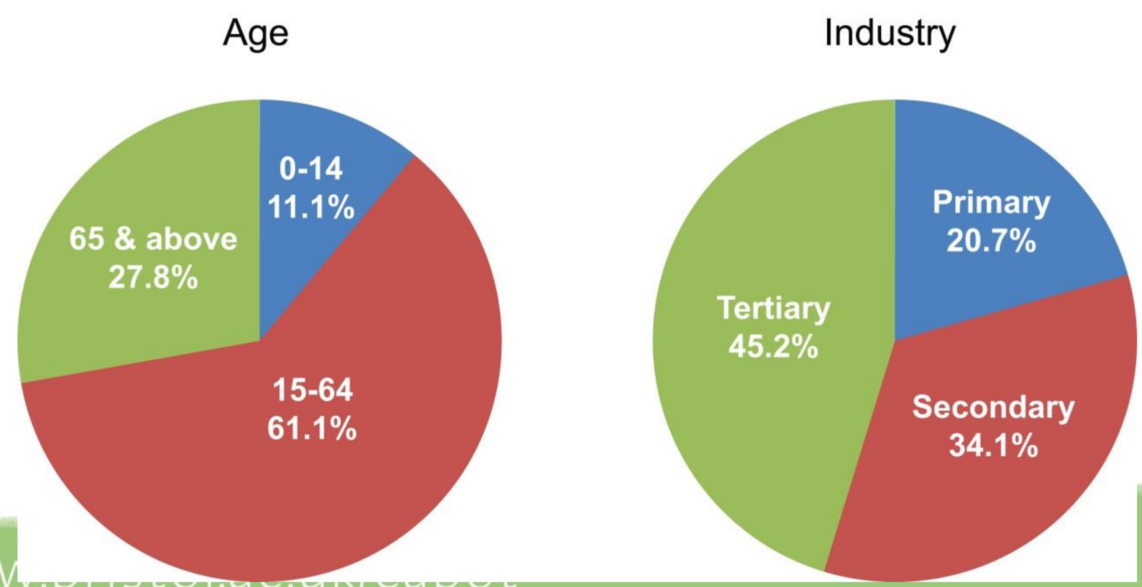


FEMA (2008)

Town of Yamamoto, Miyagi, Japan

- Coastal plains – South of Sendai (35 km).
- 676 deaths - about 90 people (only) survived by evacuating to a shelter building. This is significantly less than other neighbouring municipalities (for instance, in Watari and Natori, about 2100 and 3250 people, respectively, evacuated and survived).
- Aging society.

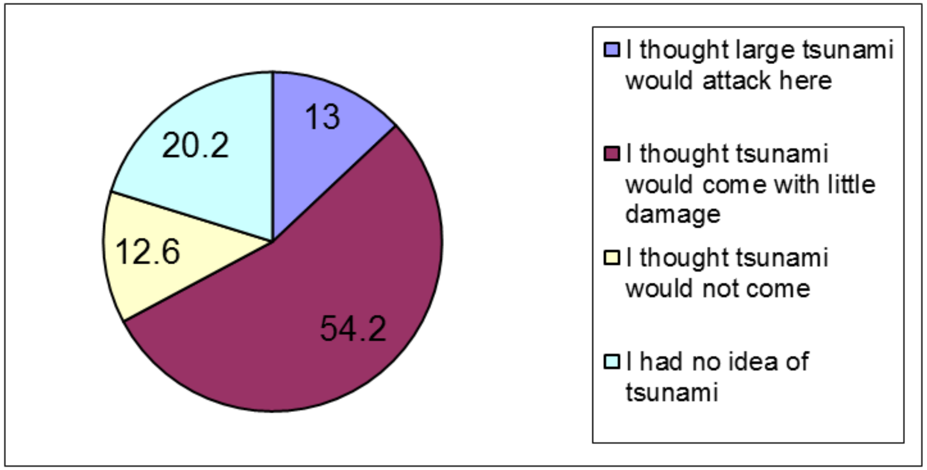
National average: **21%** for people aged over 65 years



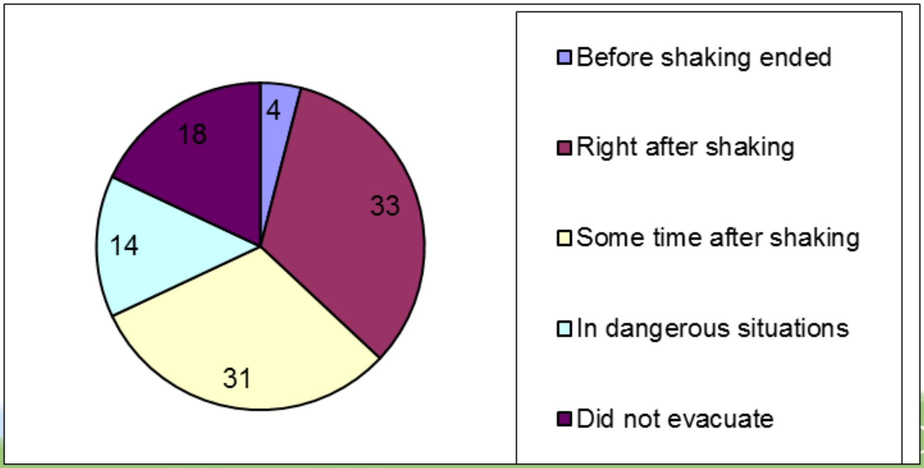
Post-Tsunami Survey

- Post-tsunami survey was conducted in Natori by Murakami et al. (2012).
- Unawareness of tsunami risks and delayed evacuation actions.
- Use of cars.

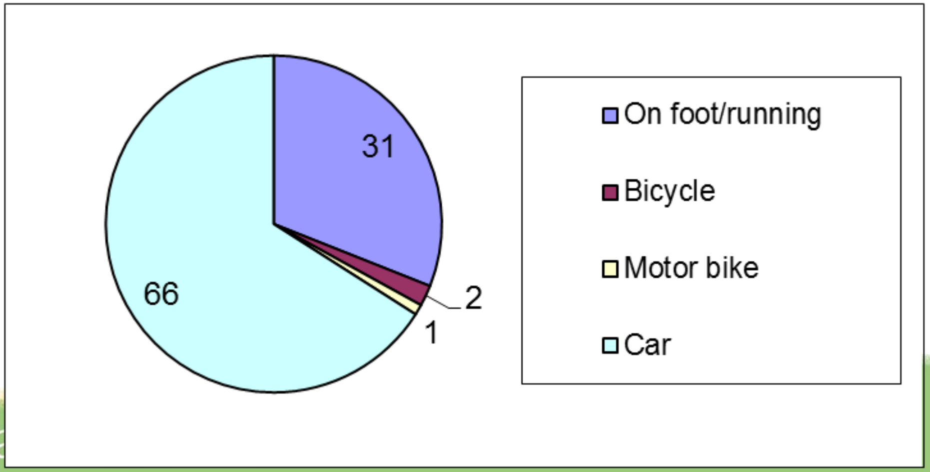
Awareness for tsunami risk



Timing of evacuation



Travel means for evacuation



Tsunami Damage in Yamamoto

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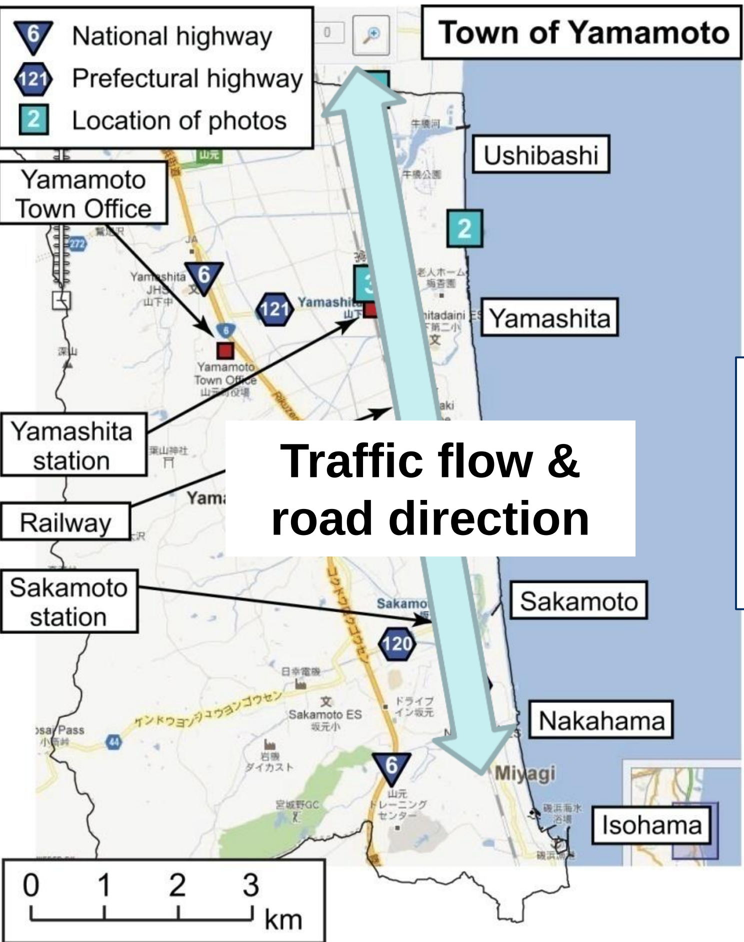
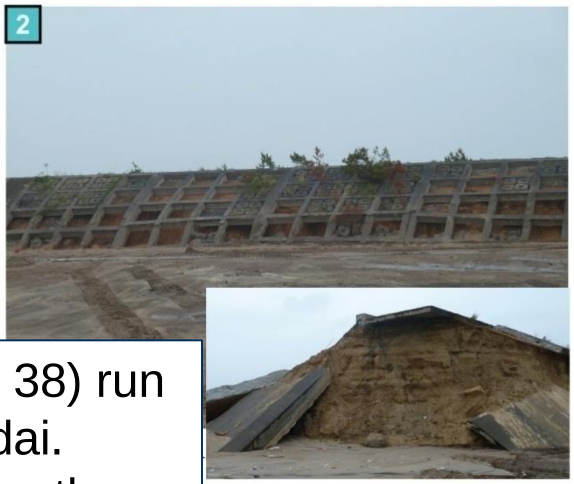
- Coastal revetments/levees were destroyed.
- Many residential houses were washed away.

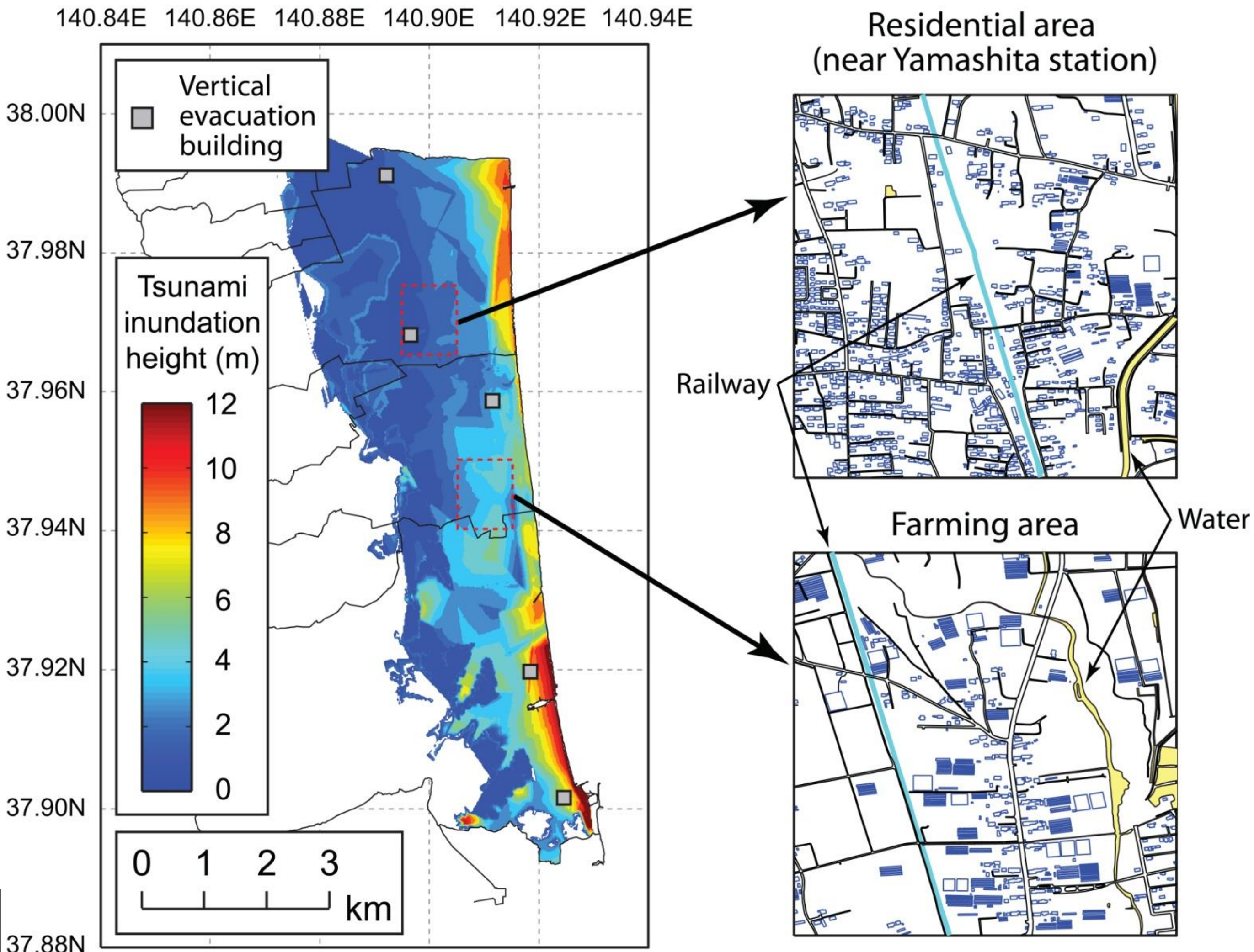


Traffic flow & road direction



- Major roads (e.g. highway 38) run North-South towards Sendai.
- Traffic jams occurred during the evacuation.

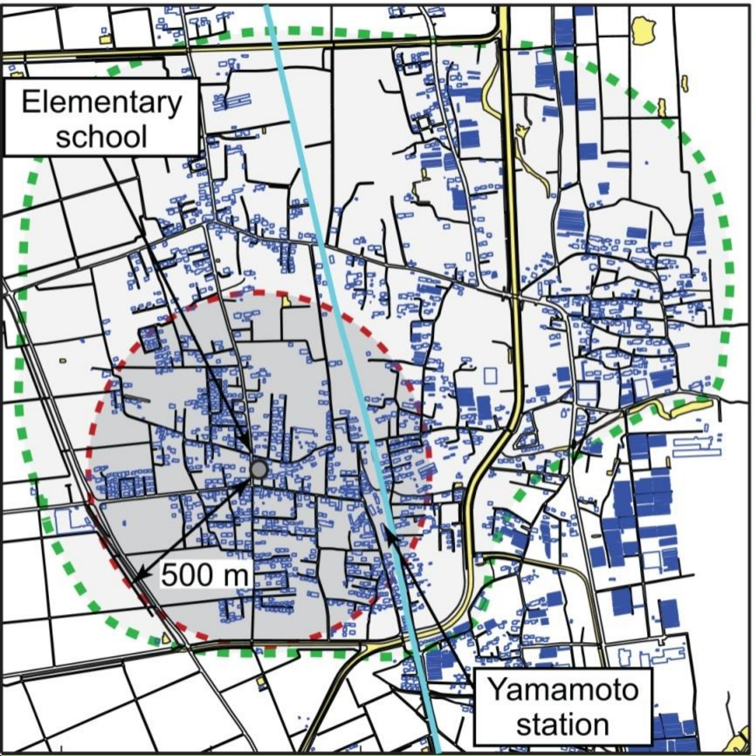
Tsunami Inundation in Yamamoto

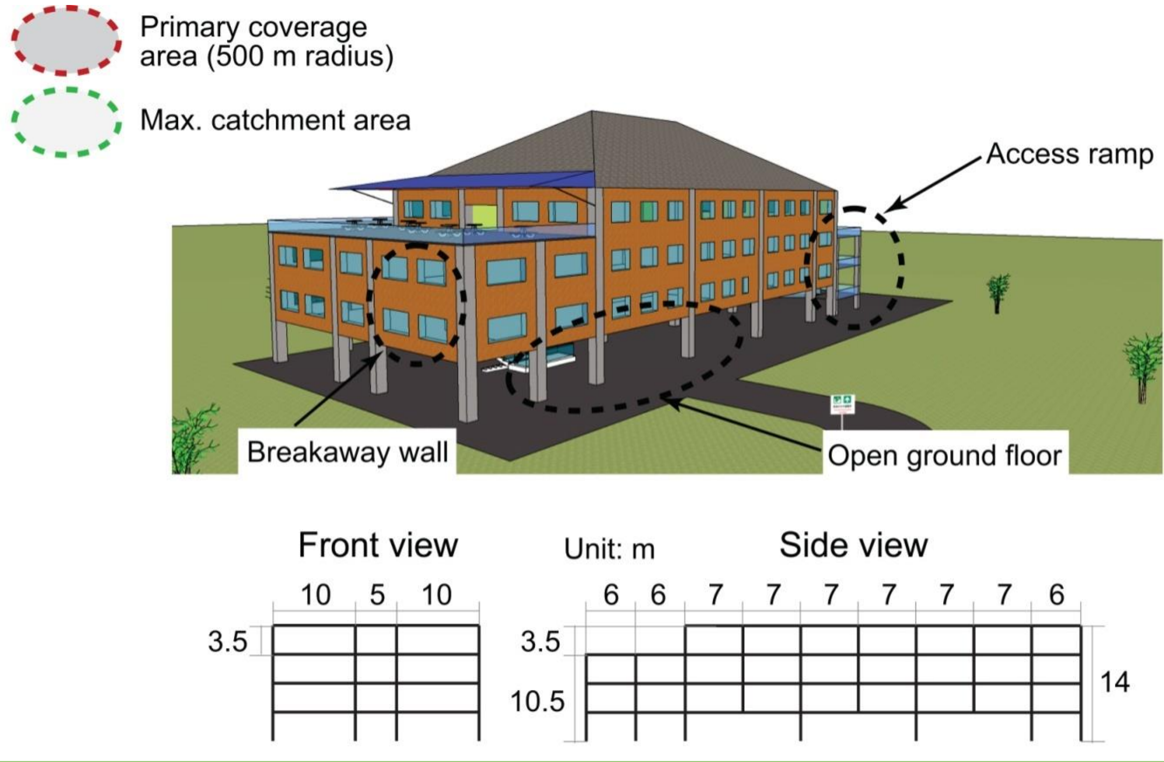


- Five sites for vertical evacuation buildings.
- Coverage area - 500 m radius (4 miles per hour and 5 minutes; FEMA, 2008).
- Occupancy: local needs for services.

Yamamoto Elementary School

- 500 m radius primary catchment and extended catchment.
- Open ground space and breakaway walls.
- Earthquake resistance and pile foundation (up to 10 m).





Informed Decision: Cost-Benefit Analysis

- Design tsunami height: anticipated inundation height (2011 event) plus some freeboard (FEMA, 2008).
- Assume 600 lives saved for £47.5 million investments.
- £80K/life versus £20-30K/quality year (UK).
- Cost-effective!

Summary of cost-benefit analysis

Evacuation building site & occupancy type	Inundation depth (m)	Design tsunami height (m)	Building height (m) [# of storeys]	Covered population [Floor area (m^2)]	Cost (million GBP)
Site 1: Care home	1.95	5.54	14 & [4]	1320 & [2400]	18.1
Site 2: Elem. school	1.85	5.41	14 & [4]	1030 & [1500]	10.82
Site 3: Sports centre	4.09	8.32	14 & [3]	780 & [1000]	6.15
Site 4: Post office	10.49	16.64	17.5 & [5]	740 & [800]	6.89
Site 5: Fish process. plant	7.76	13.09	17.5 & [5]	970 & [1000]	5.53

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Fukushima Daiichi Nuclear Power Plant Crisis

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Fukushima Daiichi NPP

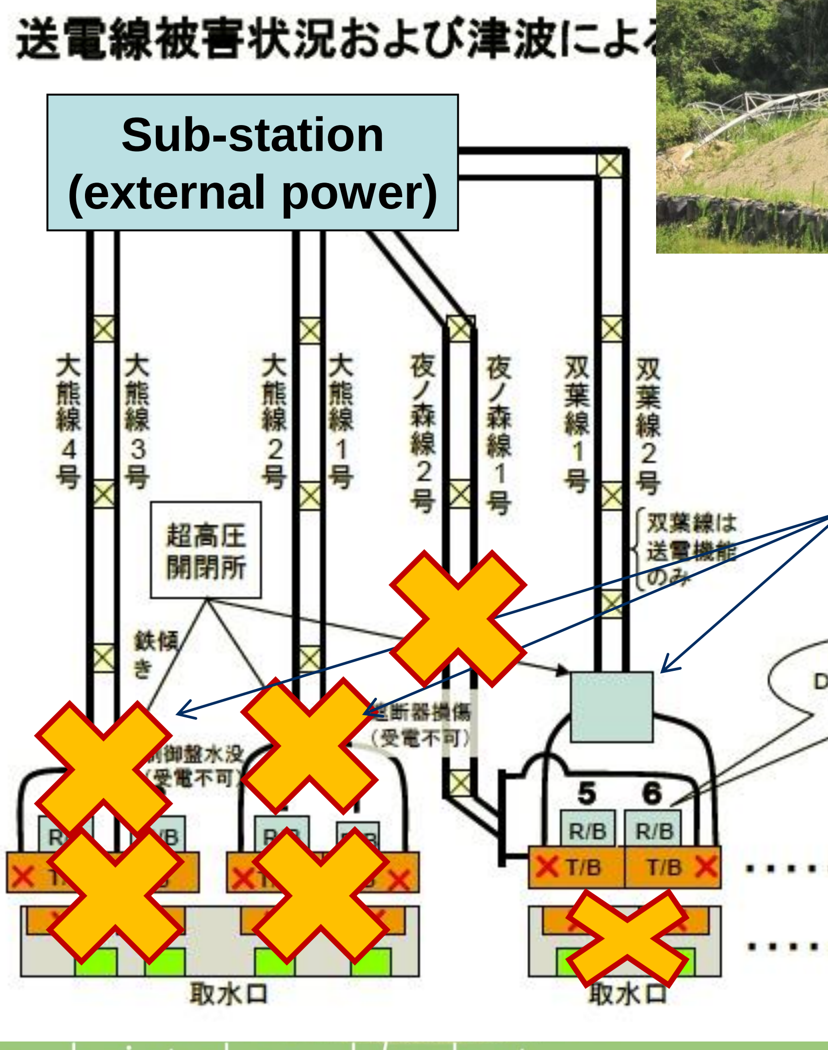
Fukushima Daiichi NPP

UK reactors: AGR (advanced gas-cooled reactors)

- Six boiling water reactor (BWR) units in the plant were constructed in 1970s. Heat is generated by nuclear fission and water is turned into steam, which drives a turbine to generate electricity.
- The facility was operated by Tokyo Electric Power Company (TEPCO).
- 14+ m tsunami (M_w9.0 event) arrived at the plant, whereas the seawall was only 6.5 m high (M_w8.2 event). Reactors 1-4 were inundated by the tsunami.
- They lost power supply, which was critical for pumping cooling water. Reactors 1-3 experienced meltdown. The emergency diesel generators and DC batteries were located at the basement of the reactor buildings.

Fukushima Daiichi Power Loss

- The loss of power supply was caused by tsunami and shaking.
- Reactors 1-4 lost emergency diesel generators, DC batteries, and sea-water pumping systems by tsunami.
- The switching station for Unit 1&2 was damaged by shaking.
- The switching station was inundated (Unit 3&4) – unable to receive power externally.



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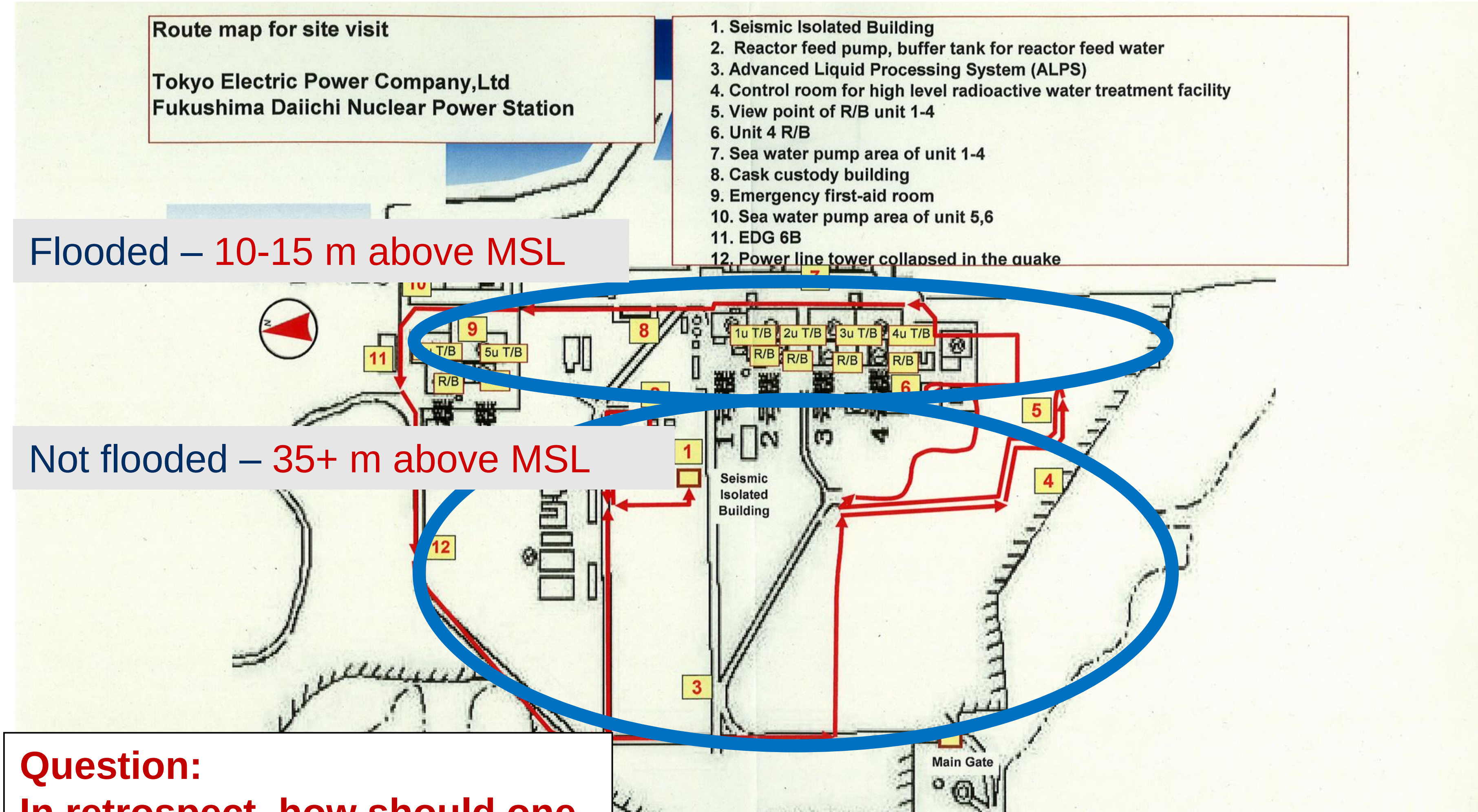
Current Situation

- Reactors 1-4 are currently under cold shut-down. They will be decommissioned (40-year plan).
- The compulsory evacuation zone is reduced from 20 km radius to 10 km radius.
- The current challenges are to continue to maintain cold shut-down status and process contaminated cooling water (400 ton per day).
- The Advanced Liquid Processing System (ALPS) has been constructed to remove all radioactive elements (e.g. caesium and strontium), except for tritium, from cooling water.

Current Situation

- A full operation of ALPS has been just started – tritium needs to be removed. At this stage, the processed water will not be released into the environment – still the low-contaminated water needs to be stored in tanks.
- Removals of the fuels from the reactor buildings – construction of outer frames and cranes to Reactors 3 and 4.

Site Layout & Design



Question:
In retrospect, how should one lay out/design/plan the NPP site?

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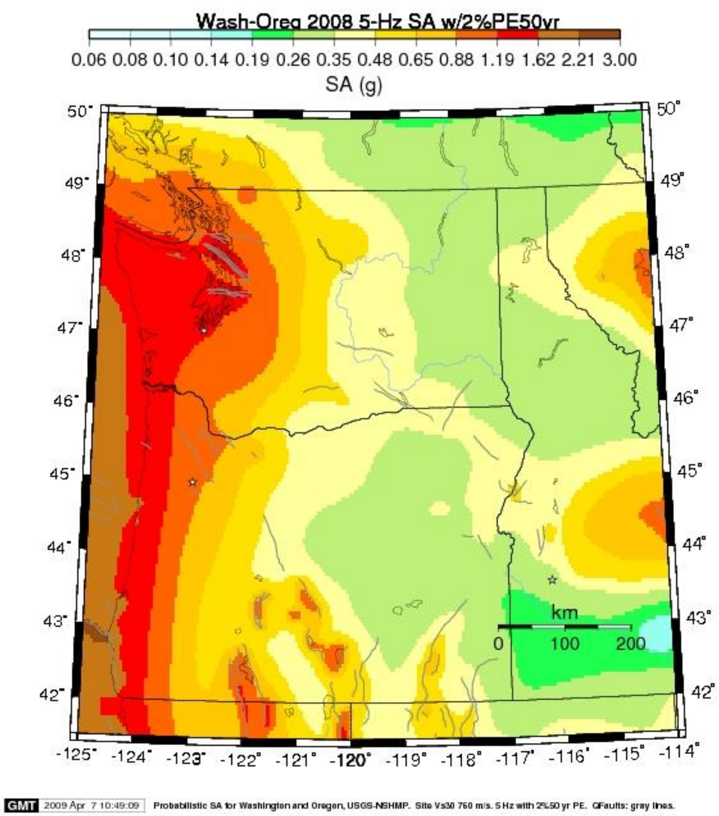
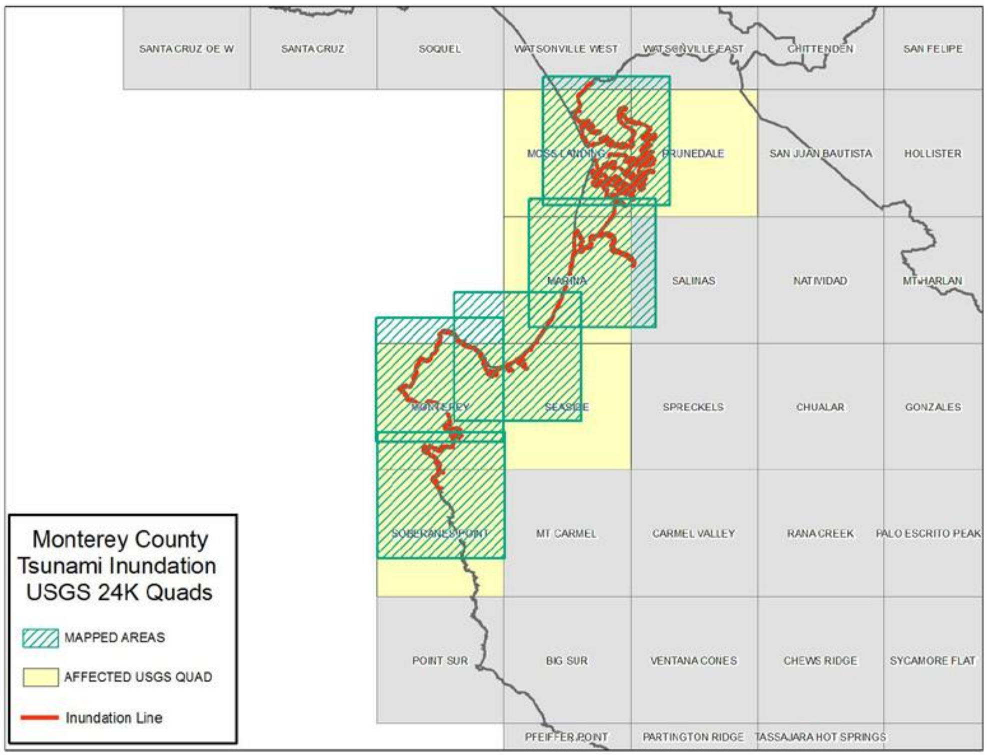
Research Challenges: Cascading Multi-Hazard & Risk Modelling due to Mega-thrust Subduction Earthquakes

Multi-Hazards Framework

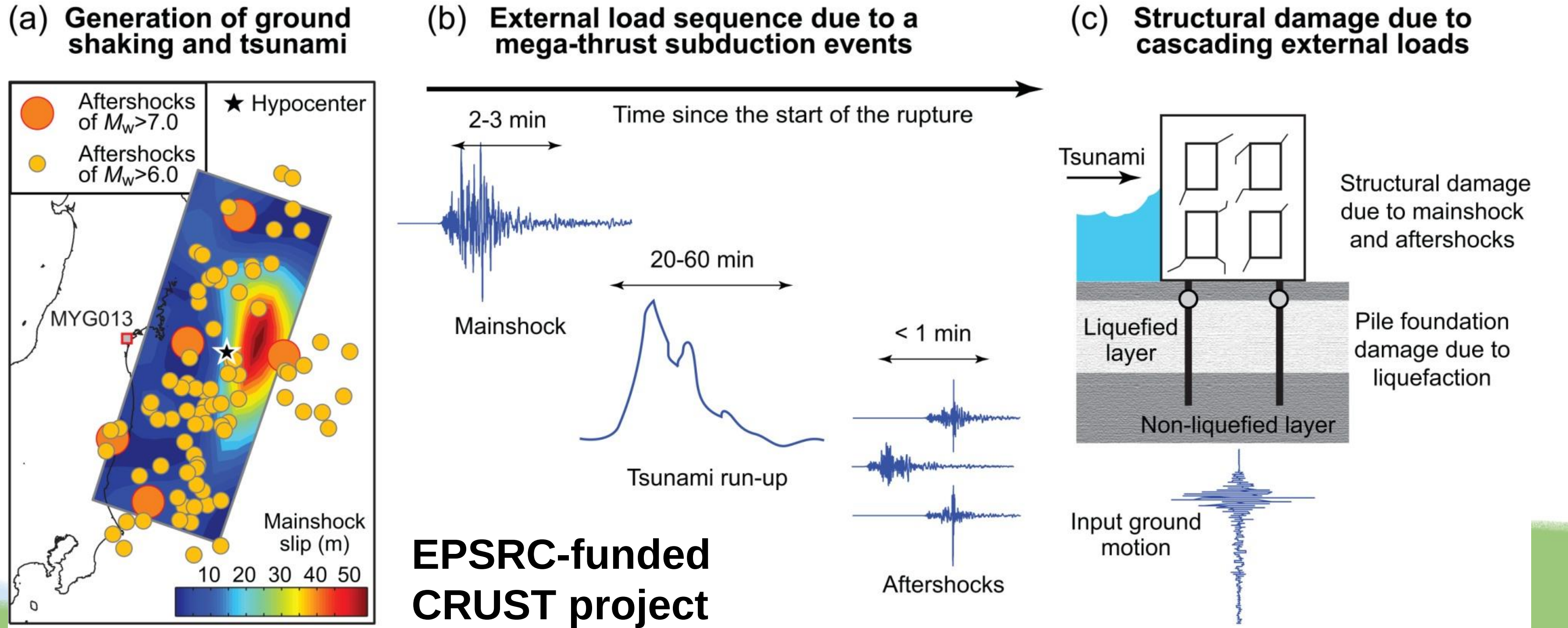
- Current approaches are fragmented – no coherent methodology and framework across different hazards.
- Multiple hazard maps – but based on different assumptions and scenarios.





Cascading Hazards & Compounding Risks

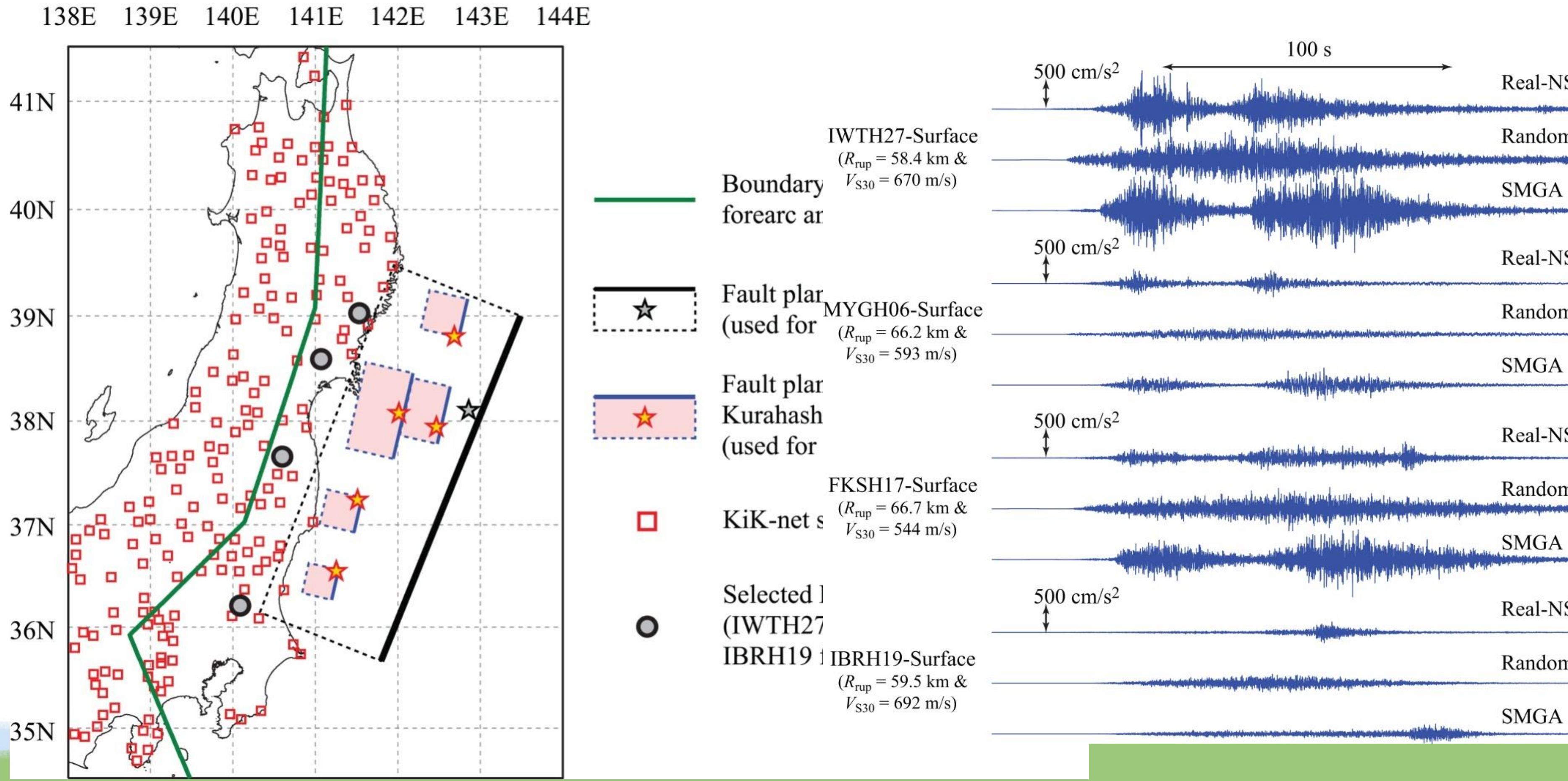
- Spatial and temporal dependency of external loading to critical infrastructure and its functionality (e.g. supply chain and business continuity planning).
- Multi-hazard modelling of a mega-thrust earthquake is important. Mainshock -> aftershocks -> ground failure -> tsunami –> fire -> …



EPSRC-funded CRUST project

Earthquake Source & Strong Motion

- Mega-thrust subduction earthquake – ground shaking modelling – large acceleration, long duration, etc.



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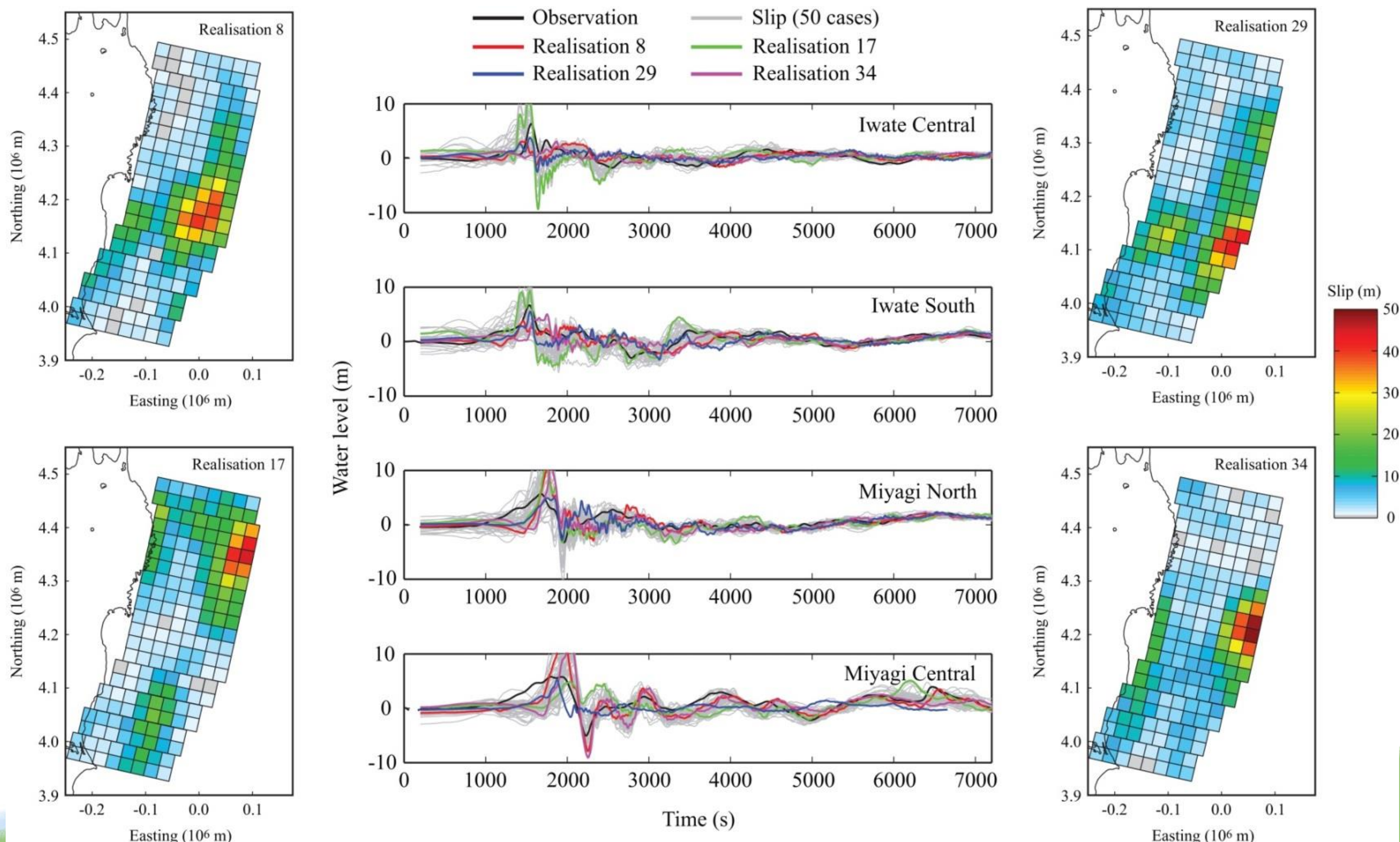
Uncertainty Quantification

- Both strong shaking and tsunami are dependent on (unknown and uncertain) earthquake source characteristics.

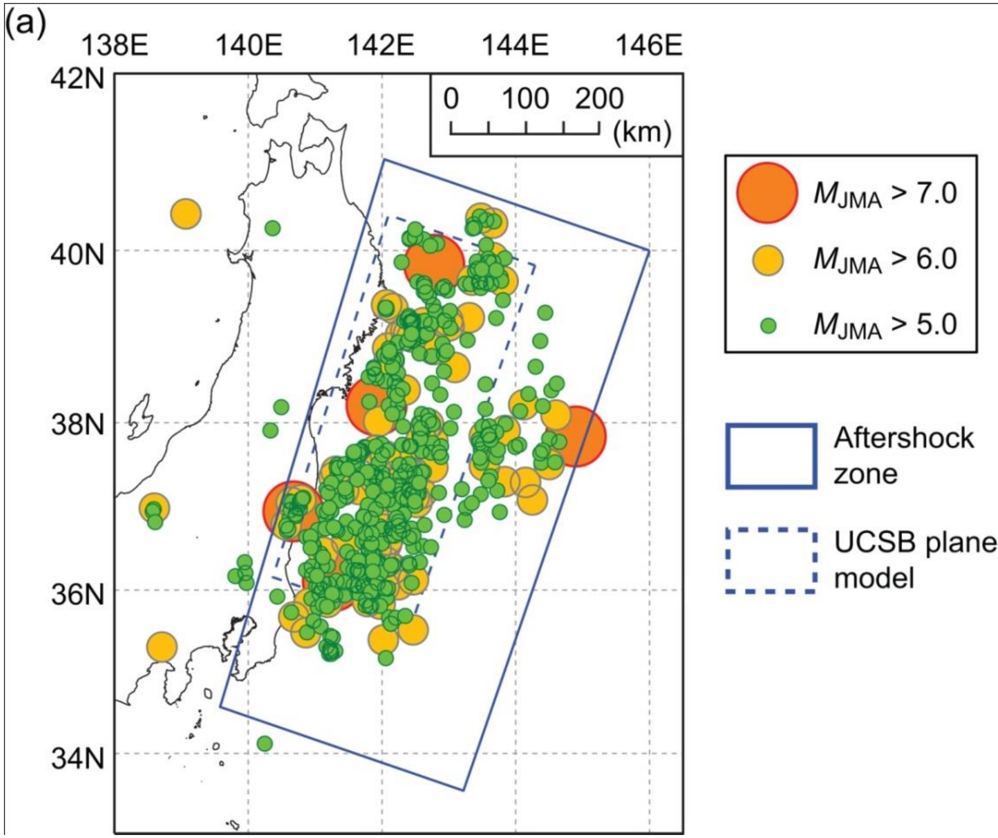
Perspectives:

•How one should quantify the uncertainties associated with hazard predictions and make informed decisions?



Aftershock Hazards & Risks

- Numerous major aftershocks over a wide spatial area.
- Post-earthquake building tagging. Evacuation – how long?
- Time-dependent hazards.
- Financial loss and insurance policy



Perspectives:
•The 2010 Darfield and 2011 Christchurch (NZ) earthquakes can be interpreted as mainshock-aftershock sequence.
•What about the 2004 Sumatra earthquake?

Water-borne Debris

- Impact forces caused by large floating objects such as ships and containers can be destructive.
- The estimation of such forces is highly uncertain.

Summary & Key Lessons

- Imagine extreme situations – scenarios!
- Cascading multi-hazards and risks.
- Uncertainty modelling and quantification.
- Combination of soft and hard measures – resistant structures plus emergency planning/evacuation.
- Vertical evacuation buildings can be justified on the cost-benefit basis.
- Multi-layer protection – system robustness & resilience.
- Cooperation among victims, Self-Defence Forces, municipalities, NGOs/NPOs, companies, governments, foreign aids, etc.

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Any Lessons for the UK?

- Any critical infrastructure in the UK may be subject to similar cascading hazards and risks (due to different trigger events).
- The 2007 Ulley reservoir crisis put local communities, M1 motorway junctions, and a crucial regional electricity substation in extreme danger.

http://www.ulleyweb.co.uk/flood.htm