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The Behavior of 3.11 Tsunamis in the Sendai Plain and the Damage of the Disaster Prevention System

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Background and objectives

- Background
  - Damage by 3.11 tsunamis
    - 20,000 people killed or missing
    - 100,000 houses totally destroyed
    - Coastal disaster mitigation system destroyed
  - Governmental policy of the disaster mitigation
    - For L1 class hazards (RP of 100 to 150 y), to rebuilt coastal levees to secure lives and assets
    - For L2 class hazards (>150 y), to secure lives and mitigate the asset damage by multiple mitigation countermeasures
  - Issues for L2 class hazards
    - How to secure lives?
    - How to rebuilt the levees not seriously destructed?
- Objectives
  - To show the causes of the damage occurrence
  - To find the possible solutions for the issues

Contents

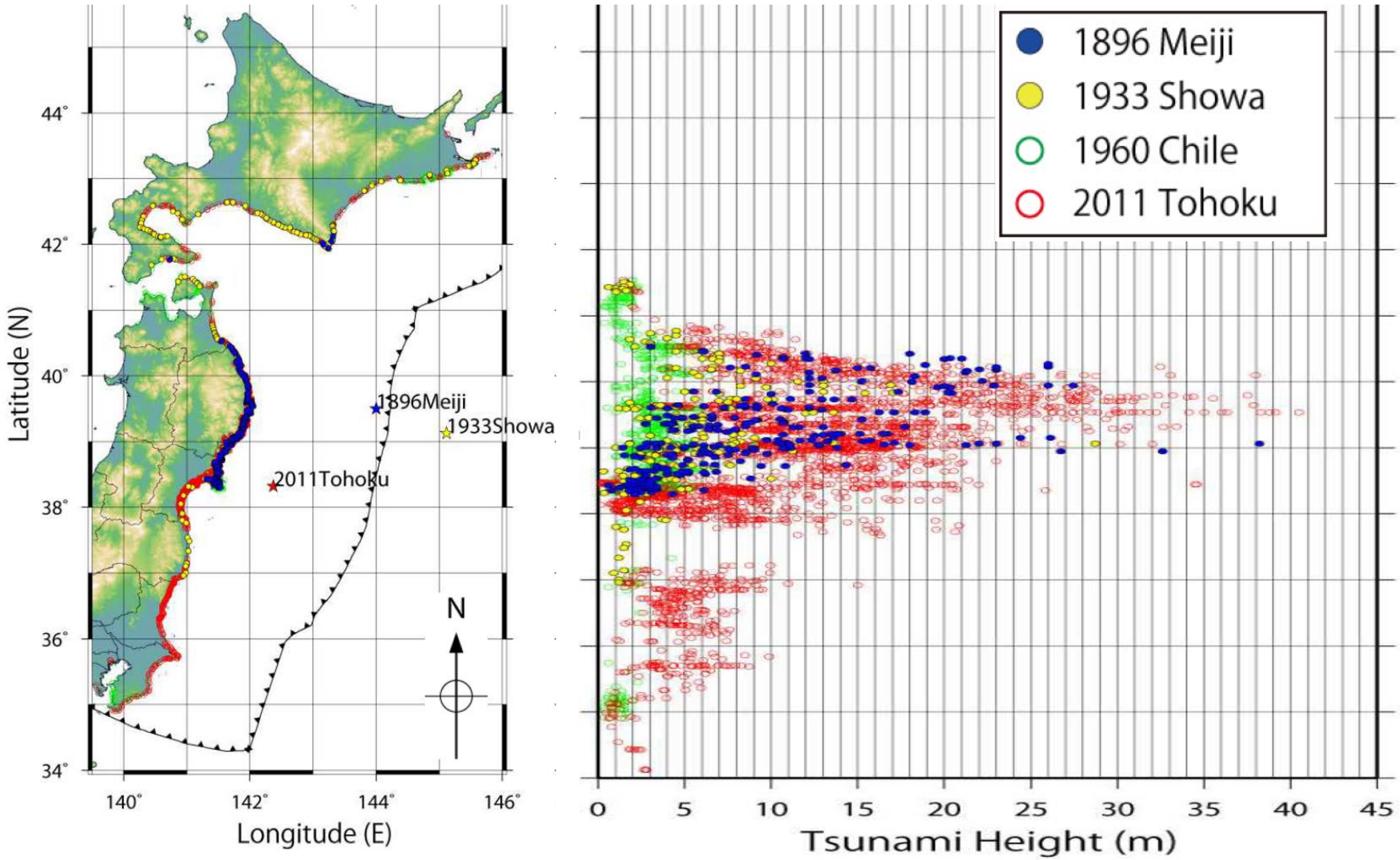
- Background and objectives
- Geology and tsunami deformation
- Human and house damages for the tsunami height
- Tsunami behavior near the coasts
- Obstacles for the evacuation
- Mechanism of coastal levee destruction
- Damage of coastal forest
- Summary: Lessons from the disaster

Geology and tsunami deformation in the three coasts

- Sariku Coast
  - Crustal uplifting in the north
    - Cliff coast
    - Tsunami collision
  - Crustal subsiding in the south
    - Submerged valleys
    - Energy concentration
    - Bay water resonance
  - Frequent tsunami attacks
- Sendai Bay Coast
  - Alluvial plain
    - Sandy beach and shallow water
    - Propagation delay and energy dissipation
  - Low frequency in large tsunamis
- Joban Coast
  - Crustal uplifting
    - Cliff coast and pocket beach
    - Tsunami collision
  - Low frequency in large tsunamis

Tsunami height in 4 major events

after Shigihara (2011)



Recent study finds Jogan Tsunami in 869 is similar to the 2011 tsunamis in the Sendai Plain through the sedimentological analysis, Sugawara (2011). This estimates RP of the tsunamis as a1000y.

Human damage

Coast	Place name	Dead	Missing	Population	Damage(%) (D+M)/P	Prefecture
Sanriku Coast	Kuji V.	4	2	35568	0.017	Iwate Prefecture
	Noda V.	37	0	4613	0.802	
	Tanohata V.	15	25	3831	1.044	
	Fudai V.	0	1	3071	0.033	
	Iwaizumi T.	11	0	10597	0.104	
	Miyako C.	525	122	58917	1.098	
	Yamada T.	600	51	18634	3.494	
	Oozuchi T.	800	586	15239	9.095	
	Kamaishi C.	882	221	39119	2.820	
	Ofunato C.	336	114	39602	1.136	
	Rikuzenatakada C.	1487	264	24246	7.222	
	Kesennuma C.	1013	395	73154	1.925	Miyagi P.
	Tome C.	17	5	83691	0.026	
	Minamisanriku T.	542	664	17378	6.940	
	Onagawa T.	448	454	9932	9.082	

*** Fudai V. was secured by the 15.5m-high levee
**** Kamaishi C. was mitigated by the tsunami breakwater
***** Ofunato C. was mitigated by the tsunami breakwater
****** A part of Toni-Hongo in Kamaishi C. was secured by mass movement to highland after 1933 Showa Sanriku Tsunamis.

Coast	Place name	Dead	Missing	Population	Damage(%) (D+M)/P	Prefecture
	Ishinomaki C.	3164	793	160336	2.468	Miyagi Prefecture
Sendai Bay Coast	Higashi-matsushima C.	1044	98	42859	2.665	
	Matsunima T.	1	7	15017	0.053	
	Shiogama C.	44	5	56325	0.087	
	Shitigahama T.	57	17	20377	0.363	
	Tagajyo C.	187	3	62881	0.302	
	Sendai C.	704	51	1046902	0.072	
	Natori C.	910	109	73576	1.385	
	Iwanuma C.	181	2	44138	0.415	
	Watari T.	254	7	34138	0.765	
	Yamamoto T.	672	20	16633	4.160	
	Shinchi T.	108	18	7960	1.583	Fukushima P.
Joban Coast	Souma C.	454	28	36741	1.312	
	Minami Souma C.	640	23	67224	0.986	
	Namie T.	146	38	19538	0.942	
	Iwaki C.	309	38	335678	0.103	
	Total	15592	4161	2010774	0.982	

*Futaba T., Okuma T. Naraha T. Hirono T. have no data because of NPPA
**The numbers are updating.

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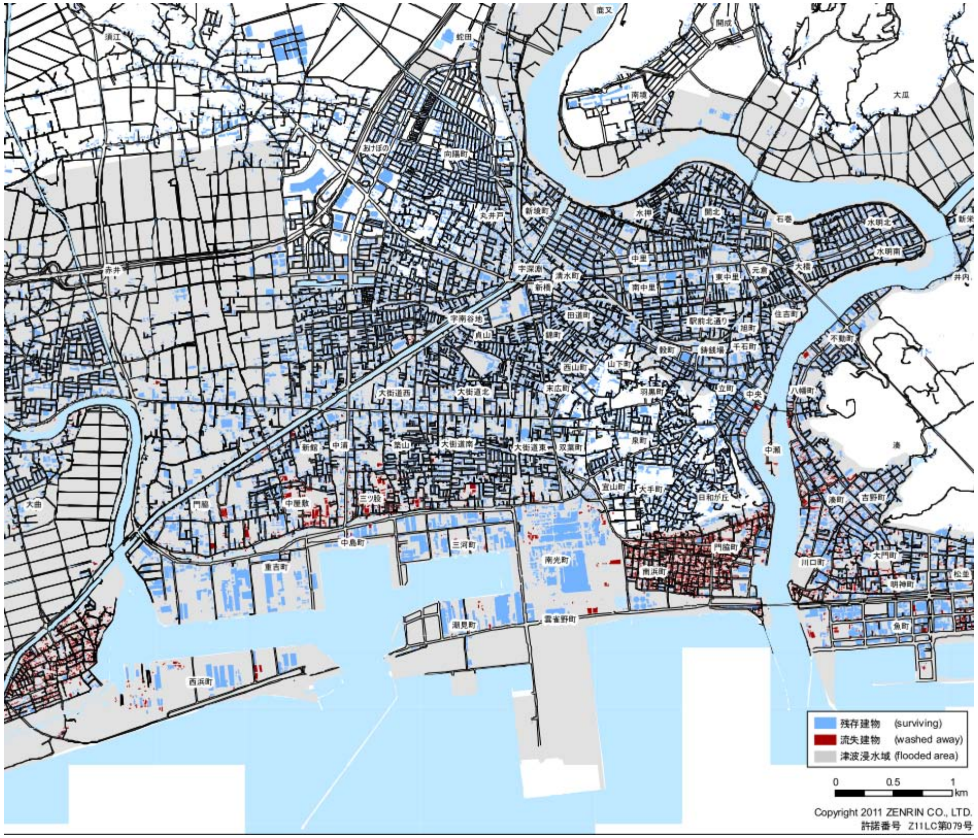
Tsunami characteristics of the coasts

	Sanriku Coast	Sendai Bay Coast	Joban Coast
Morphology	Rocky coasts and submerged valleys	A long sandy beach	Rocky coasts and pocket beaches
Major hazards in recent 100 y before 2011	Tsunamis	Storm surges	Wind waves
Height of coastal levee	5 to 16 m	6 to 7 m	4 to 6 m
Major land use in the coasts	Fishery	Agriculture, fishery and industry	Fishery and NPP
Max tsunamis in recent 150y	10 to 25 m in 1896	3 m in 1960 Chili	4 m in 1960 Chili
2011 tsunamis	15 to 35 m	8 to 14 m	6 to 10 m
Dead and missing	a9600	a8500	More than 1700

High rareness in large tsunamis gave inattention in Sendai Bay and Joban areas.
No tsunamis larger than levee height in one century gave relief in Sanriku area.

House damage in Ishinomaki C. West

Koshimura(2011)



Inundation area
house washed away
house survived

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University of Tokyo

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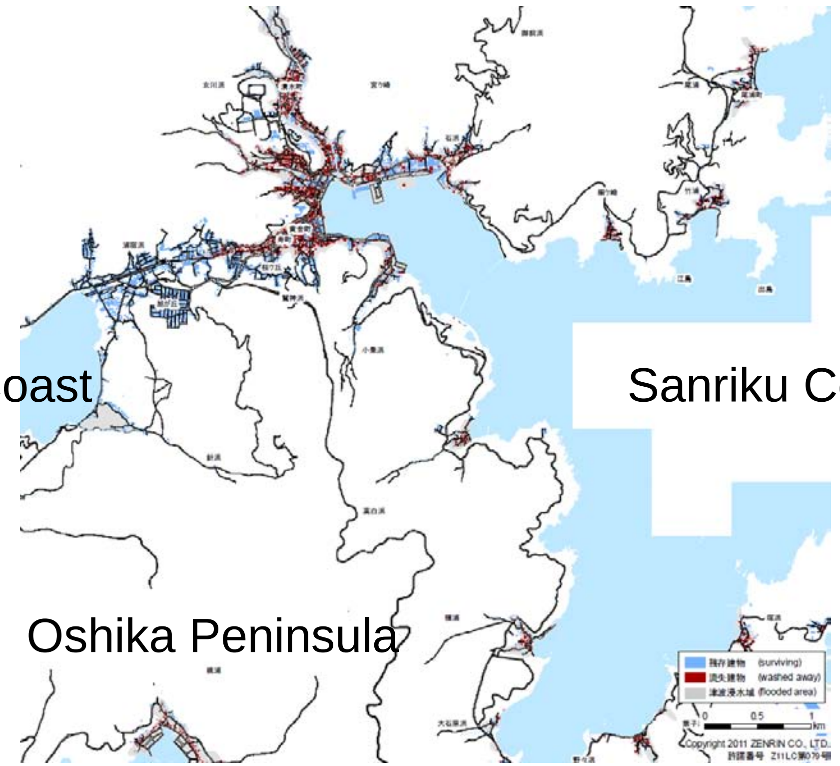
Tsunami inundation depth varies from 3m to 10m. More than 80% of houses were washed away for the tsunami inundation height > 5m.

House damage in Onagawa T.

Koshimura(2011)



Inundation area
house washed away
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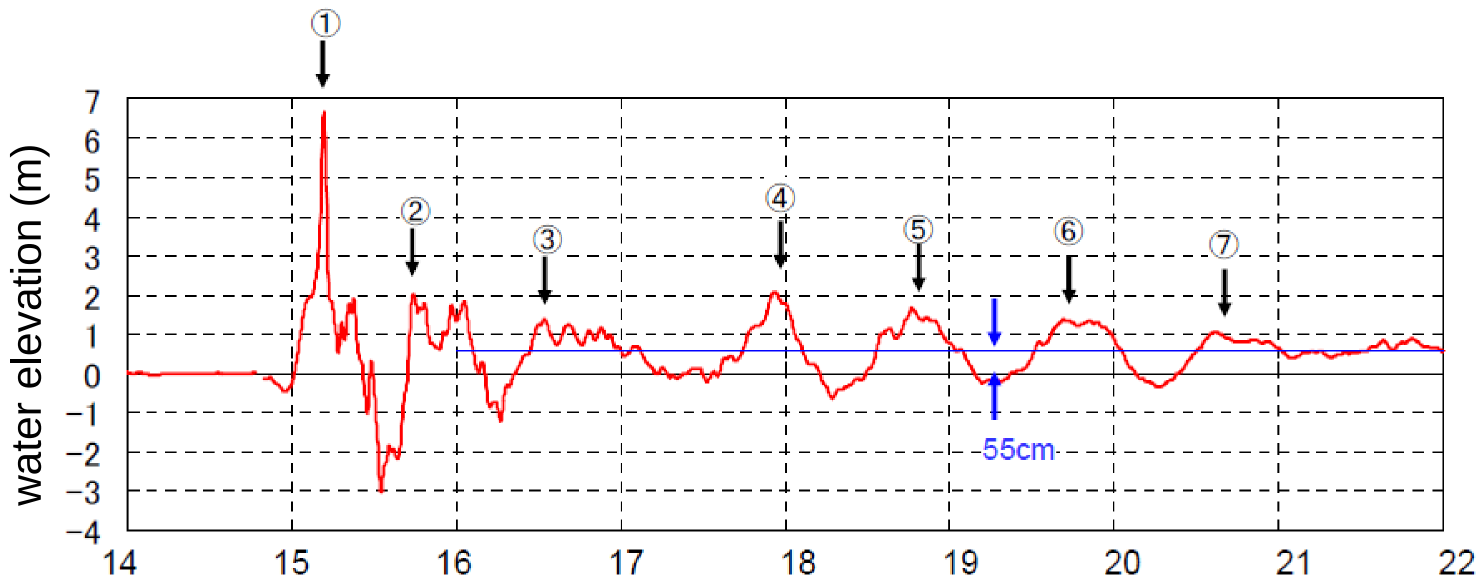
Tsunami inundation depth reaches 18 m. More than 70% of the houses in this town were washed away by the tsunamis.

Tsunami shape near the source

http://www.pari.go.jp/files/items/3527/File/results.pdf

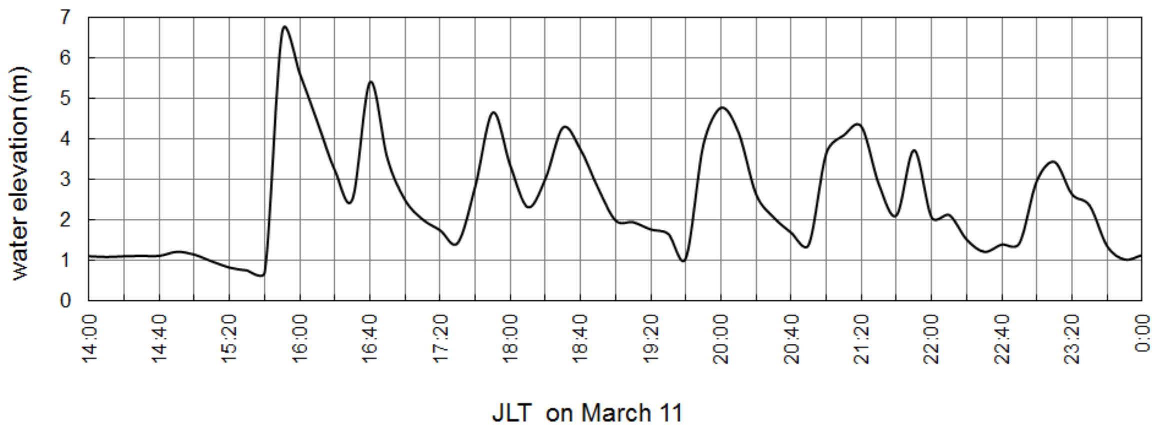


JLT on March 11

Measured by GPS wave gauge installed at the place with the depth 200m off Kamaishi

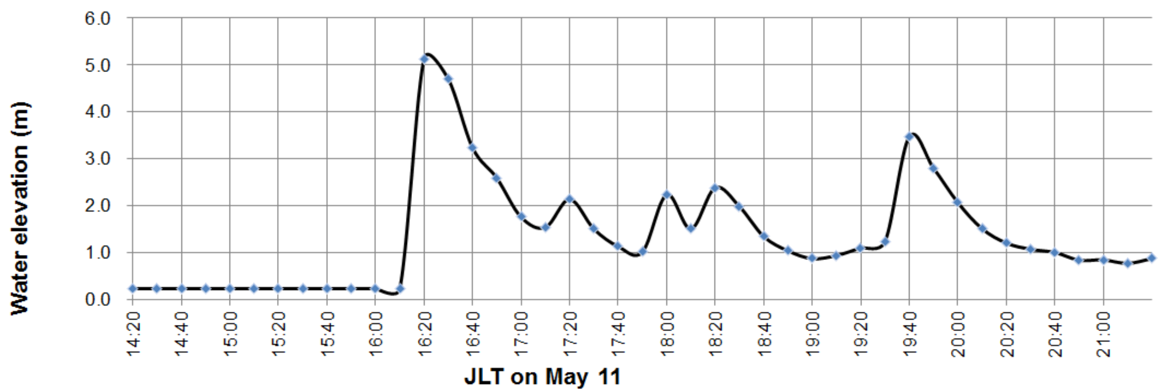
- The first wave is the maximum with 6.5 m amplitude at 26 minute after the quake
- 6 waves follow with a1 m amplitude and 50m periods

Tsunami shape along Sendai Bay Coast



The Naruse River, 0.5 km upstream from the Sendai Bay Coast

The first wave is bore like and has the maximum at 15:50 which estimates the peak time 15:49 at the coast, 63 minutes after the quake.

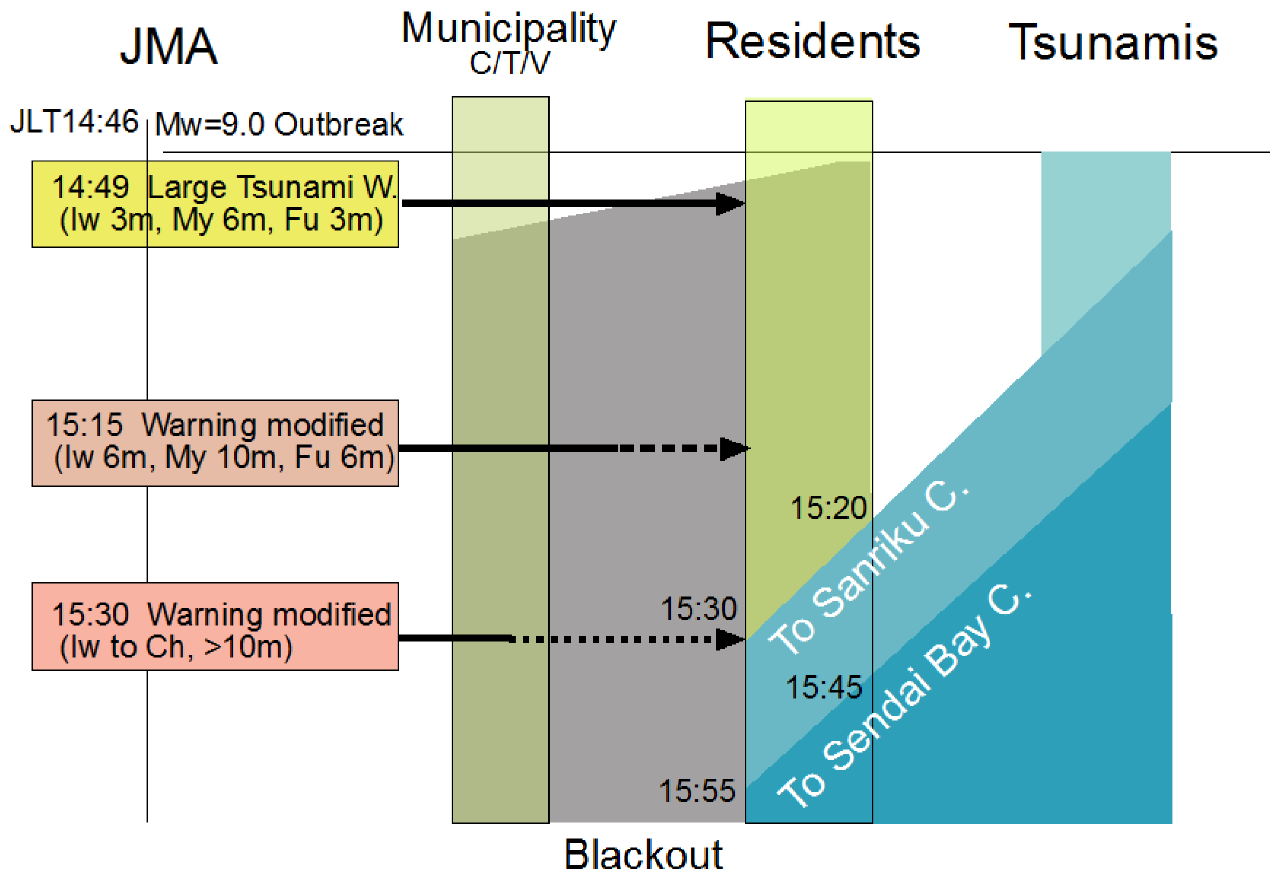


The Abukuma River, 10km upstream from the Sendai Bay Coast

The first wave is bore like and has the maximum at 16:20 which estimates the peak time 15:55 at the coast, 69 minutes after the quake.

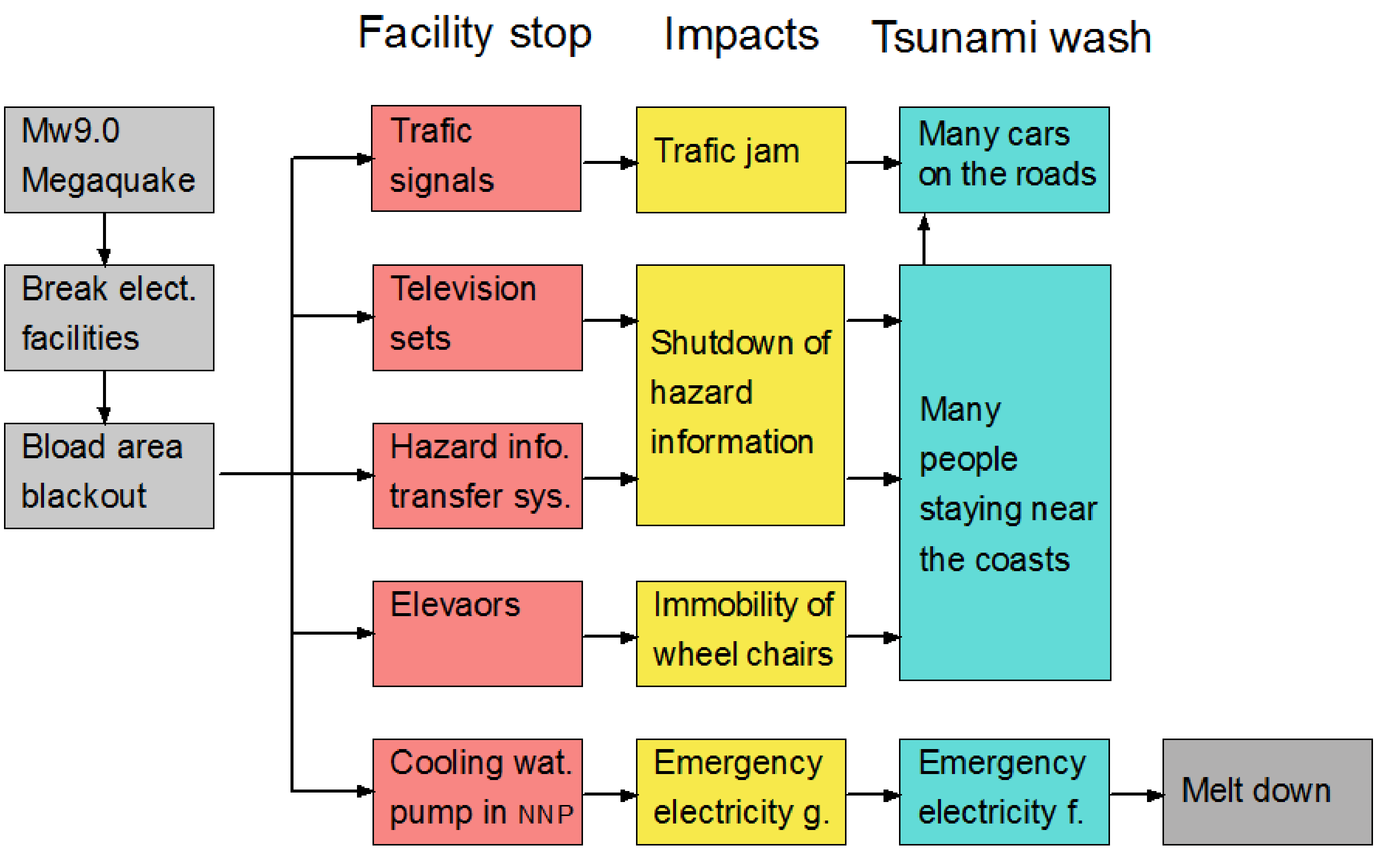
Tsunamis intruding into the residential area
at Yuriage, Natori C, photo by Mainichi News

Modified tsunami warning transmission



High underestimate in the Initial tsunami warning gave relief to prevent evacuation.
Modified warning did not reach residents in many places by blackout .

Multiple damage chains caused by blackout

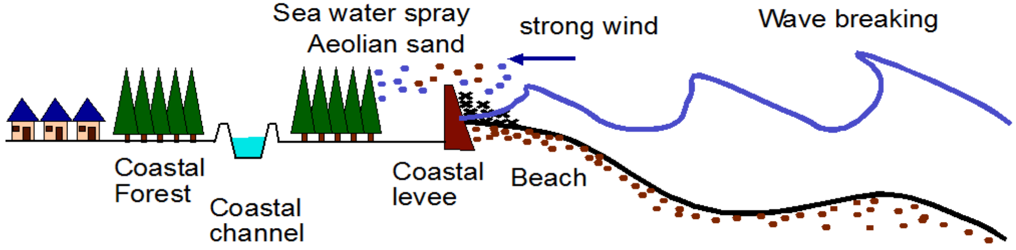


The other obstacles for the evacuation

- Returning back to the home to see the family or to bring something.
- Being in the line of duty, such as firemen, community leaders, truck drivers, etc.
- Nursing homes near the coasts.
- Inappropriately specified asylums and shelters lower than the tsunami inundation height.
- Fire caused by floating cars, ships, and oils.

Disaster mitigation system along Sendai Bay Coast

- Coastal disaster mitigation system
  - Sandy beach：Natural wave energy dissipation function
  - Coastal channels：Construction started in 1601 by Masamune Date and was continued by Meiji government. The functions of conveyance and drainage.
  - Coastal forests：Black pine trees have been planted to prevent sea water spray and aeolian sand after Masamune.
  - Coastal levees：6 to 7m high levees have been constructed to prevent storm surges.
- Present vulnerability for huge hazards
  - New town developed by cutting coastal forests
  - Important buildings such as airport, oil factory, sewage plant, industrial complex built near coasts
  - Disappearance of beaches



Coastal levee destruction

at Ido, Wakabayashi, Sendai C.

Satellite image on 20110314

Mild slope levee

Steep slope levee

- The first flood tsunami scattered armor blocks on the mild slope levee landward.
- Concentration of the return flow eroded the back of the steep slope levee up to 3m, and changed the lands to sea.

Concentration of the return flow to the channels
at Kabasaki, Iwanuma C.

Before, 20090814

After, 20110314

- The return flow was collected to the coastal channel and then to the crossing channel to return back to the sea.
- These channels could be used to control the return flow.

Breach of the coastal levee
at the right bank of the Abukuma River mouth

- The Abukuma River mouth at JLT 16:33, March 11
- Turbid water flowing out from the breach and big vortices indicate steadiness and strong erodibity of the return flow.

- Aerial photo on March 14 by GSI Japan
- Erosion channel at the back of riverine and coastal levees by the return flow.

Levee destruction
at the right bank of the Abukuma River mouth

➢Undamaged fore-slope and eroded back-slope of the riverine levee. The vertical concrete blocks at the top called parapet were flushed away.

➢The backland of the coastal levee was eroded to form a channel.
➢The concrete block with wave returning was broken at some place.
➢The boundary of the riverine and coastal levees was breached.

Catastrophic destruction of coastal levees
in the Yamamoto Coast, Sendai Bay area

Before the tsunamis

津波で防波堤が寸断され海水が流れ込む宮城県山元町の海岸(3月19日)＝共同

After the tsunamis

T-jettys were constructed to prevent beach erosion.
Thin beaches raise the levee destruction here and there by the flood tsunamis.
The return flow concentrated to the destructed points to erode the land and levees.

Concentration of return flow to the breach point

at Watari T. , videoed by a helicopter at JLT 16:35

- At the moment, huge amount of sea water filled inundation area.
- The return flow along the back of the levee and through the coastal forests concentrated toward the breach point to erode the land and levees.

Mitigation by the coastal forests

Bird eye view of the fallen woods, Miyagino Bor., Sendai C.

The tsunamis fell coastal forests to washout the houses behind.
The houses behind non-fallen forests were secured.

Fallen woods by domino topping?
Miyagino Bor., Sendai C.

There would be feedback effects that fallen trees promote flow concentration which again promotes tree falling. High pine trees could caused domino topping.

Summary: Lessons from the disaster

- Decrease of the human damage requires
  - disaster mitigation education and evacuation training
  - improvement of the tsunami warning
  - to have mobile radio
  - to avoid the residence in high hazard areas

- Reconstruction of robust levees requires
  - restoration of broad beaches
  - control of the return flow concentration through the development of coastal channels and forests
  - anti-erosion armoring at the flow concentration


Thank you for the attention