Verifying Estimations of Tsunami Inundation Velocity and Building Damage by Tsunami Inundation Modeling

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Background

Major factors in destruction of buildings

8 sec after flood | 10 sec after flood

The 2011 Tohoku tsunami (At Fujitsuka, Wakabayashi-ku, Sendai)

Hydrodynamic force against structure

$$F = \frac{1}{2} C_D \rho u^2 D$$

- C_D : drag coefficient
- ρ : water density
- u : the current velocity
- D : the inundation depth

It is important to obtain tsunami velocities accurately for estimating structural damages.

Problems with measuring inland tsunami velocity

» Three methods: field survey, survivor video analysis, and numerical modeling.

Simulation results have not been sufficiently validated.

Objective & Study Flow

Objective

Improving tsunami inundation modeling with regard to tsunami inundation velocity in order to estimate destruction of building.

STEP 1 **Verification of Tsunami Inundation Modeling**

Measured vel. ⟷ Comparison ⟷ Modeled vel.

Find problems with modeling and improve its reproducibility.

STEP 2 **Development of New Roughness Coefficient Model**

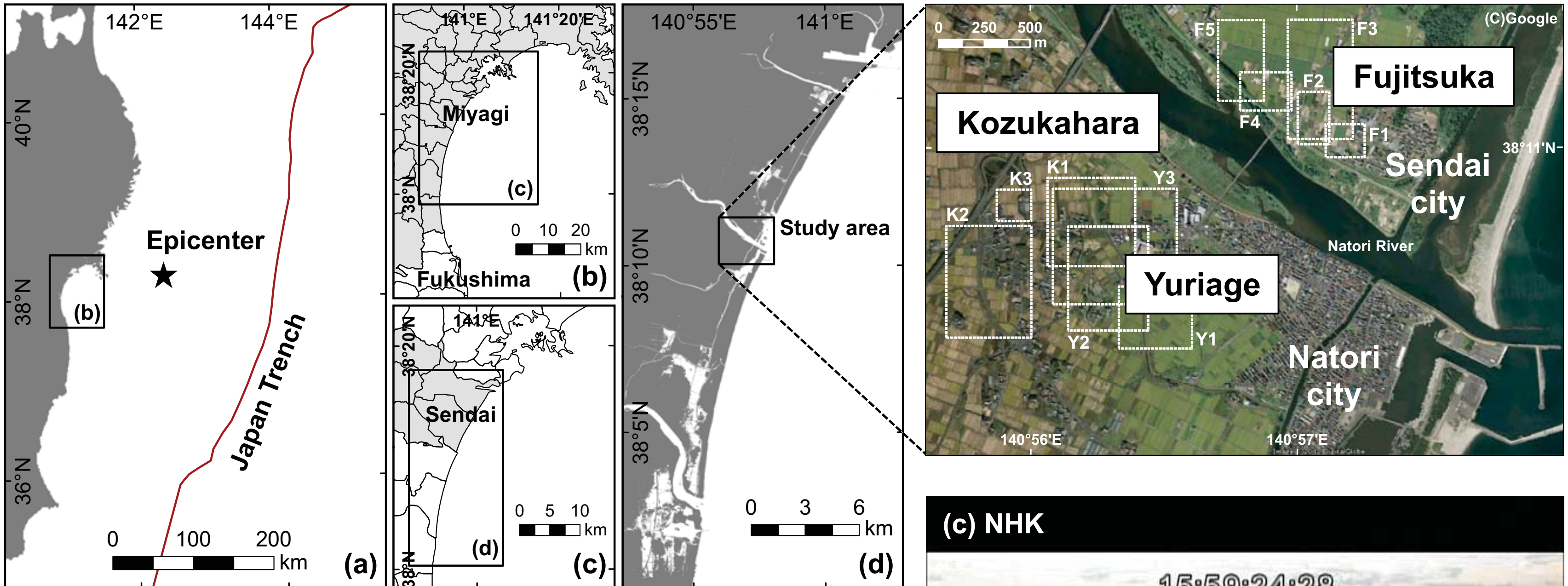
Tsunami fragility functions

Reference values of structural destruction

→ Integration → Time-dependent building destruction model

Develop new composite equivalent roughness coefficient model reflecting the devastated buildings.

Study Area & Tsunami Video



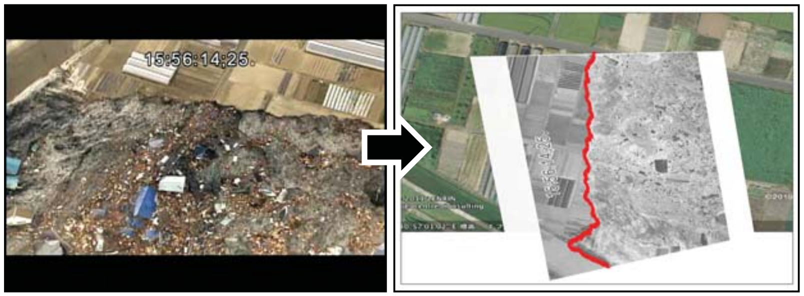
Values of tsunami front and flow velocities were estimated by aerial video analysis.

- Tsunami front velocity : the speed of tsunami front moving
- Tsunami flow velocity : the speed of flow within flooding zone

Methodology of Aerial Video Analysis

STEP1

1 Geometric Correction



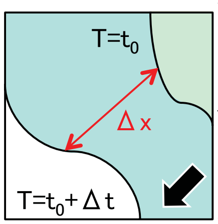
» Calibrate and rectify by 2-D projective transformation.

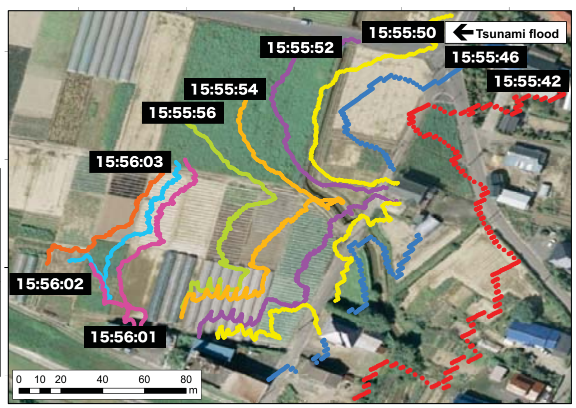
» Mapping the tsunami front and the debris on pre-event image.

2 Measure Tsunami Velocity

Tsunami front vel.

$$v_p = \frac{\Delta x}{\Delta t}$$

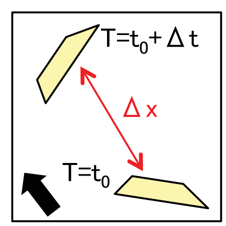


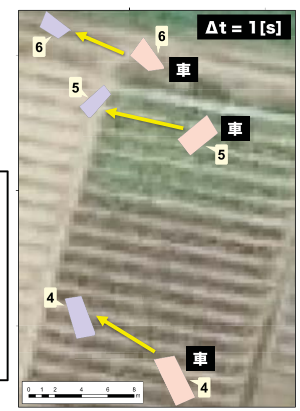


» The distance between two tsunami front lines is divided by the time.

Tsunami flow vel.

$$v_f = \frac{\Delta x}{\Delta t}$$



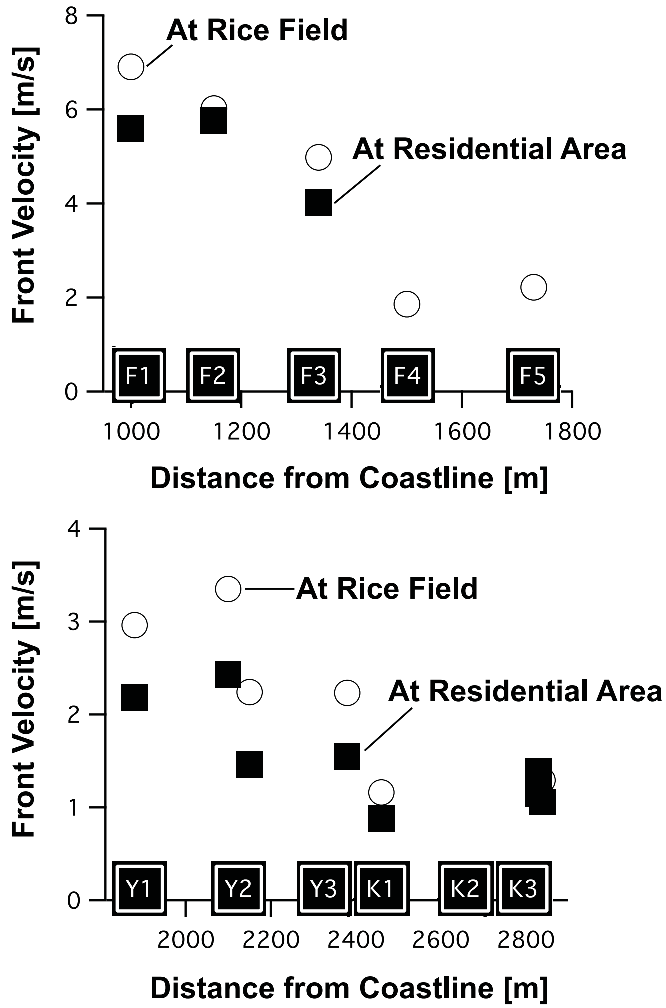


» The movement distance of floating objects per unit time.

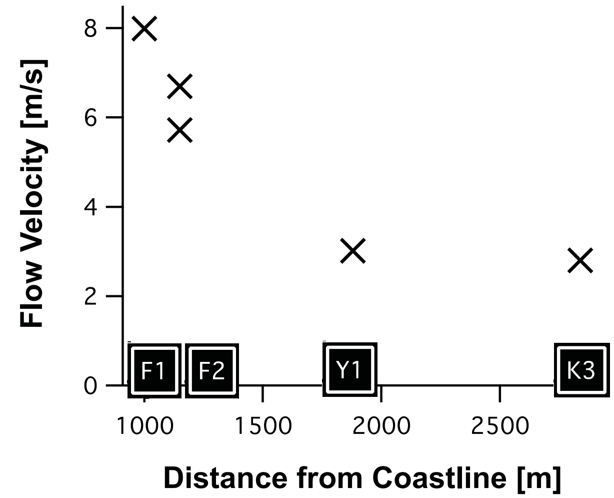
Measured Value of Tsunami Velocities

STEP1

Tsunami front vel.



Tsunami flow vel.



Within 1 km inland from the shoreline, tsunami velocities reached …

- Tsunami front velocities : **7 m/s**
- Tsunami flow velocities : **8 m/s**

Tsunami flow velocities reduced as the inland distance gets longer.

Simulation of The 2011 Tohoku Tsunami

STEP1

Tsunami numerical modeling

Governing equation	Non-linear shallow water theory
Numerical scheme	Staggered leap-frog scheme
Grid size (Inland)	10 m × 10 m
Tsunami source	Satake et al. (2013)
Roughness coefficient	❖ **The composite equivalent roughness coefficient model** (Aburaya and Imamura, 2002 ; Imai et al., 2013) ❖ **Manning's roughness coefficient model** (Kotani et al., 1998)

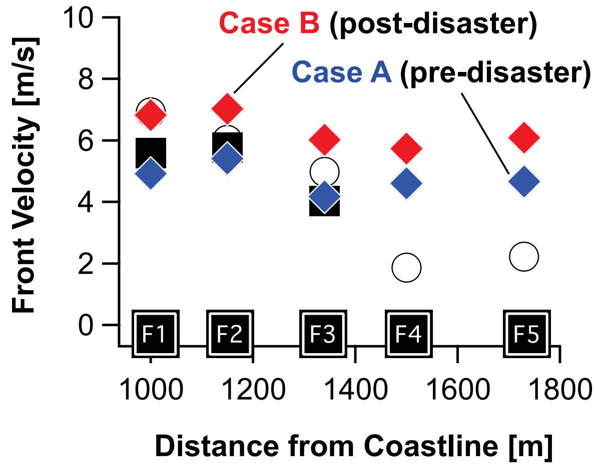
Tsunami run-up modeling conditions

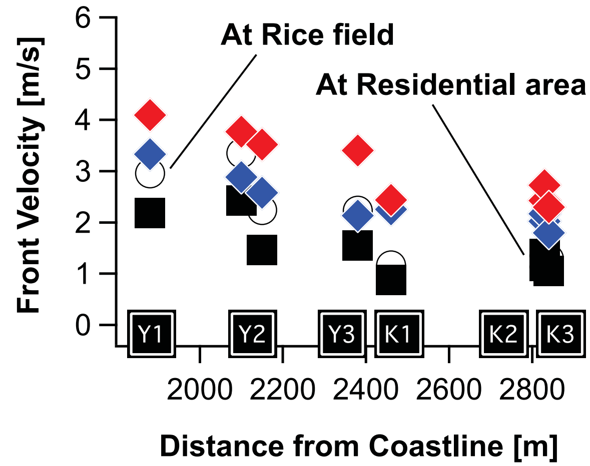
	Tsunami control forest	Buildings	
		Surviving	Washed-away
Case A (pre-disaster condition)	○	○	○
Case B (post-disaster condition)	×	○	×

Reproducibility of Tsunami Velocities

STEP1

Tsunami front velocities





» The reproducibility of Case A is higher than Case B.

Effects of structures and land use on tsunami inundation characteristics are well reproduced.

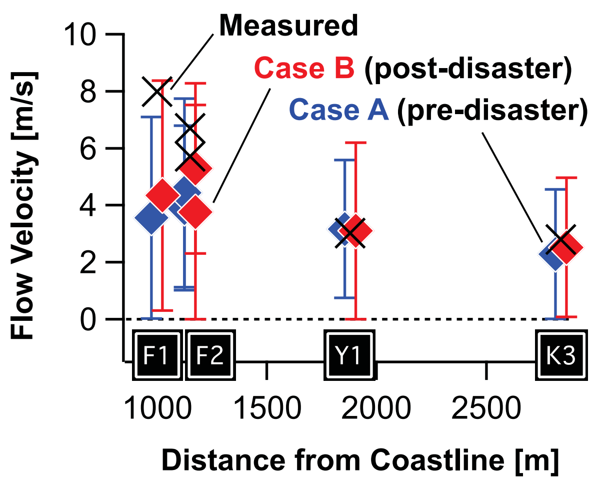
» Devastated buildings and drifting debris at tsunami front affect the tsunami penetration.

Need to improve the tsunami front boundary conditions including these resistances.

Reproducibility of Tsunami Velocities

STEP1

Tsunami flow velocities



» The **post-disaster** condition is quite consistent with measured velocities.

The flow field can be well represented by the current tsunami inundation model.

Front Vel.	**The pre-disaster condition was the most consistent to yield good estimates of tsunami front velocity.**
Flow Vel.	**The reproducibility of tsunami flow velocity was quite good in the post-disaster condition.**

Need to model the tsunami front boundary conditions considering the devastated buildings and the drifting debris.

Objective & Study Flow

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STEP 2 Development of New Roughness Coefficient Model

Tsunami fragility functions

Reference values of structural destruction

Integration → Time-dependent building destruction model

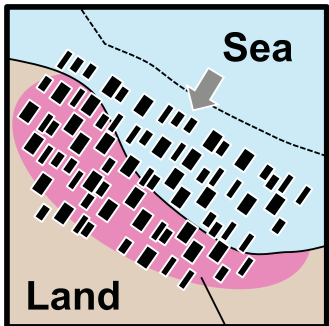
Develop new composite equivalent roughness coefficient model reflecting the devastated buildings.

Methodology of New Model

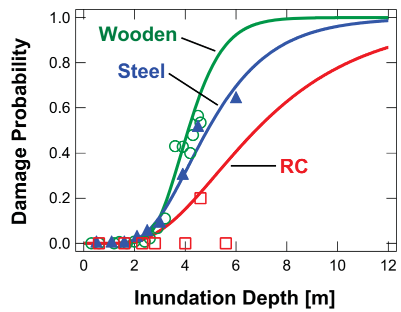
STEP2

The Time-dependent building destruction model

$T = t_1$



1 Tsunami fragility functions

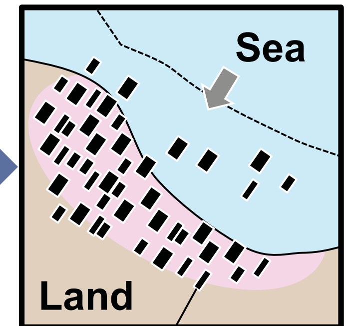


2 Reference values for structural destruction

Wooden	h ≧ ···
Steel	F ≧ ···
RC	u ≧ ···

Adriano et al. (2014)
Hayashi et al. (2013)
Narita and Koshimura (2013)
Suppasri et al. (2012)

$T = t_1 + \Delta t$



» Combining tsunami fragility functions and reference values of structural destruction with the tsunami numerical modeling.

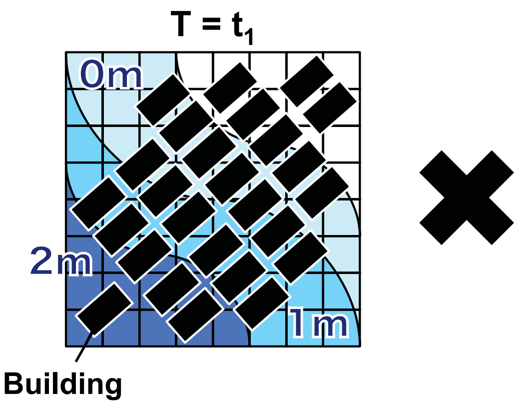
Roughness coefficients are gradually changed in response to the time variation of building damage.

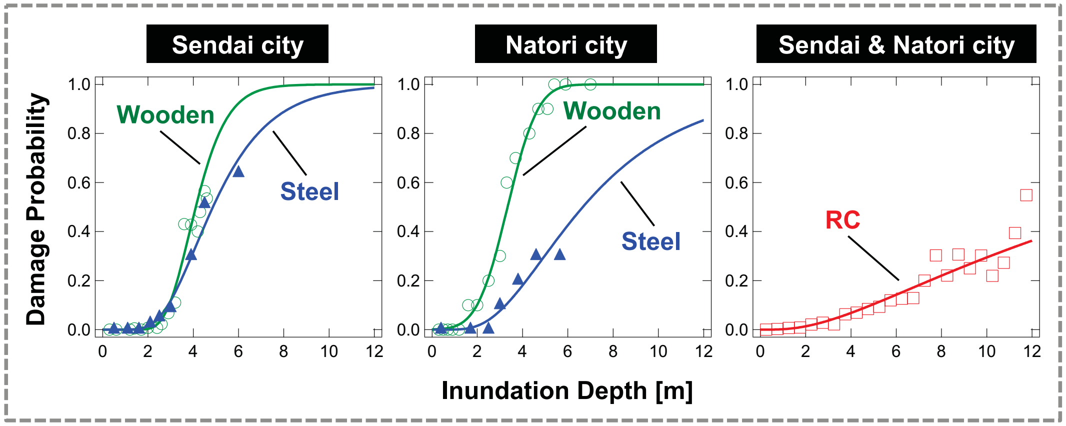
Methodology of New Model

STEP2

The Time-dependent building destruction model

1 Calculating the number of buildings being simultaneously damaged from fragility curves





Hayashi et al. (2013) ; Narita and Koshimura (2013) ; Suppasri et al. (2012)

- Count the number of exposed buildings N in 1m intervals of inundation depth.
- The multiplication of the number of exposed buildings N and the damage probability $P(x_1,\cdots,x_i)$. (Adriano et al., 2014)

The number of buildings being simultaneously damaged was calculated.

Methodology of New Model

STEP2

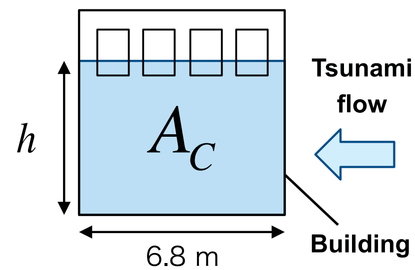
The Time-dependent building destruction model

2 **Selecting devastated buildings by reference values for structural destruction**

» Determine the reference values for structural destruction by surveyed data and preceding studies.

Selected the appropriate buildings and washed out in descending hydrodynamic force order.

Inundated parallel area



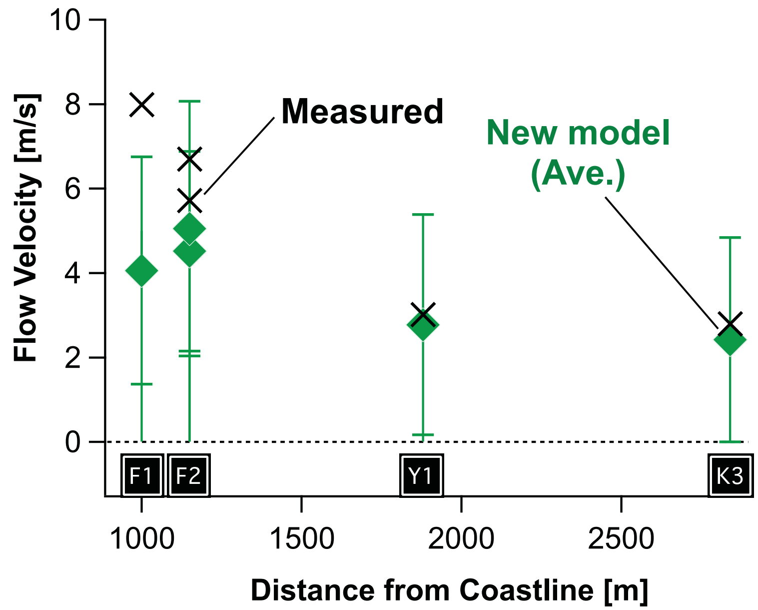
Matsutomi et al. (2012 ; 2013)

	Sendai city	Natori city
Wooden	Inundation depth h ≧ 3.5 m (MLIT, 2011)	Inundation depth h ≧ 1.5 m (MLIT, 2011)
Steel	Inundated parallel area $A_C \leqq 6.8 \times h$ (Matsutomi et al., 2013)	Inundated parallel area $A_C \leqq 6.8 \times h$ (Matsutomi et al., 2013)
RC	Inundated parallel area $A_C \leqq 6.8 \times h$ (Matsutomi et al., 2012)	Inundated parallel area $A_C \leqq 6.8 \times h$ (Matsutomi et al., 2012)

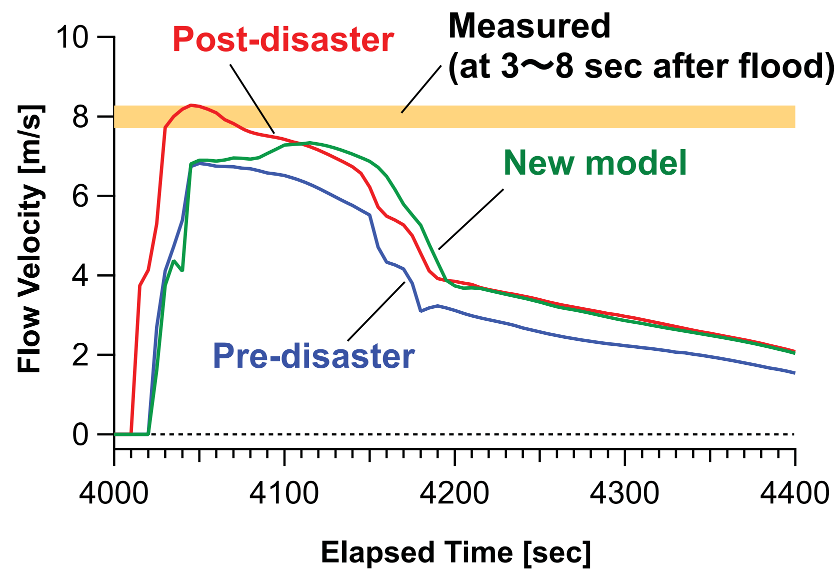
Recent Progress of New Model

STEP2

Tsunami flow velocities



Time series data of flow velocity at F1 area



» The result of tsunami flow velocity shows high accuracy in new model.

Tsunami flow velocity was underestimated at F1 area.

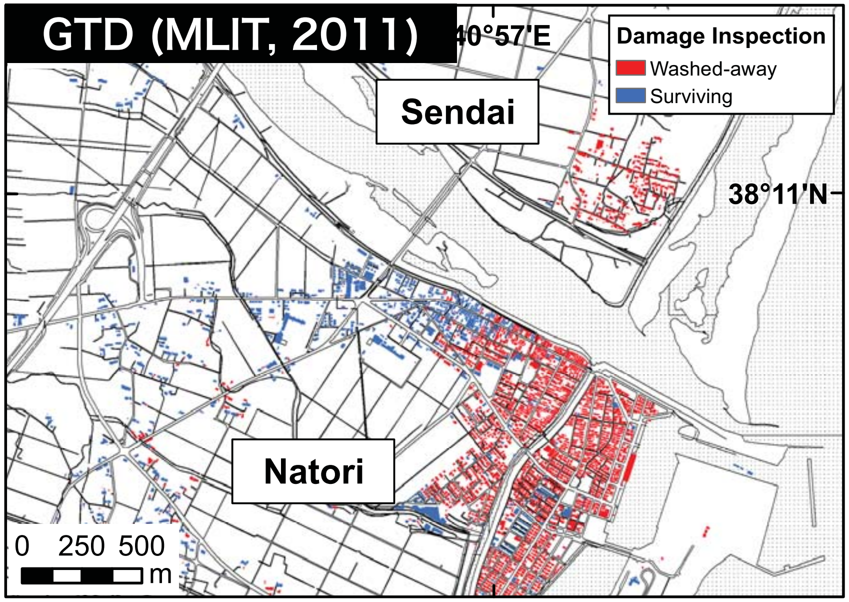
» The peak value has not reach the measured value at F1 area.

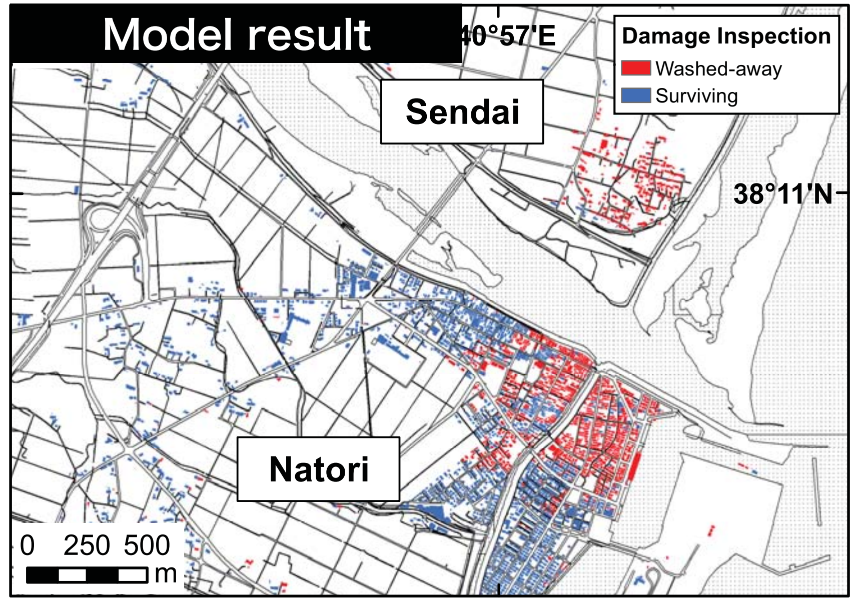
Devastated buildings could not be estimated well.

Recent Progress of New Model

STEP2

Distribution of devastated buildings





	Sendai	Natori
Washed-away	476	2187
Surviving	318	1252

	Sendai	Natori
Washed-away	393	1266
Surviving	401	2173

Need to model the tsunami front boundary conditions considering the drifting debris in built-up area.

Summary

Verification of Tsunami Inundation Modeling

- The model accuracy with regard to tsunami front and flow velocities increased when the roughness coefficient was determined by responding to actual land use.
- The tsunami inundation velocities could not be reproduced well at some inland areas.

We need to develop new composite equivalent roughness coefficient model reflecting the devastated buildings.

Development of New Roughness Coefficient Model

- By combining tsunami fragility functions and reference values for structural destruction, we developed the time-dependent building destruction model.
- The number of devastated buildings could not be reproduced well in Natori city (built-up area).

Need to model the tsunami front boundary conditions considering the drifting debris in built-up area.