Coupled Problem 2015

Modeling and Simulation of Tsunami Using Virtual Reality Technology

Kazuo Kashiyama, Guoming Ling, Taiki Fumuro, Takeshi Kawabe (Chuo University)
Junichi Matsumoto (AIST)、Masaaki Sakuraba (Nippon Koei Co. Ltd.)
Shinsuke Takase, Kenjiro Terada (Tohoku University)

- Introduction
- VR Technology
- Modeling and Simulation of Tsunami
- Visualization and Auralization using VR technology
- Conclusions

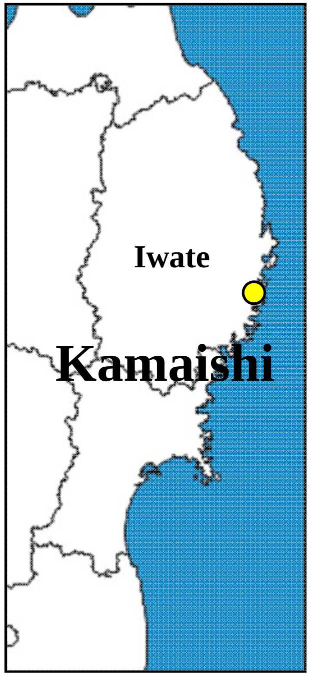
Power of Tsunami

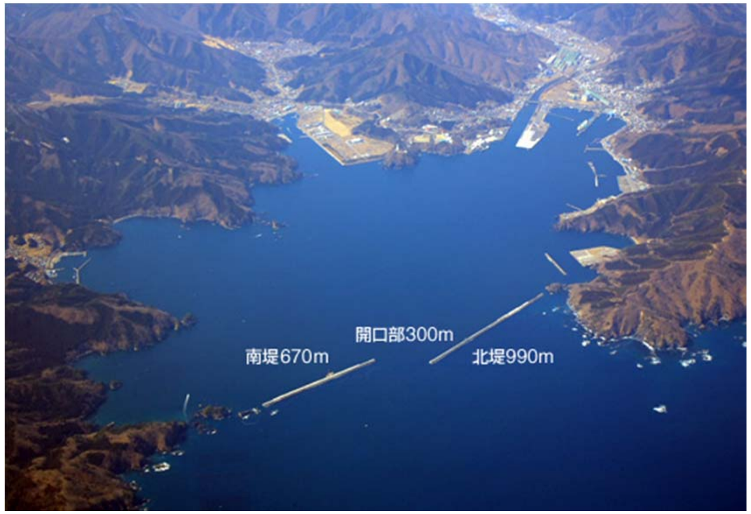
Rikuzen Takada city (http://www.syasinkikaku.co.jp/enganjisin/index.html)

Power of Tsunami

Rikuzen Takada city (http://www.syasinkikaku.co.jp/enganjisin/index.html)

Tsunami Hazard (Kamaishi-Iwate)





http://www.pa.thr.mlit.go.jp/kamaishi/l

This type of damage occurred at every port and harbors

↓

National Crisis

The new guideline for tsunami disaster management measures has been build.

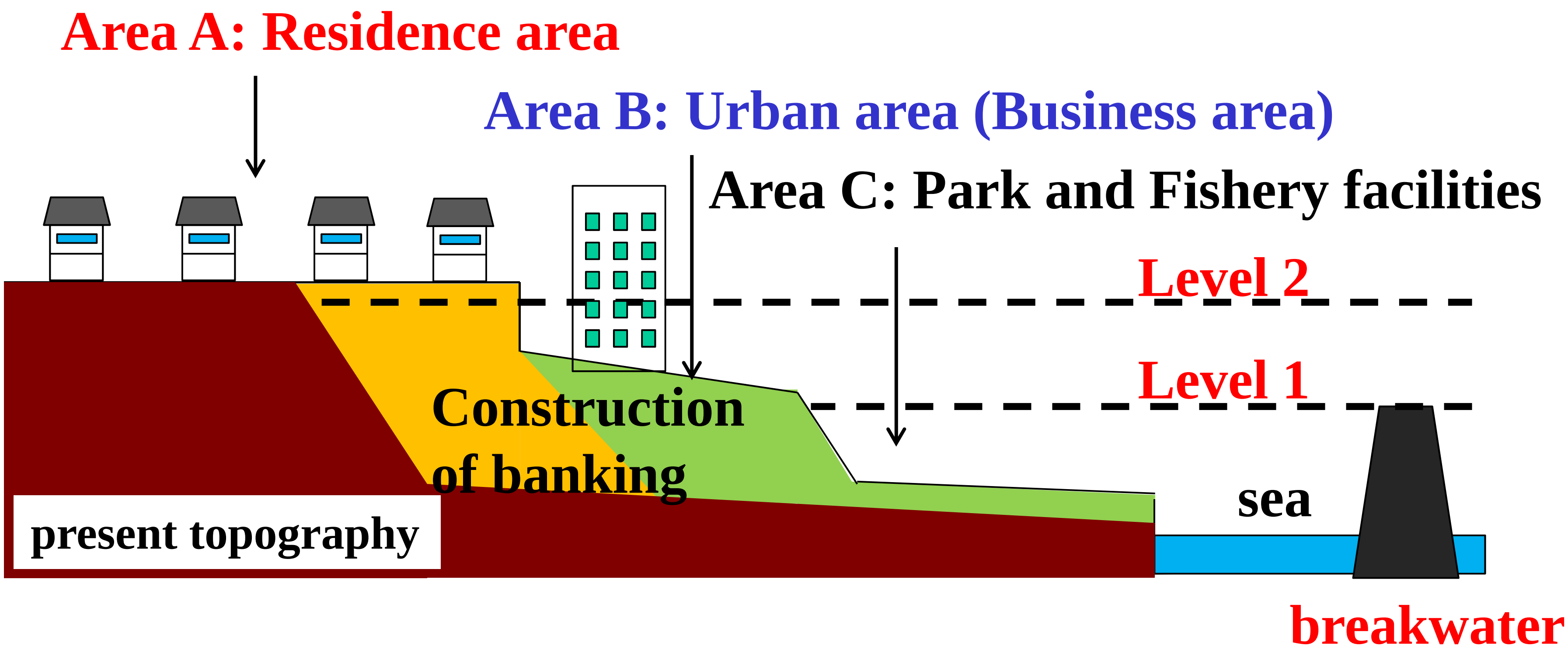
Deepest braekwater (-63m) (1973-2008:1.5 billion US$)

Guideline for Tsunami Disaster Management Measures

- **Tsunami disaster management Level (Tsunami Level 1)**
  - Tsunami scale of this level would be as large as the one which will occur once in several decades to several century.
  - The design of coastal protection facilities should be based on the tsunami protection level (Tsunami Level 1).

- **Tsunami disaster reduction Level (Tsunami Level 2)**
  - Level 2 tsunami is an extreme tsunami event and may have much higher tsunami wave and stronger tsunami power, and it would exceed the tsunami protection function of structural measures.
  - To save human lives from this extreme event, all possible measures should be applied.
    →Evacuation and city planning are very important.

New Guideline for City Planning



Construction of Banking (Rikuzen Takada City)



The construction work will be finished in March 2018.

Purpose

Development of an useful planning, designing and educational tools for the disaster prevention for Tsunami.

⇒ VR Technology

⇒ Modeling and simulation of Tsunami

    2D/3D coupling simulation

    FSI simulation

    Evacuation simulation

⇒ Visualization and auralization using VR/AR technology

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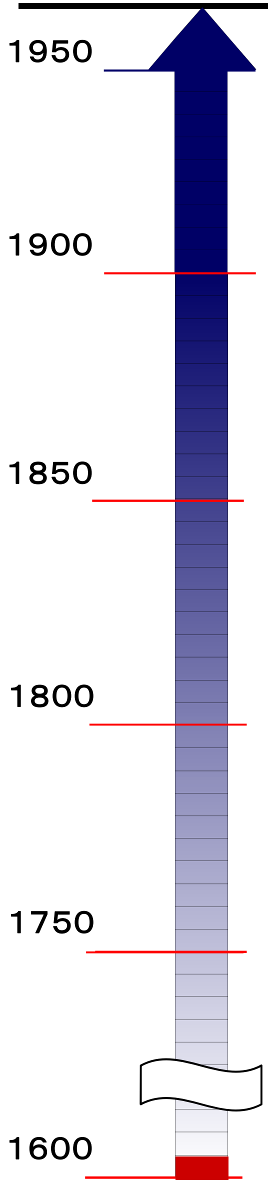
History of Stereoscopic Image Generation



1912 Hess: Principle of lenticular lens sheet

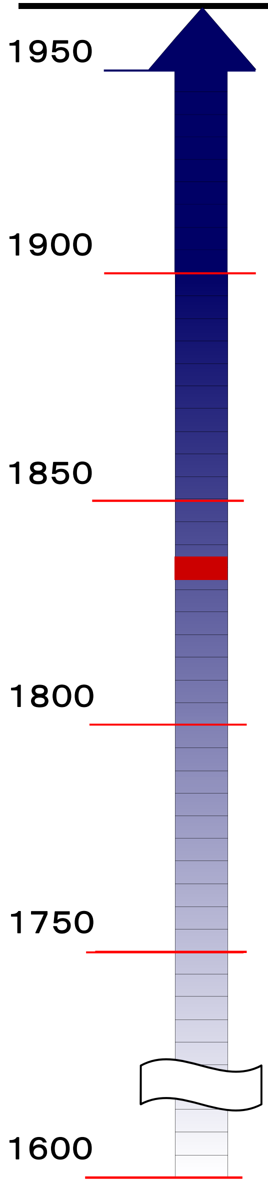
1893 Anderson: Patent for 3D display using polarizing filter

1853 Rollman: Anaglyph method

1838 C. Wheatstone: Stereoscope based on a combination of prisms and mirrors

About 1600: Stereogram by hand

History of Stereoscopic Image Generation

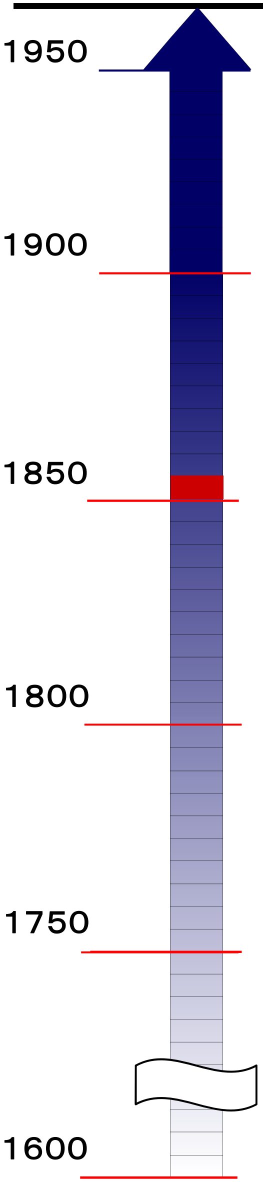


Wikipedia

1838 C. Wheatstone: Stereoscope based on a combination of prisms and mirrors

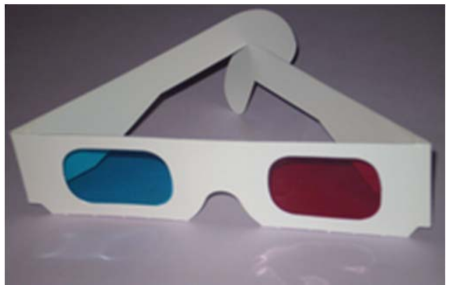
About 1600 Giovanni Battista della Porta: 3D drawing

History of Stereoscopic Image Generation



1852 W. Rollman: Anaglyph method

Wikipedia



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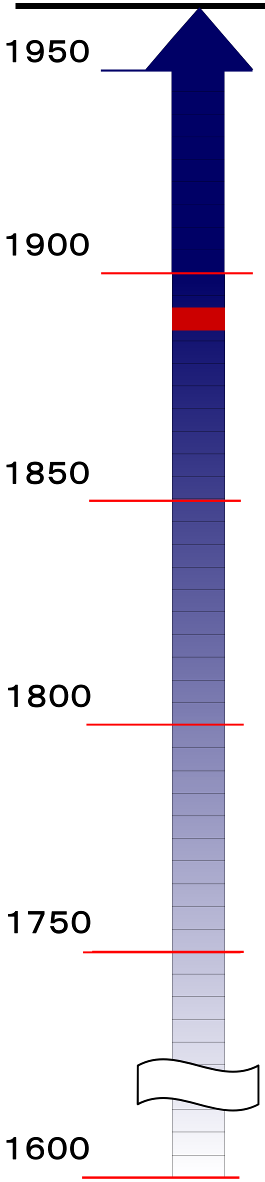
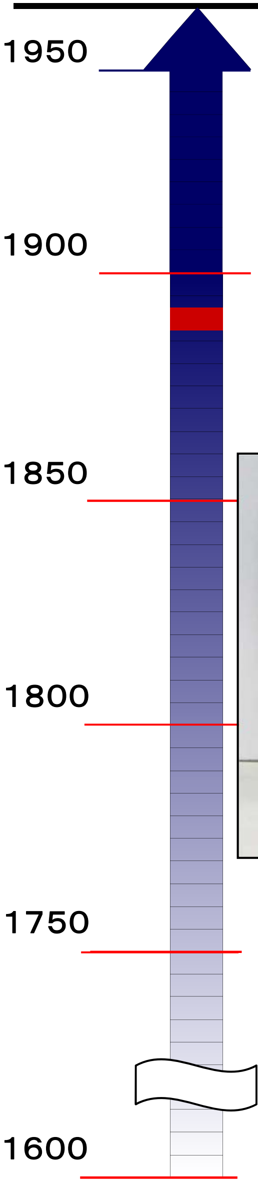


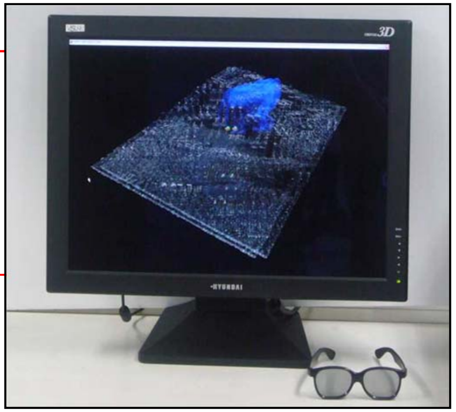
1893 Anderson: Patent for Polarized 3-D display

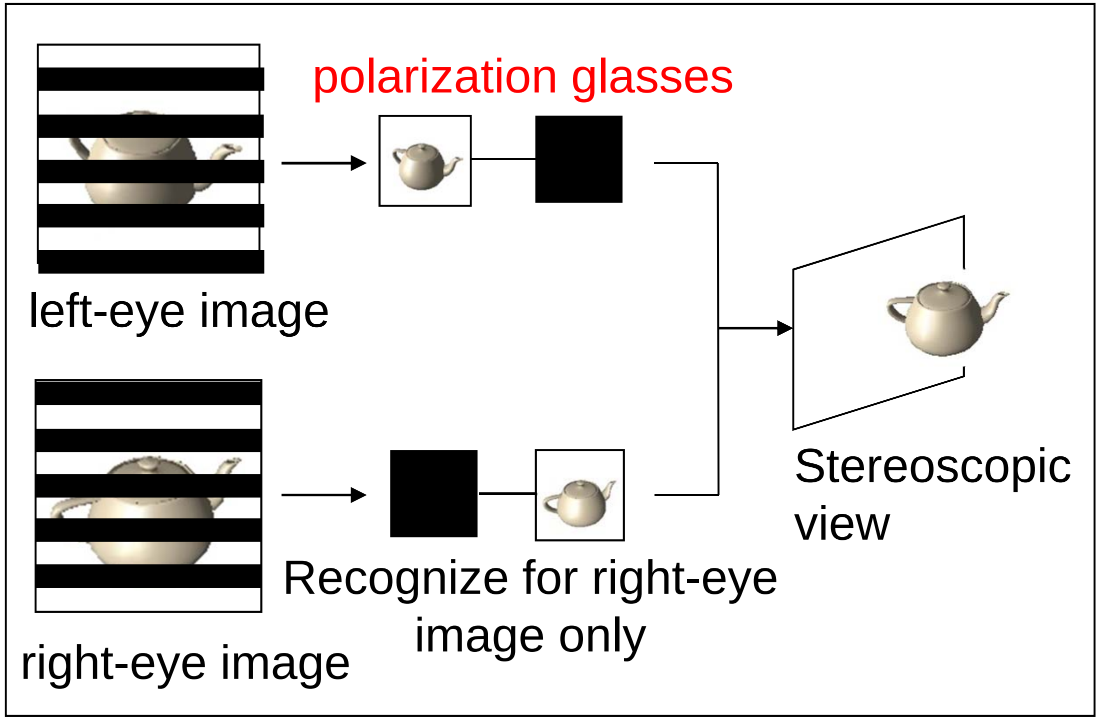
History of Stereoscopic Image Generation



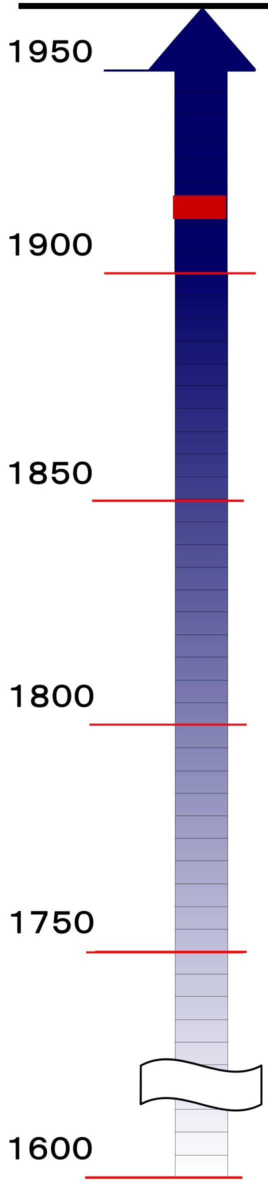
1893 Anderson: Patent for Polarized 3-D display

Stereoscopic view by binocular parallax



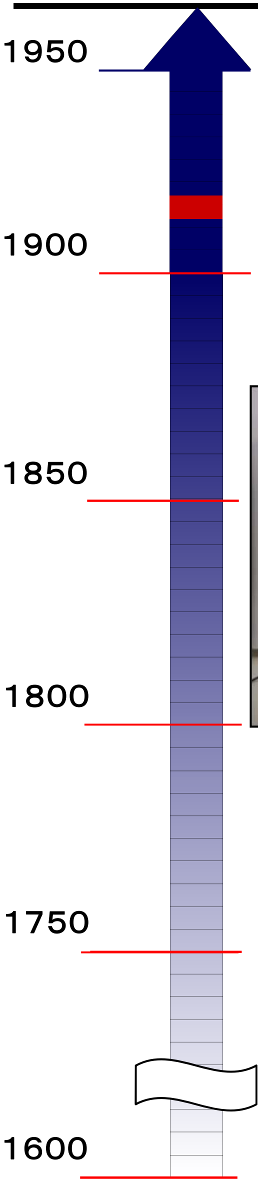


History of Stereoscopic Image Generation



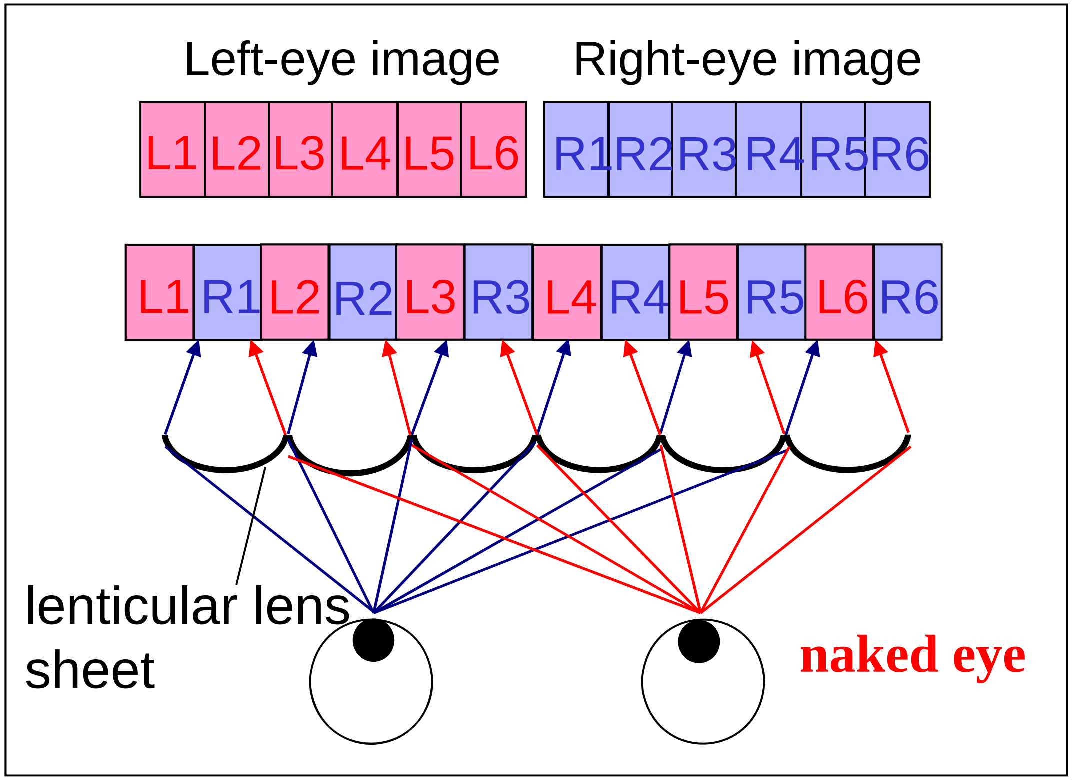
1912 W. Hess: Patent for lenticular lens sheet

History of Stereoscopic Image Generation

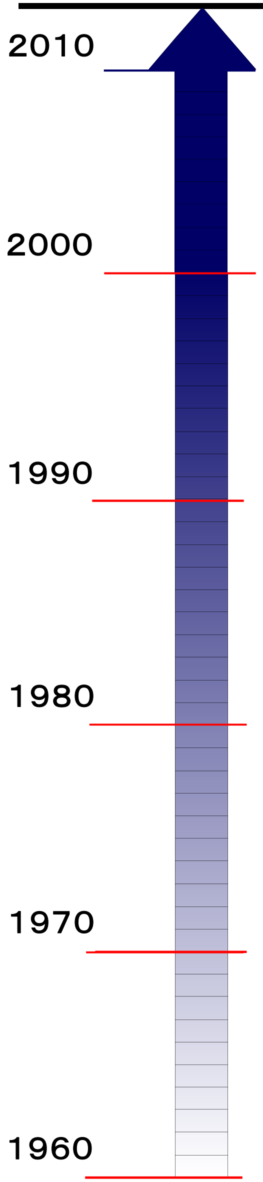


1912 W. Hess: Patent for lenticular lens sheet

Stereoscopic view by binocular parallax
using lenticular lens sheet (refraction)



History of Stereoscopic Image Generation



2010: First year of 3D (3D television, 3D PC, 3D camera･･･)

2000s : 2D/3D conversion technology

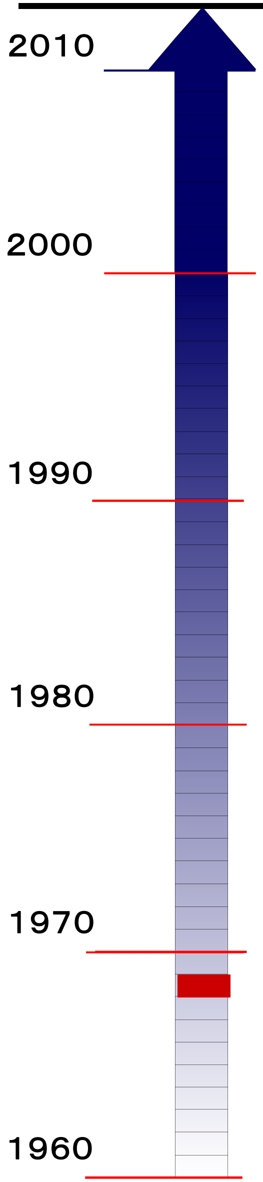
1993 : Cave automatic virtual environment (CAVE)

1990s : Naked-eye stereoscopic displays

1985 Lipton: 3D display using liquid crystal shutter glasses

1968 Ivan E. Sutherland: Head Mounted Display (HMD)

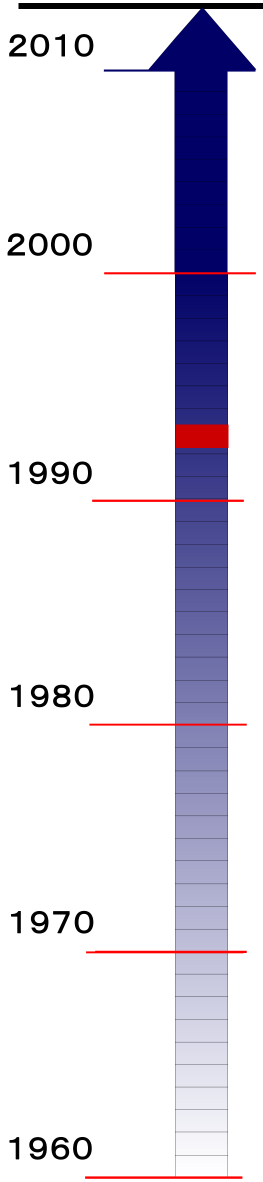
History of Stereoscopic Image Generation



(Wikipedia)

1968 Ivan Edward Sutherland: Head Mounted Display (HMD)

History of Stereoscopic Image Generation



1993 : Cave automatic virtual environment (CAVE)

CAVE（Univ. Illinoi, 1993; Wikipedia）

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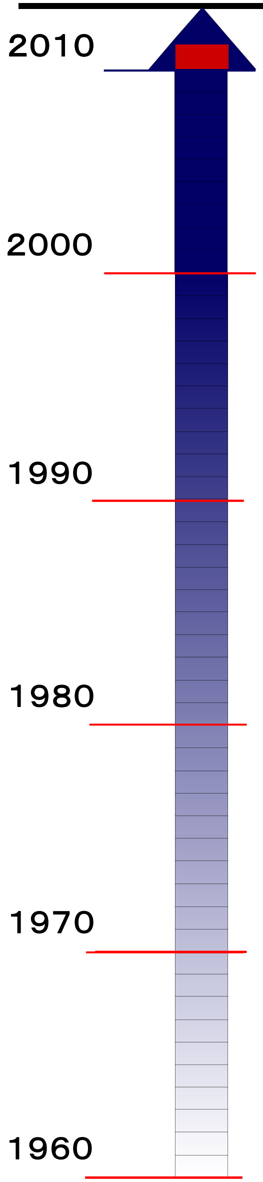

2010: “First year of 3D” (3D television, 3D PC, 3D camera・・・)

Large scale visualization system

HMD
Head Mounted Display

(Wikipedia)

Merit: space-saving

Demerit: difficult for
bodily sensation with full scale

CAVE
CAVE Automatic Virtual Environment

CAVE（Univ. Illinoi, 1993; Wikipedia）

Merit:
・easy for bodily sensation with full scale
・easy to share the common VR space with multiple people

Demerit: wide-space

Large scale visualization system

HMD
Head Mounted Display

(Wikipedia)

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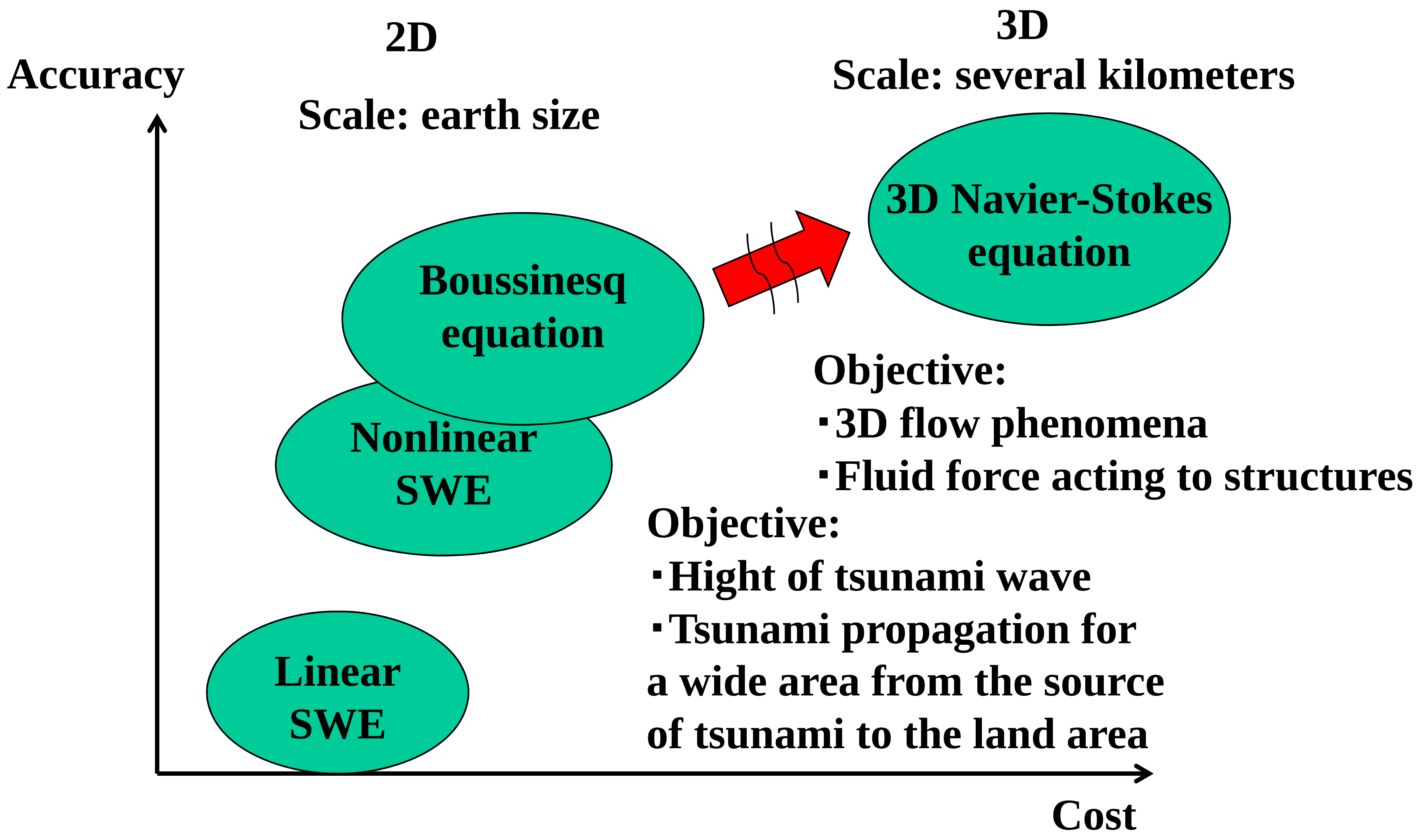
Governing equations for Tsunami



Governing equation

Boussinesq equation;

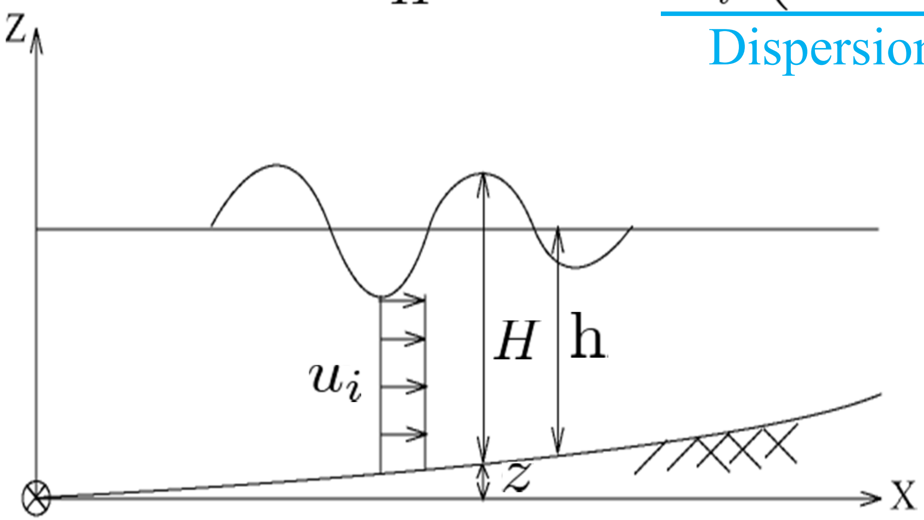
$$\frac{\partial H}{\partial t}+\frac{\partial (u_i H)}{\partial x_i}=0$$ — Continuity equation

$$\frac{\partial (u_i H)}{\partial t}+\frac{\partial (u_j u_i H)}{\partial x_j}+gH\frac{\partial (H+z)}{\partial x_i}$$

Nonlinear term

$$+\frac{gn^2 u_i\sqrt{u_j u_j}}{H^{\frac{1}{3}}}+\frac{\partial}{\partial x_i}\left(\frac{h^2}{3}\frac{\partial (u_j H)}{\partial t \partial x_j}\right)=0$$ — Momentum equation

Dispersion term



H : total water depth

h : still water depth

g : acceleration of gravity

z : bed slope

u_i : mean velocity (u_1, u_2)

n : Manning's coefficient

Governing equation

Boussinesq equation;

$$\frac{\partial H}{\partial t} + \frac{\partial (u_i H)}{\partial x_i} = 0$$ — Continuity equation

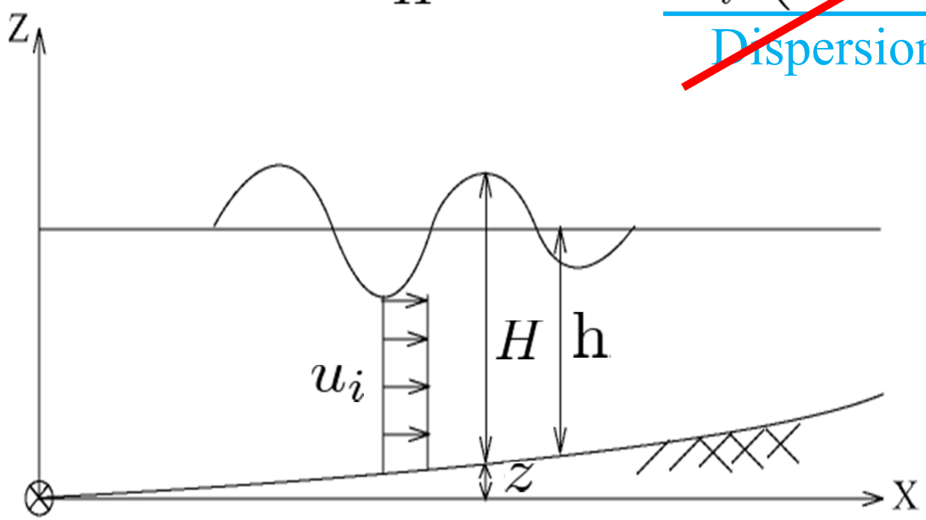
$$\frac{\partial (u_i H)}{\partial t} + \frac{\partial (u_j u_i H)}{\partial x_j} + gH \frac{\partial (H + z)}{\partial x_i}$$

Nonlinear term

Shallow water equation

$$+ \frac{g n^2 u_i \sqrt{u_j u_j}}{H^{\frac{1}{3}}} + \frac{\partial}{\partial x_i}\left(\frac{h^2}{3} \frac{\partial (u_j H)}{\partial t \partial x_j} \right) = 0$$ — Momentum equation

Dispersion term



H : total water depth

h : still water depth

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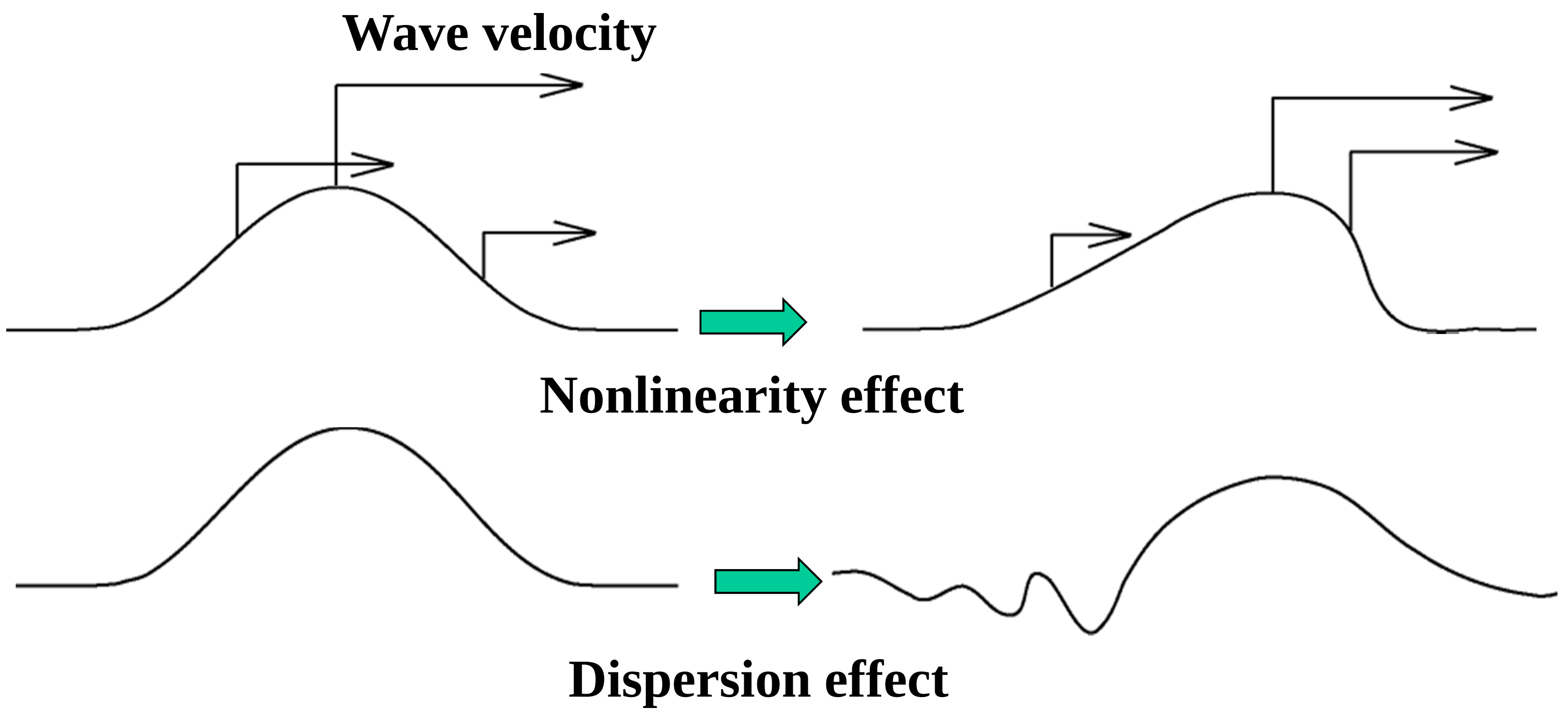
n : Manning's coefficient

Wave nonlinearity and dispersion

The wave velocity is determined by the water depth and wave length

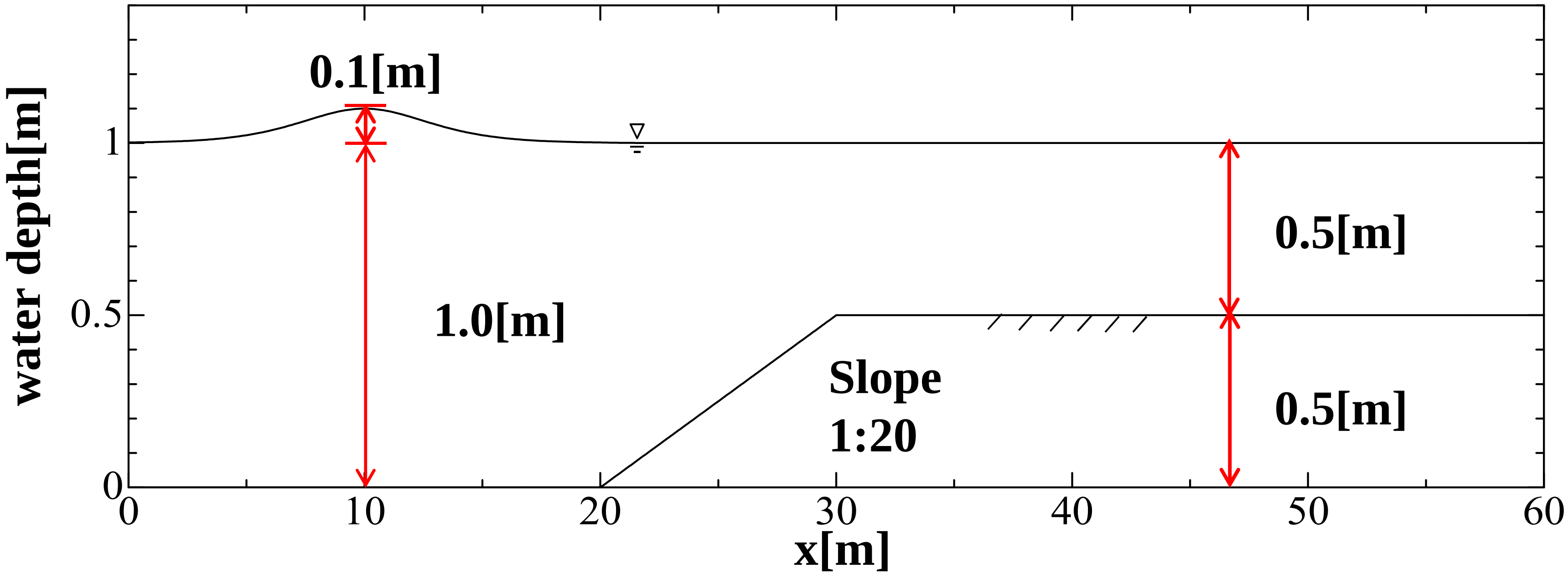


Shallow Water Equation : Nonlinearity effect

Boussinesq Equation : Nonlinearity effect + Dispersion effect

Governing equations for Tsunami

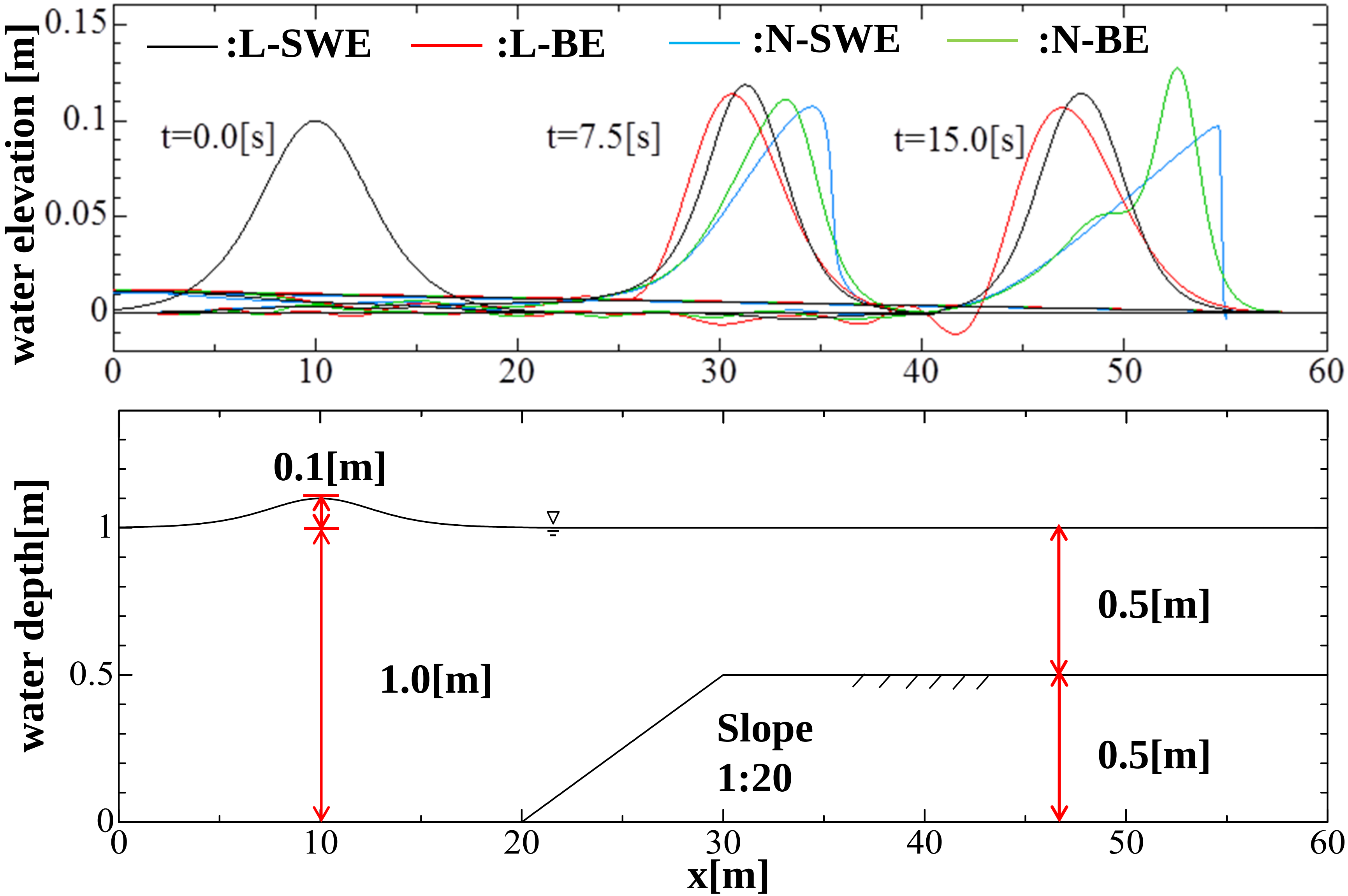
Street (Street, R.L. , 1968)



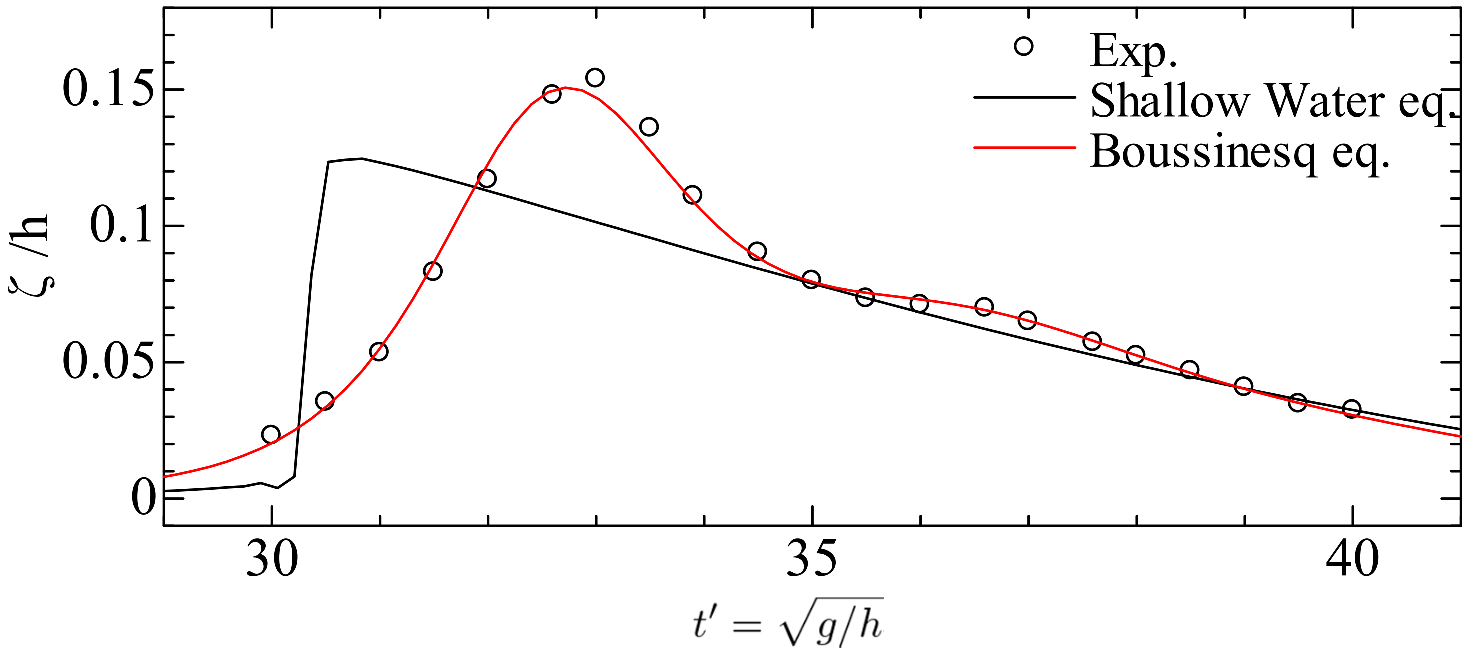
Comparison:

- Linear shallow water equation (L-SWE)
- Nonlinear shallow water equation (N-SWE)
- Linear Boussinesq equation (L-BE)
- Nonliner Boussinesq equation (N-BE)

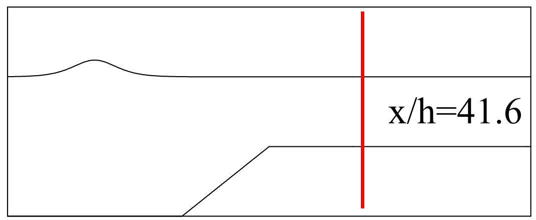
Comparison of Governing equations for Tsunami



Comparison of Governing equations for Tsunami



Time history of water elevation at x/h = 41.6



Governing equation

Momentum equations;

$$\frac{\partial(u_i H)}{\partial t} + \underbrace{u_j \frac{\partial(u_i H)}{\partial x_j} + (u_i H)\frac{\partial u_j}{\partial x_j}}_{\text{Nonlinear term}} + gH\frac{\partial(H+z)}{\partial x_i}$$

$$+ \frac{g n^2 u_i \sqrt{u_j u_j}}{H^{\frac{1}{3}}} + \underbrace{\frac{\partial}{\partial x_i}\left(\frac{h^2}{3}\frac{\partial(u_j H)}{\partial t \partial x_j}\right)}_{\text{Dispersion term}} = 0$$

Time-splitting

$$\frac{\partial(u_i H)}{\partial t} + u_j \frac{\partial(u_i H)}{\partial x_j} = 0$$

— Advection phase

$$\frac{\partial(u_i H)}{\partial t} + (u_i H)\frac{\partial u_j}{\partial x_j} + gH\frac{\partial(H+z)}{\partial x_i}$$

$$+ \frac{g n^2 u_i \sqrt{u_j u_j}}{H^{\frac{1}{3}}} + \frac{\partial}{\partial x_i}\left(\frac{h^2}{3}\frac{\partial^2(u_i H)}{\partial t \partial x_j}\right) = 0$$

— Non-advection phase

Computation for CIVA-SUPG

Advection phase

$$\frac{\partial(u_i H)}{\partial t} + u_j \frac{\partial(u_i H)}{\partial x_j} = 0$$ — Momentum equation

→ CIVA method

Non-advection phase

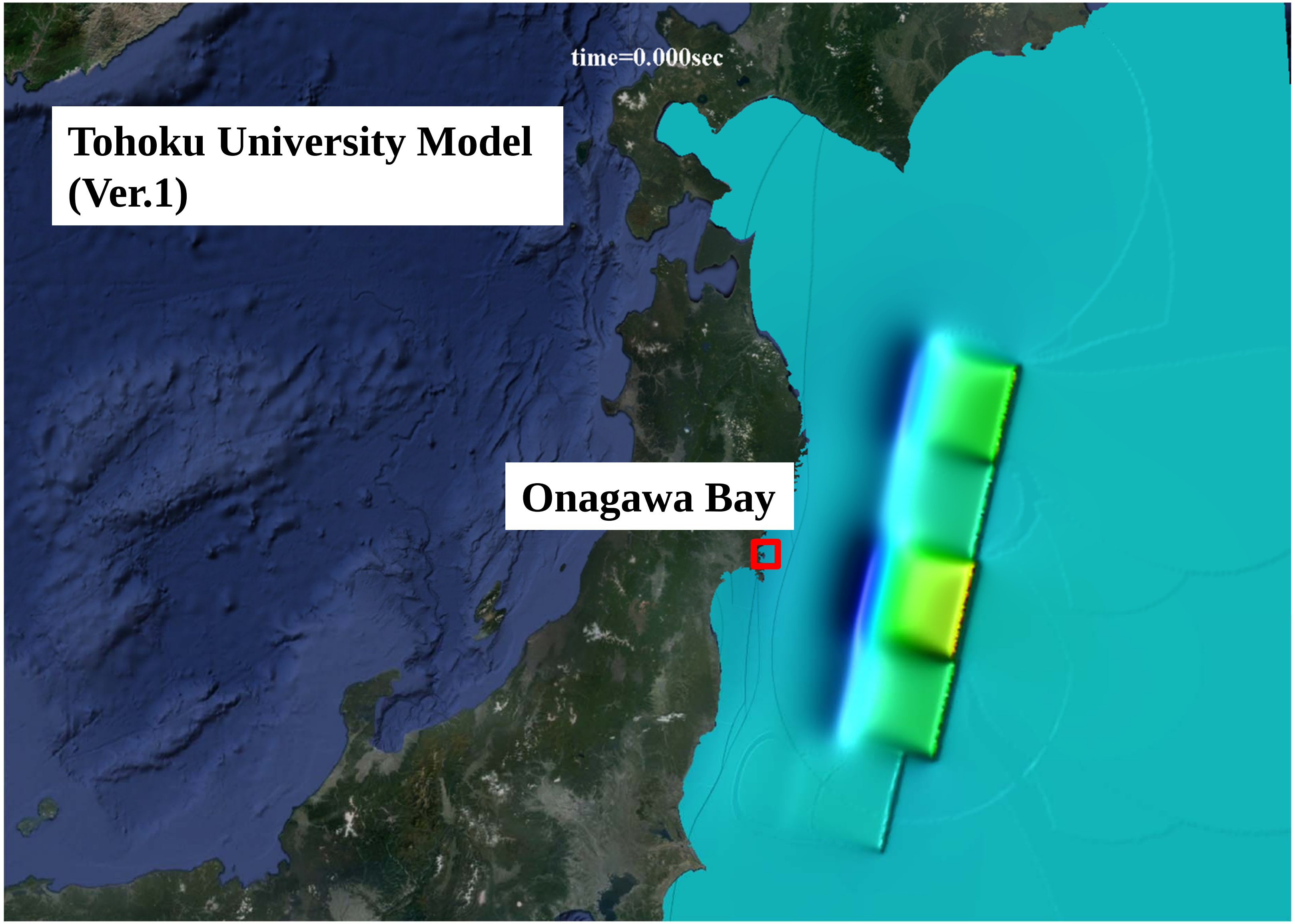
$$\frac{\partial H}{\partial t} + \frac{\partial(u_i H)}{\partial x_i} = 0$$ — Continuity equation

$$\frac{\partial(u_i H)}{\partial t} + (u_i H)\frac{\partial u_j}{\partial x_j} + gH\frac{\partial(H+z)}{\partial x_i} + \frac{gn^2 u_i \sqrt{u_j u_j}}{H^{\frac{1}{3}}} + \frac{\partial}{\partial x_i}\left(\frac{h^2}{3}\frac{\partial^2(u_i H)}{\partial t \partial x_j}\right) = 0$$ — Momentum equation

→ Stabilized finite element method based on SUPG formulations

Y, Takahaashi, M. Sakuraba, K. Kashiyama, A CIVA-Stabilized FEM for Tsunami Simulation J. JSCE, Ser. A2, Vol. 70, No. 2, 2014

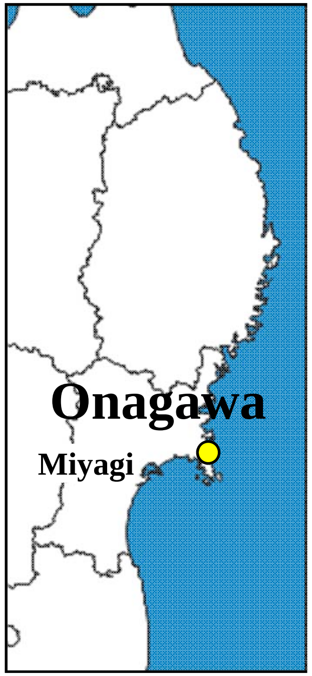
Tsunami Simulation

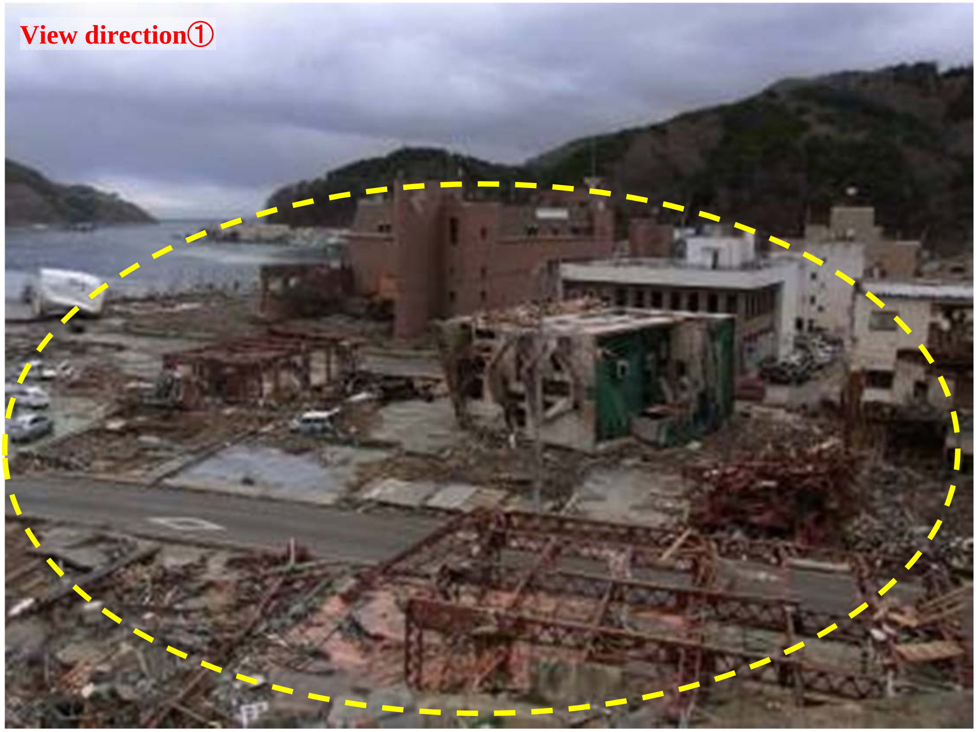


Tsunami Hazard (Onagawa-Miyagi)

Onagawa city

Tsunami Hazard (Onagawa-Miyagi)

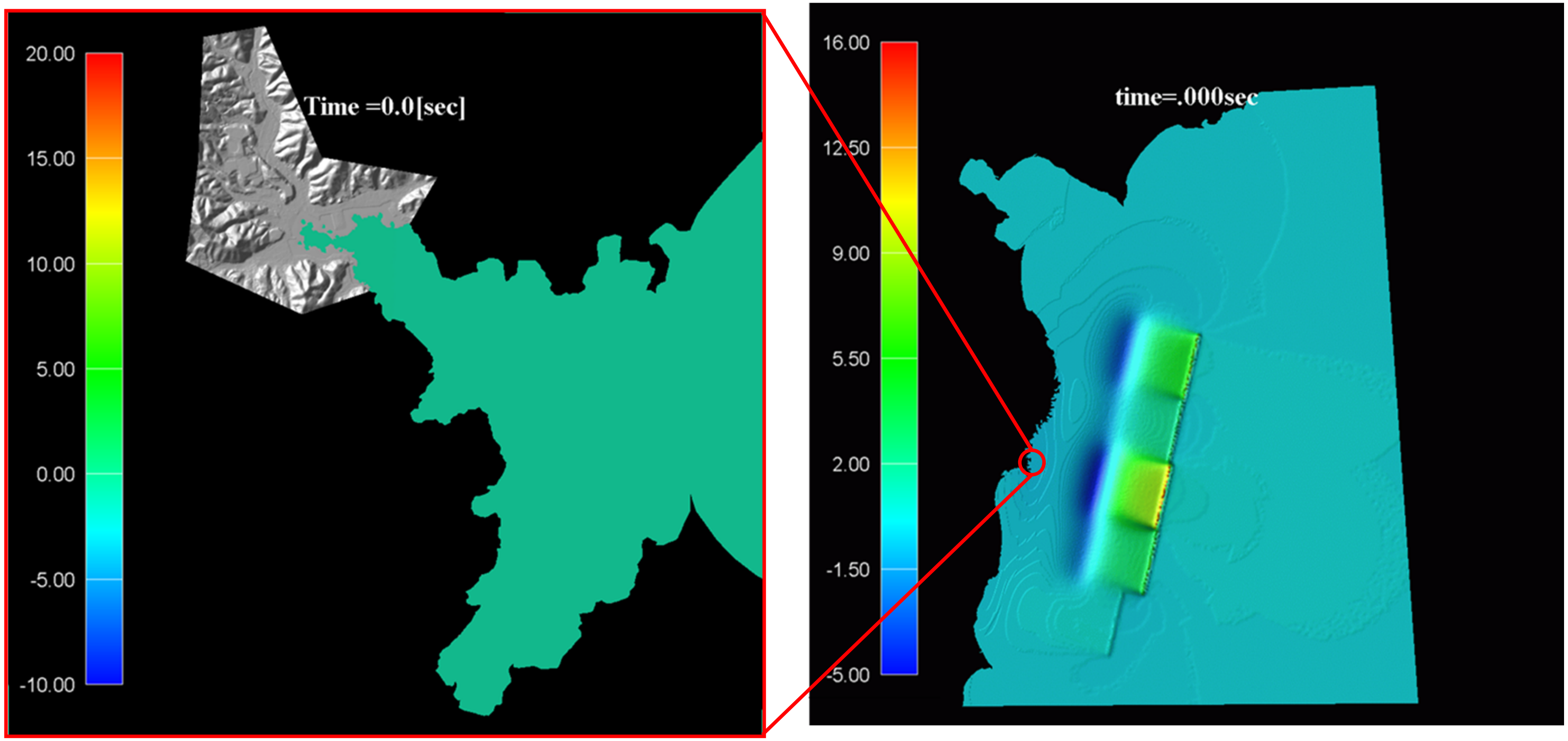




Many Reinforced concrete buildings are destroyed by the Tsunami

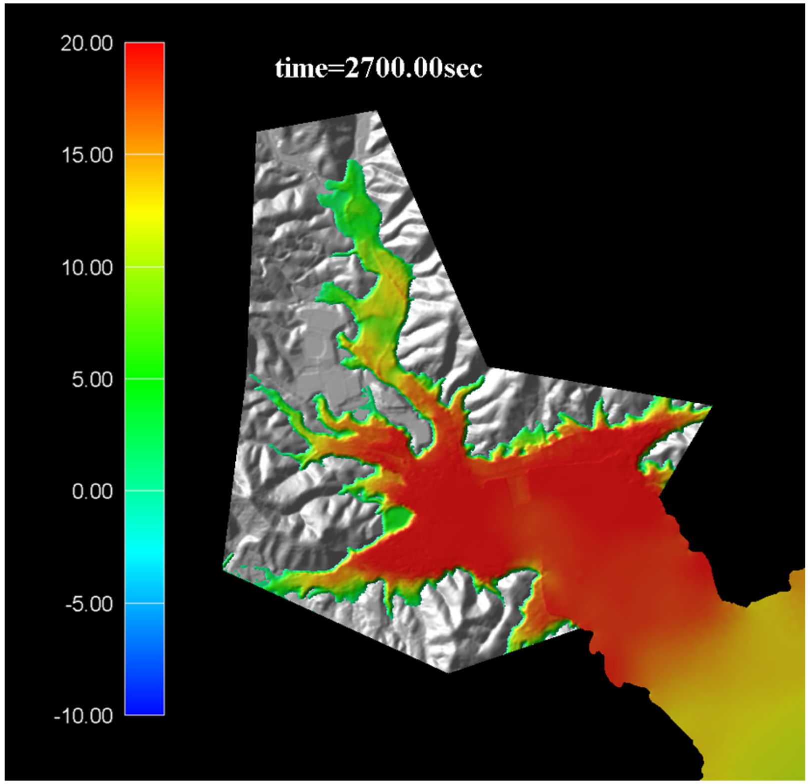
Computed results (animation)

Tsunami run-up simulation

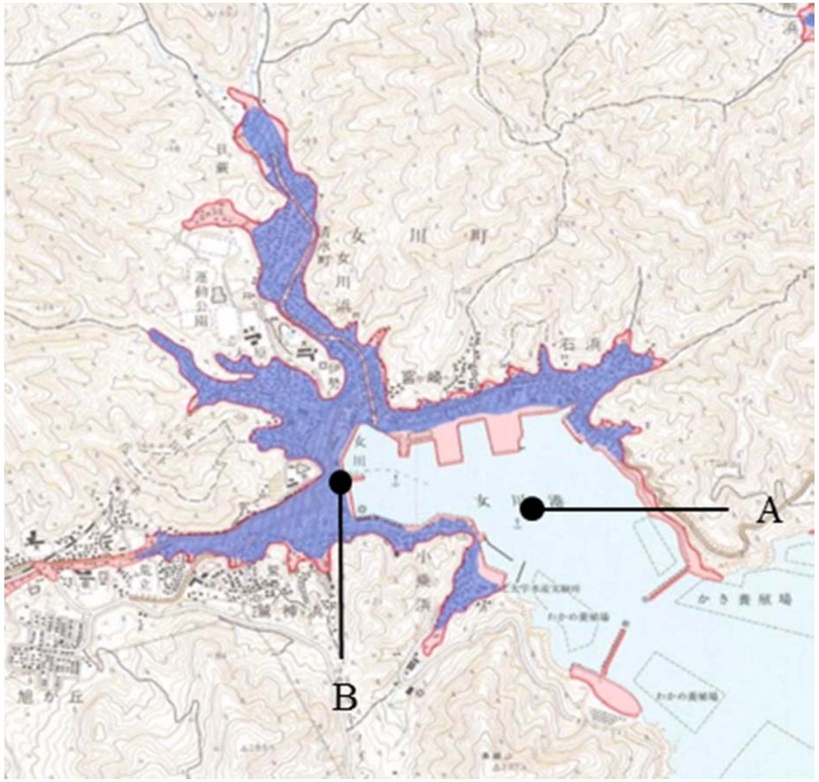


Onagawa-Miyagi

Comparison of Computational Results

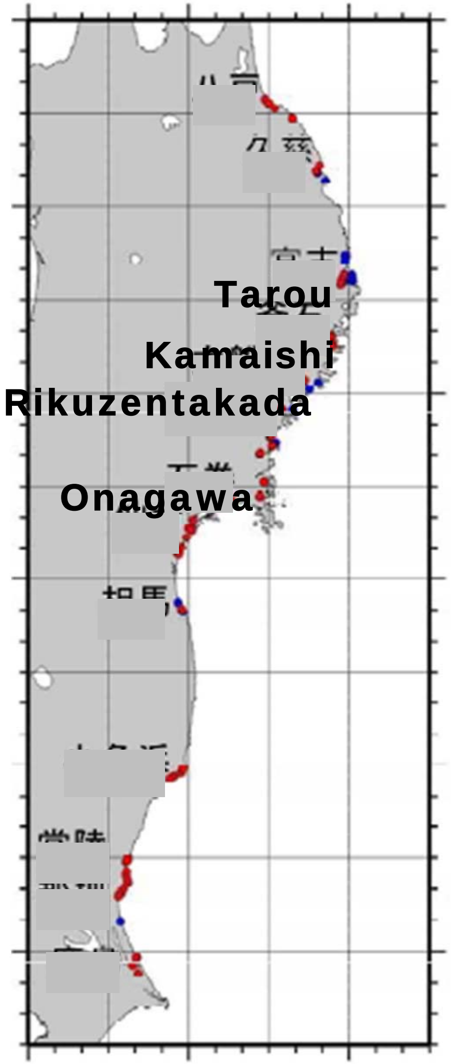


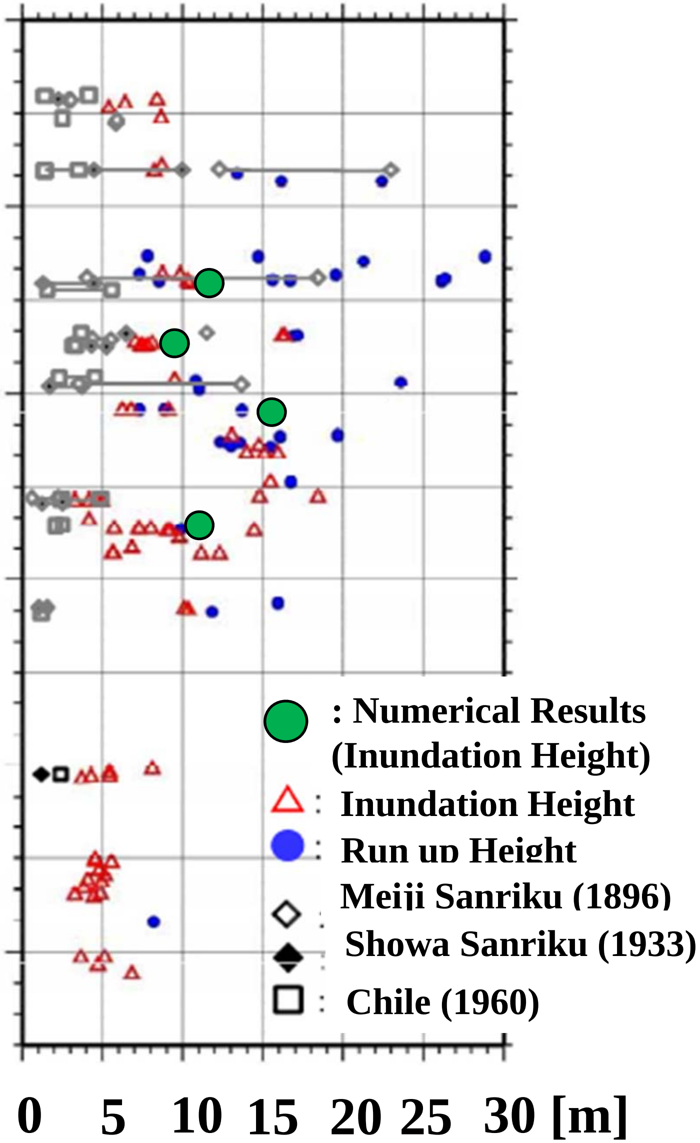
Computed inundation area



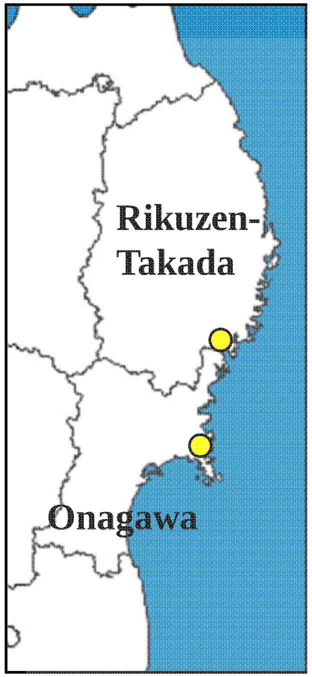
Observed data
(Red: inundation area
Blue: building damaged area)

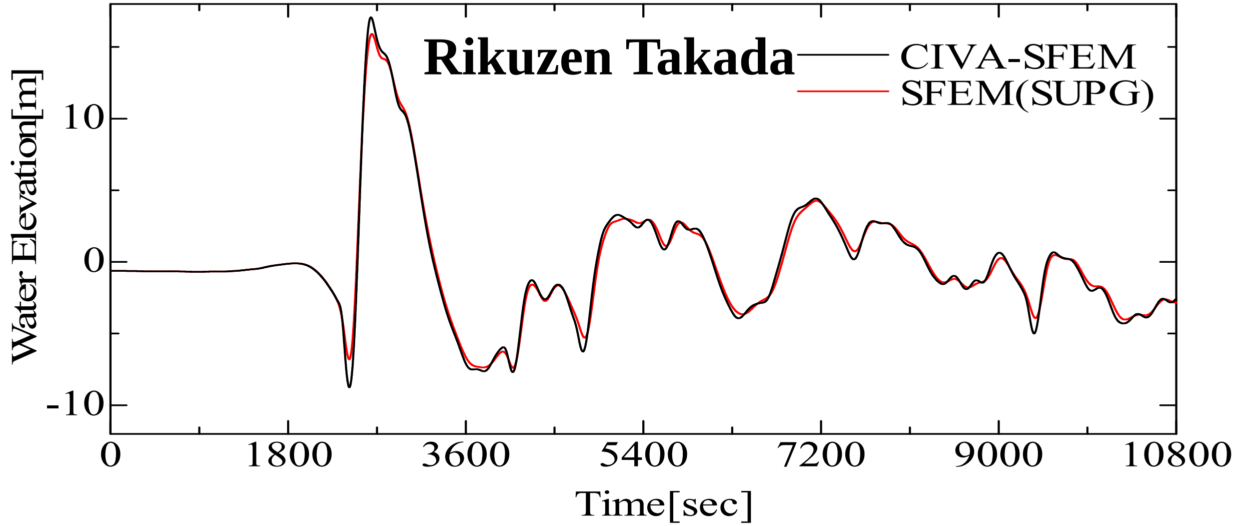
Comparison of Computed and Observed Results

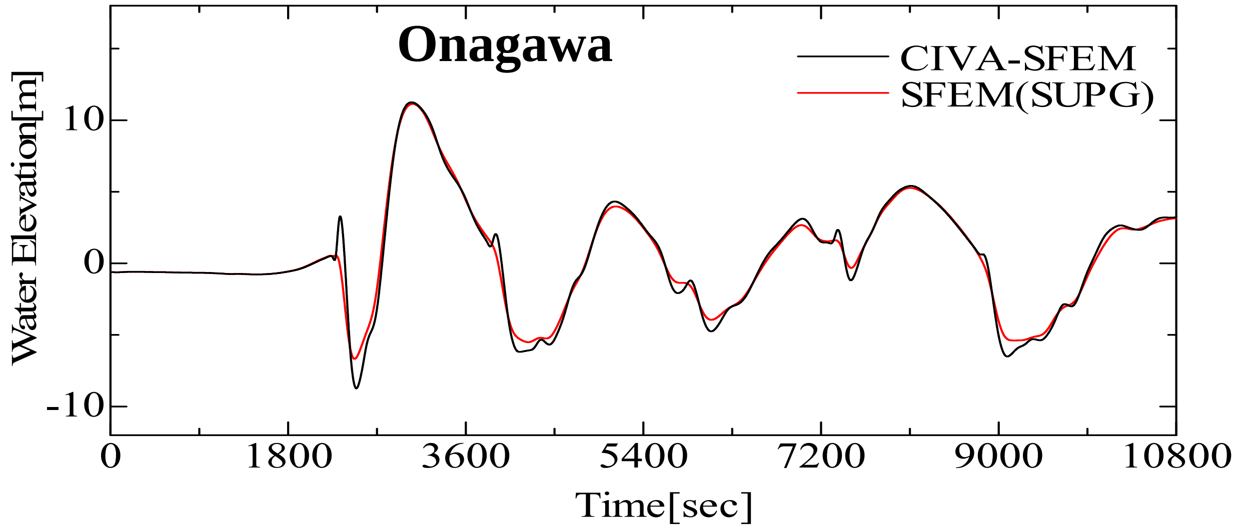




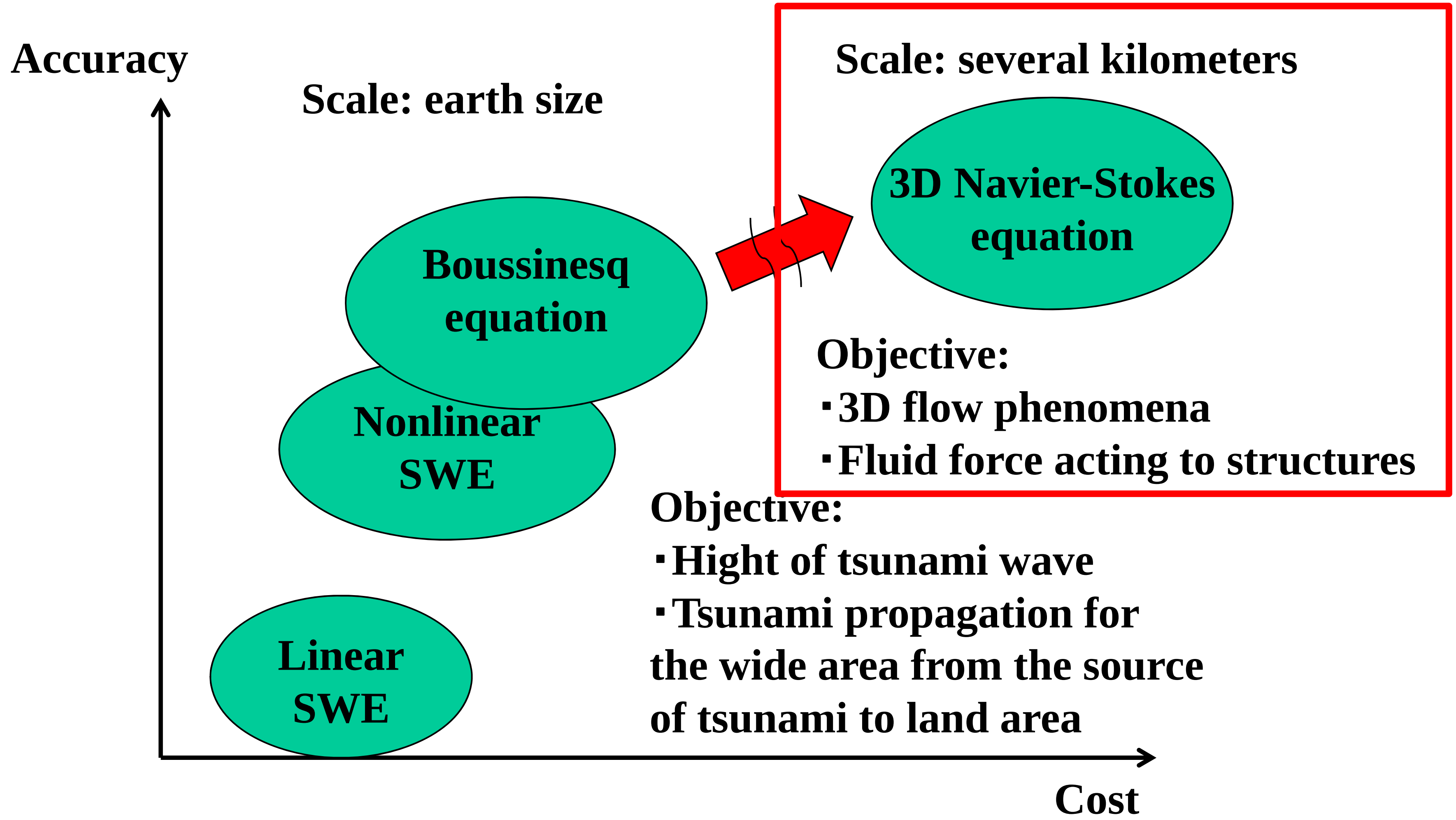
Comparison of CIVA/SUPG and SUPG







Governing equations for Tsunami



Governing Equation for 3D

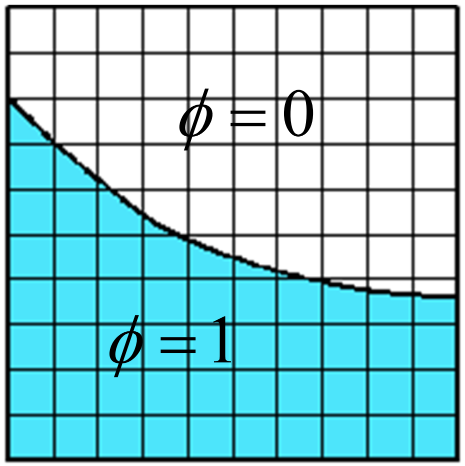
Navier-Stokes Equation

$$\nabla \cdot \mathbf{u} = 0 \qquad \text{on } \Omega_t \quad \forall t \in [0, T]$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - \mathbf{f} \right) - \nabla \cdot \sigma(\mathbf{u}, p) = 0 \qquad \text{on } \Omega_t \quad \forall t \in [0, T]$$

$$\sigma = -p\mathbf{I} + 2\mu\varepsilon(\mathbf{u})$$

$$\varepsilon(\mathbf{u}) = \frac{1}{2} \left(\nabla \mathbf{u} + (\nabla \mathbf{u})^T \right)$$



Interface Function

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = 0 \qquad \text{on } \Omega_t$$

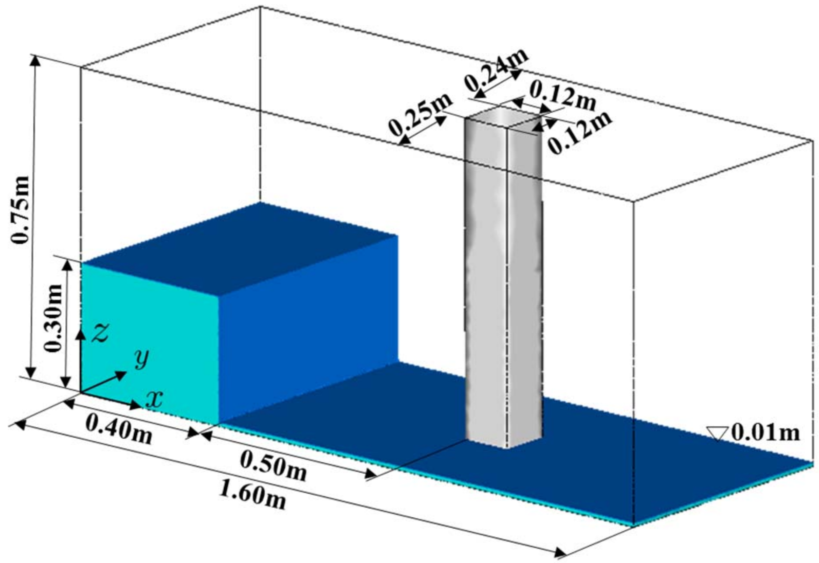
$$\rho = \rho_l \phi + \rho_g (1 - \phi)$$

$$\mu = \mu_l \phi + \mu_g (1 - \phi)$$

Numerical Example

An evaluation of the fluid force acts on a strucure

Purpose : accuracy verification of 2D analysis and 3D analysis for the fluid force problem

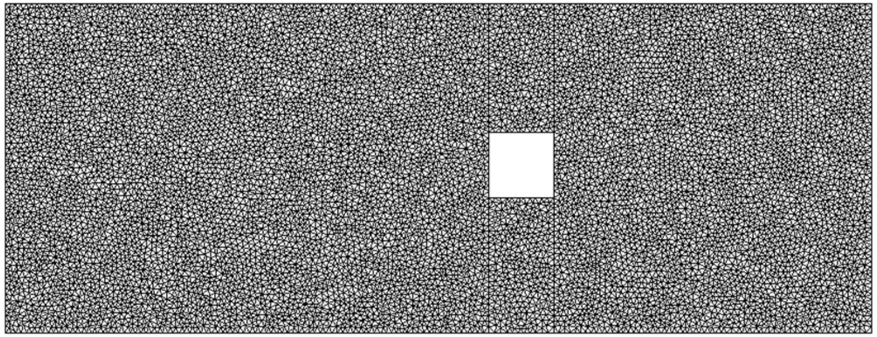


Computational model and the initial condition

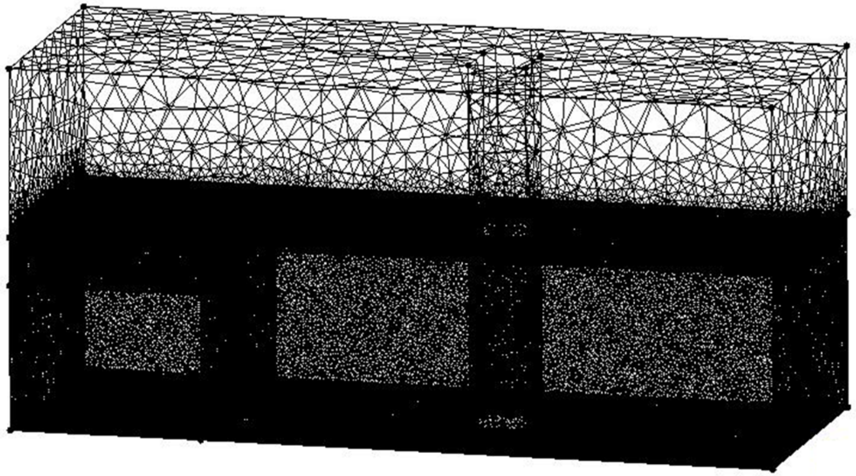
Analysis conditions : time increment 0.001s, slip boundary condition

Numerical Example

The meshes for the analysis of 2D and 3D



The mesh for the 2D analysis

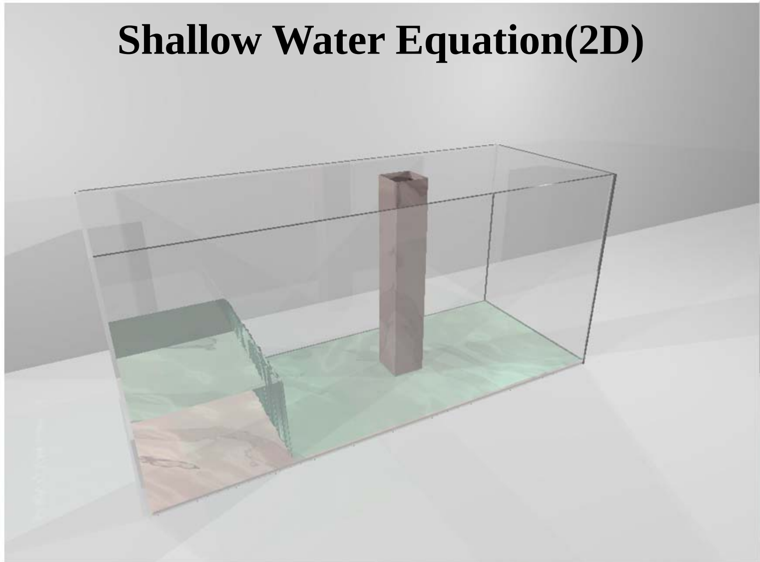


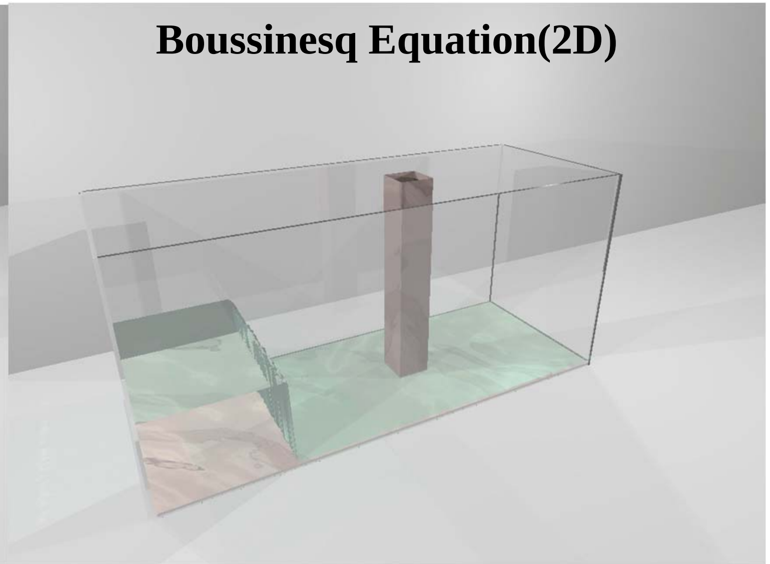
The mesh for the 3D analysis

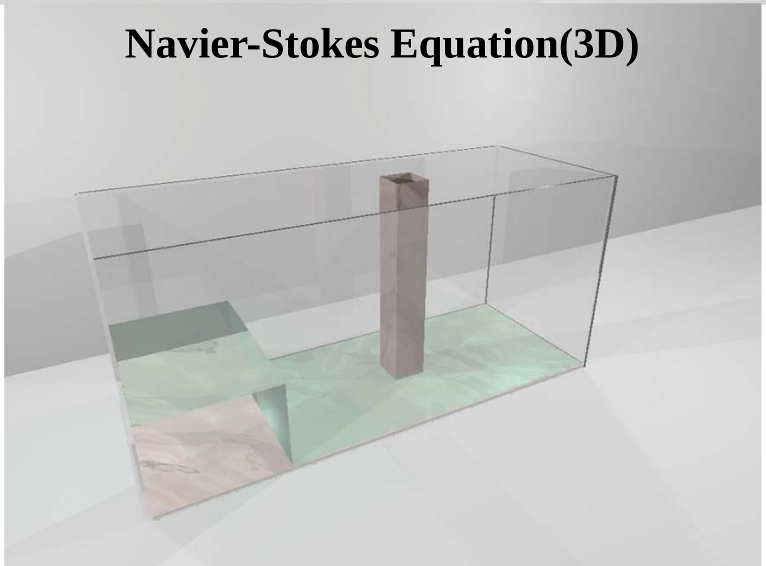
	Nodes	Elements	Min-width(m)
2D analysis	10,196	19,910	0.01
3D analysis	970,071	5,701,404	0.01

Comparison of Numerical Results

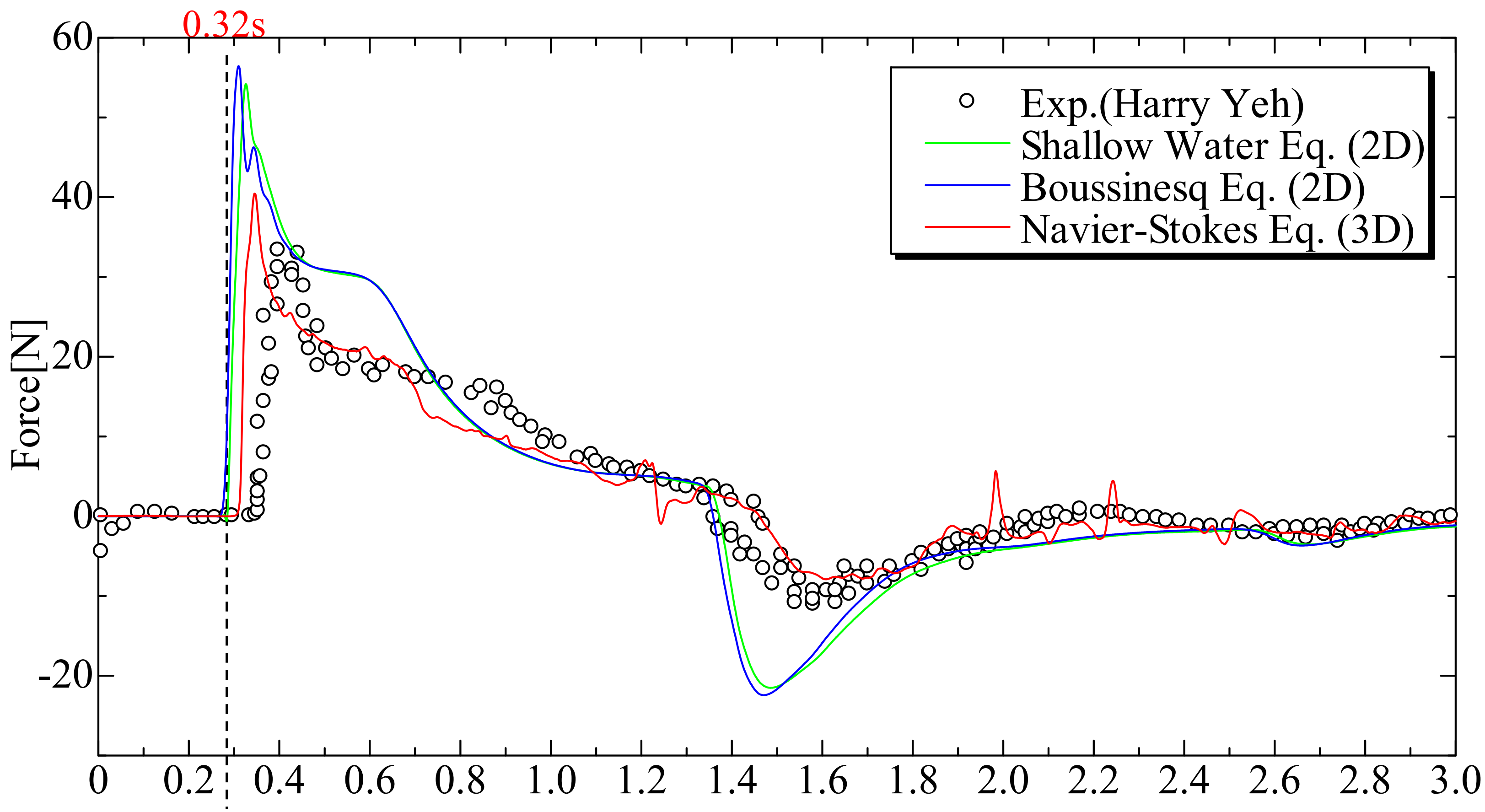
time=0.050sec







Comparison of Numerical Results

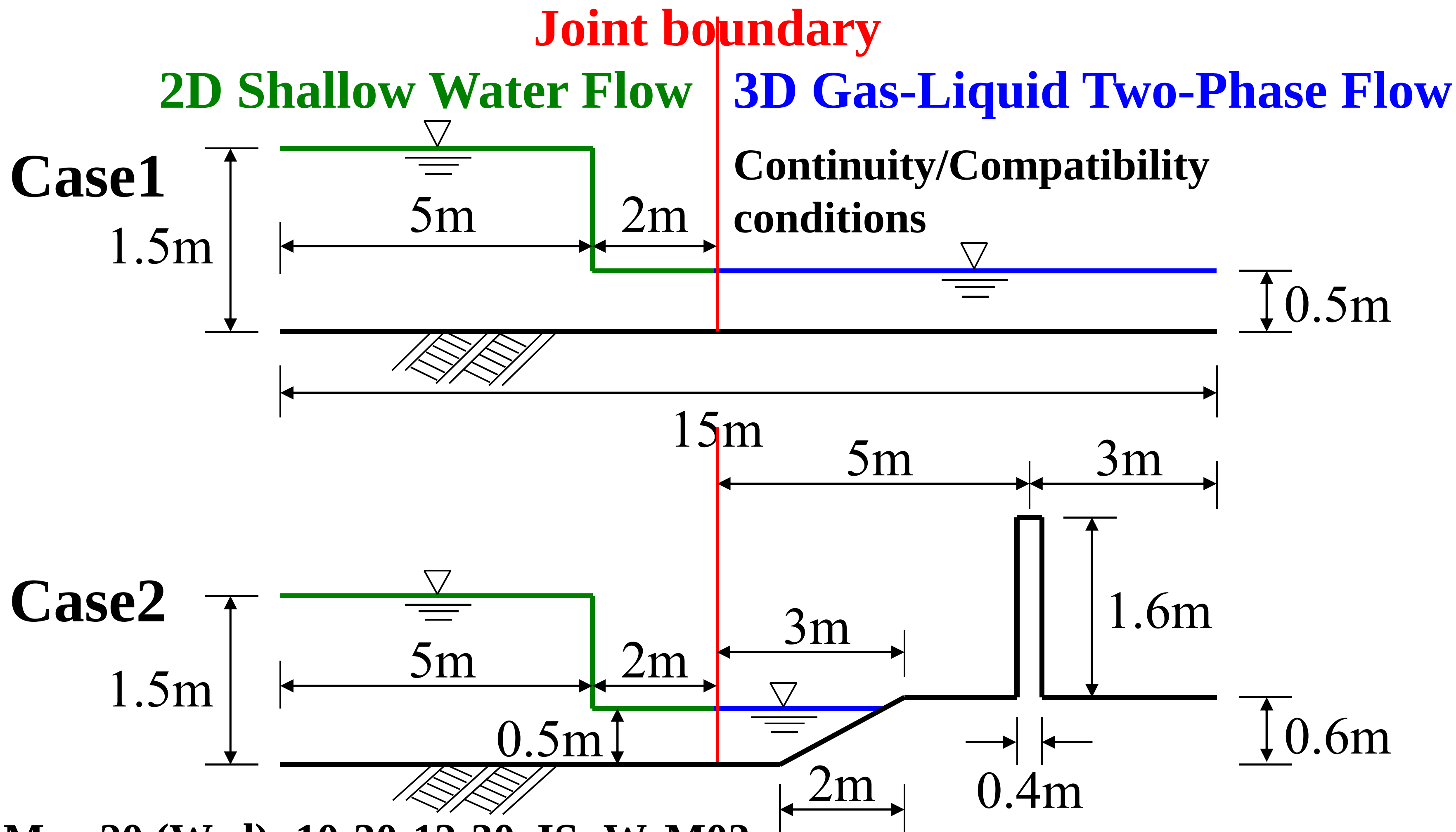


Time history of fluid force acting on the structure

May 20 (Wed); 13:30-15:30 IS: WeA02

M. Sakuraba et al., Numerical study of tsunami forces by stabilized FEM

2D/3D coupling simulation

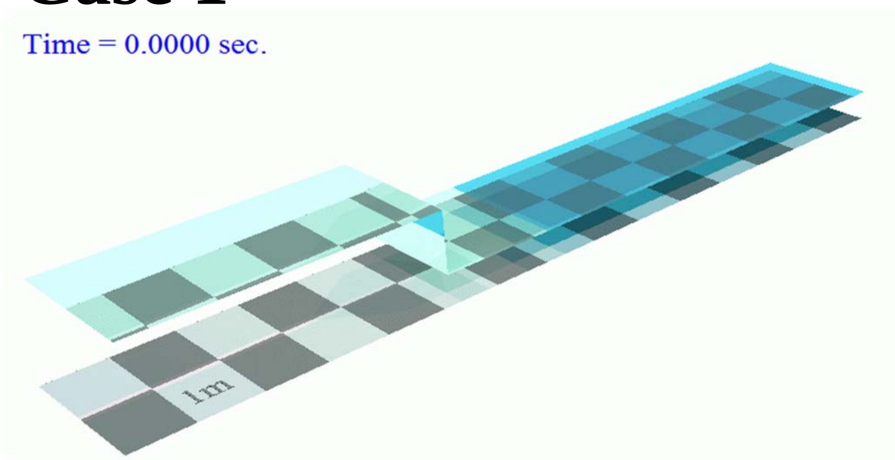


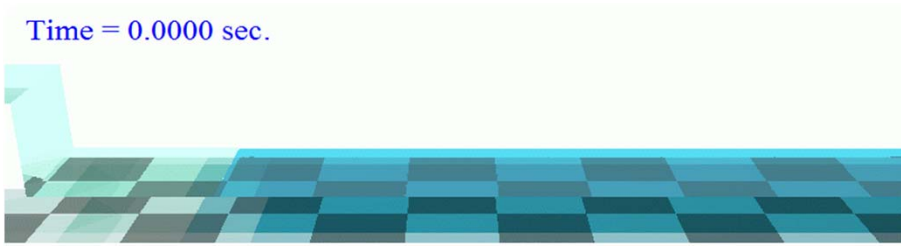
May 20 (Wed); 10:30-12:30, IS: WeM02

J. Matsumoto et al., A Coupling method using stabilized MINI element of 2D Shallow water flow and 3D gas liquid two phase flow

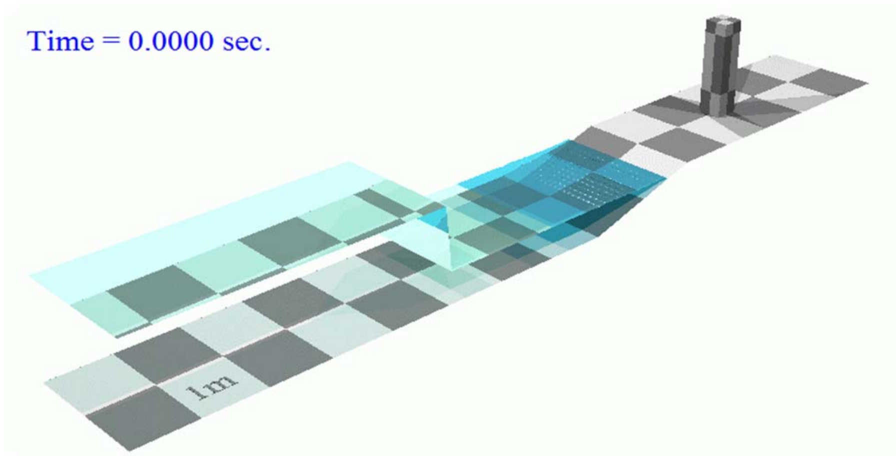
2D/3D coupling simulation

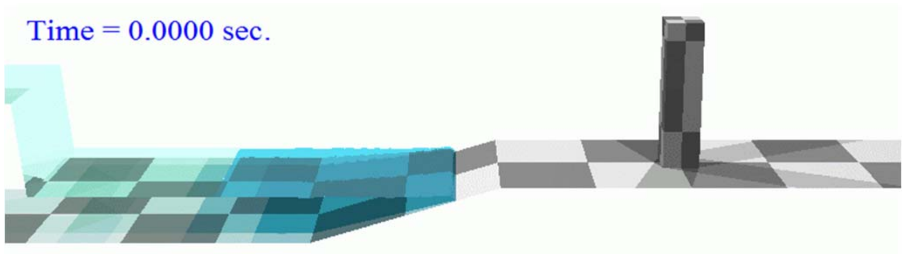
Case 1



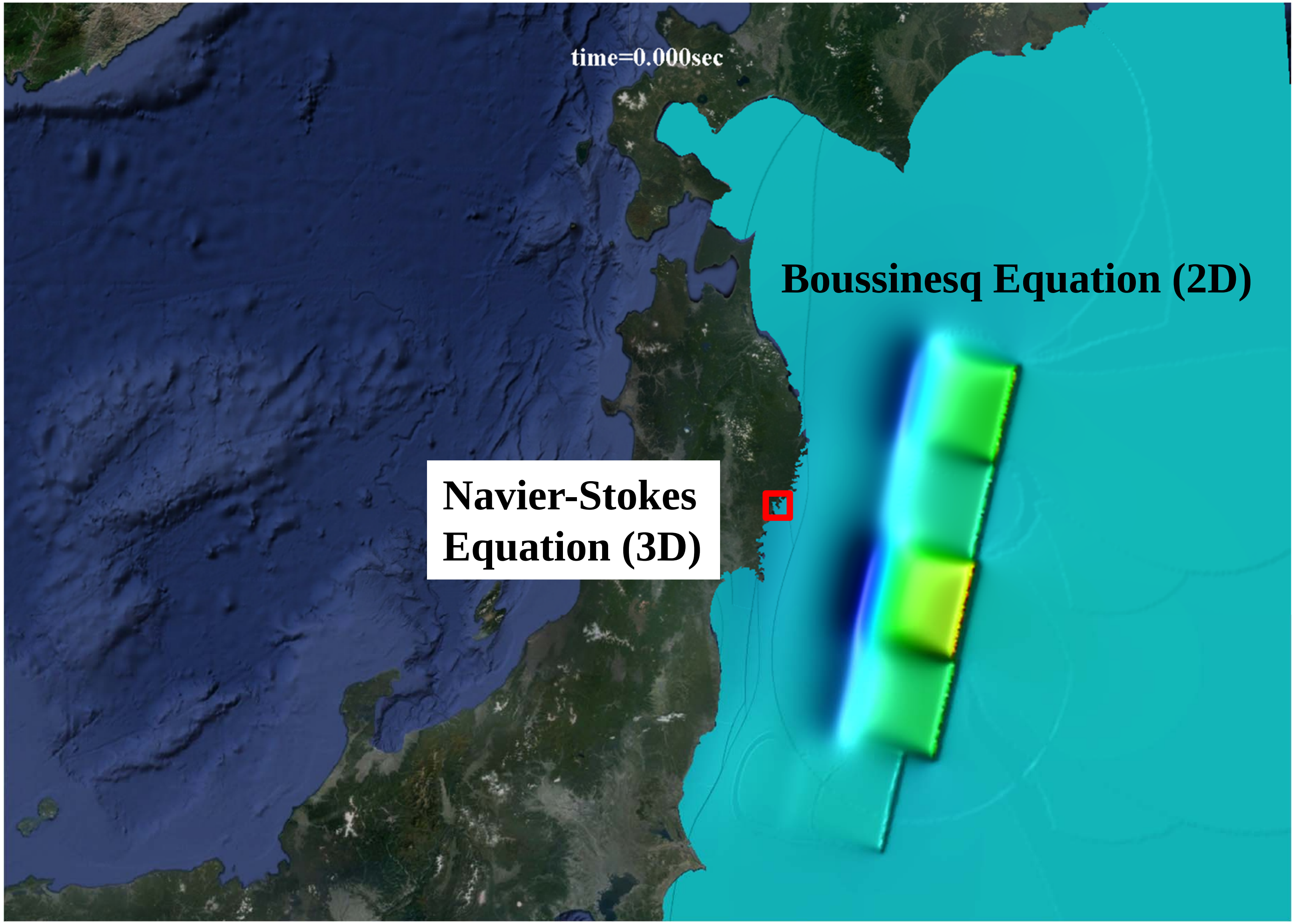


Case 2

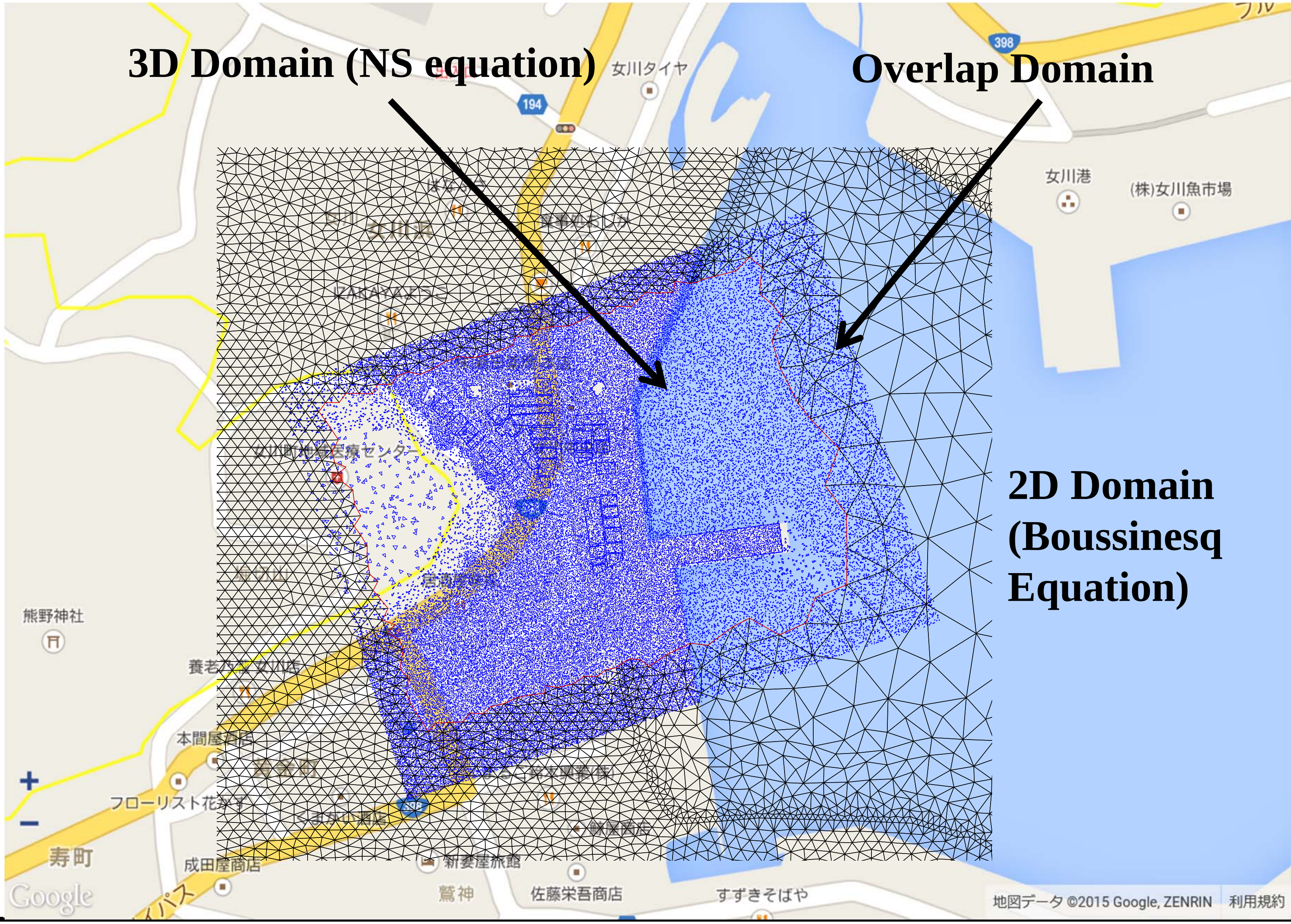




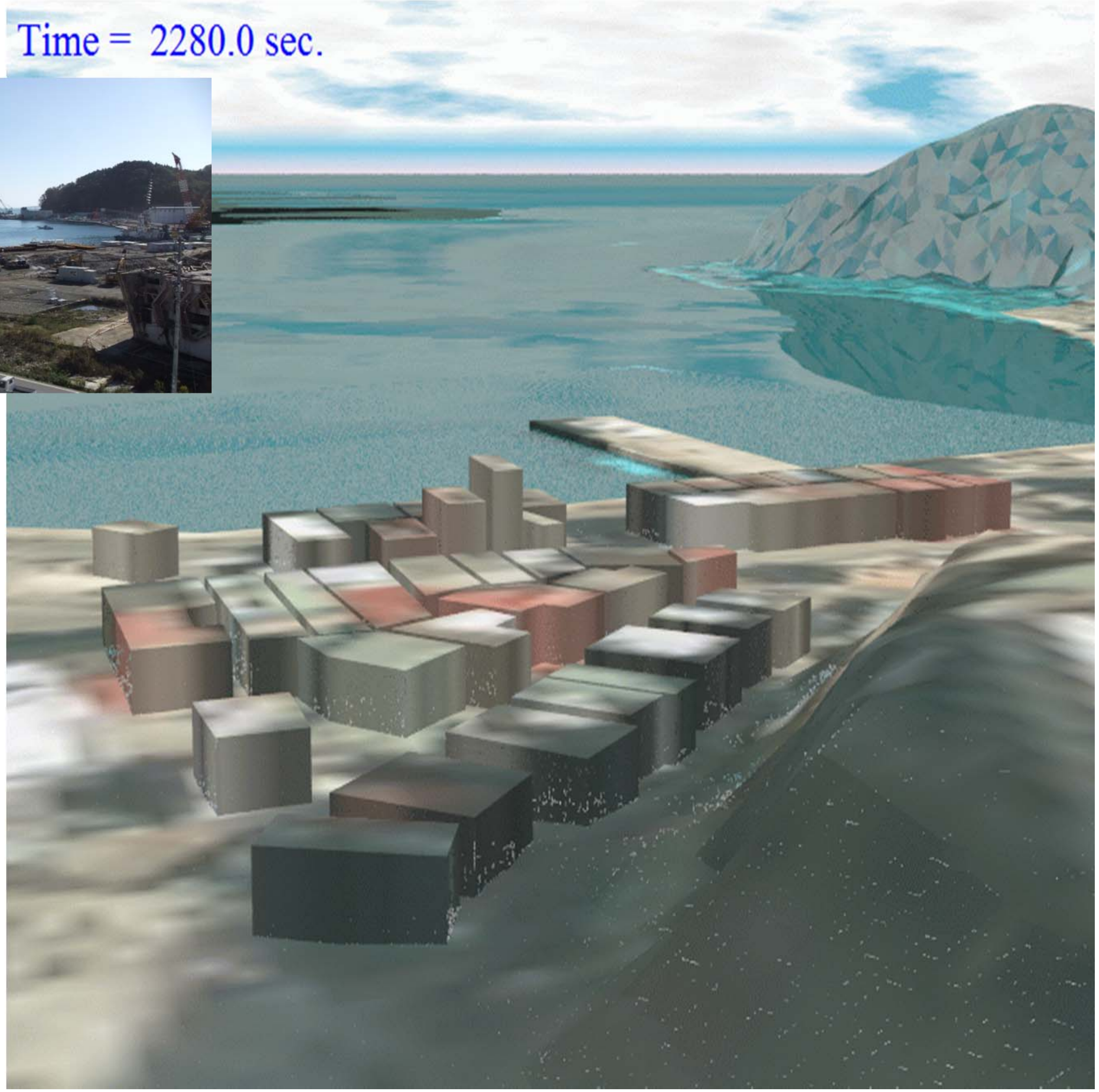
2D/3D coupling simulation



2D/3D coupling simulation



2D/3D coupling simulation



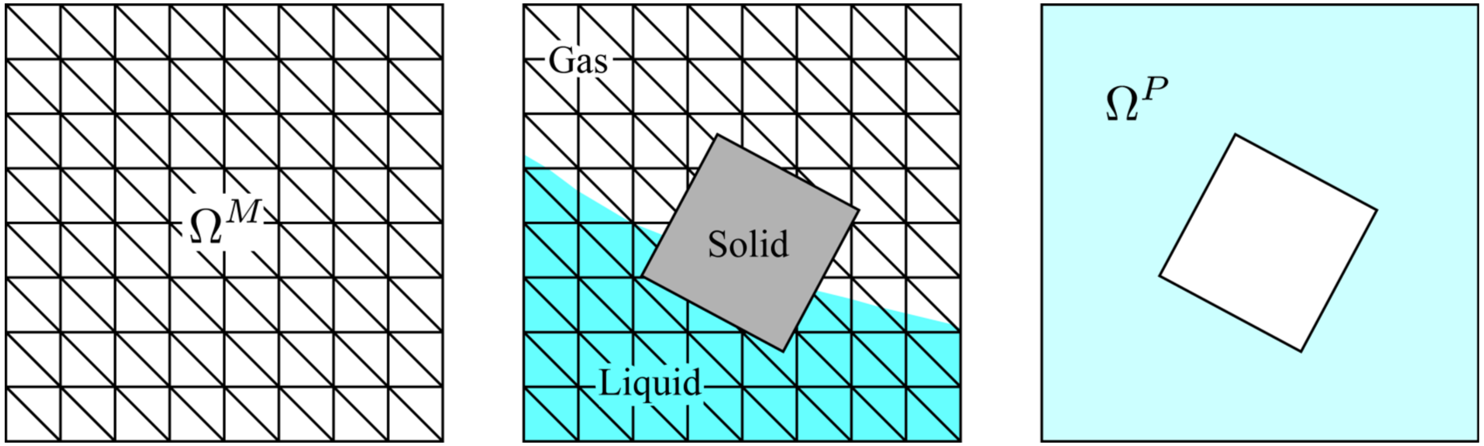
FSI using Finite Cover Method (FCM)

Finite Cover Method (FCM) is known as the generalized version of finite element approximations, which has been developed for computational solid dynamics.

Terada K, Asai M, Yamagishi M.; IJNME, 2003; 58: 1321-1346.

FCM can define the physical domain independently of mathematical one.

$$\Omega^M \neq \Omega^P$$



mathematical domain

physical domain (Fluid part)

FSI using Finite Cover Method (FCM)

Finite Cover Method (FCM) is known as the generalized version of finite element approximations, which has been developed for

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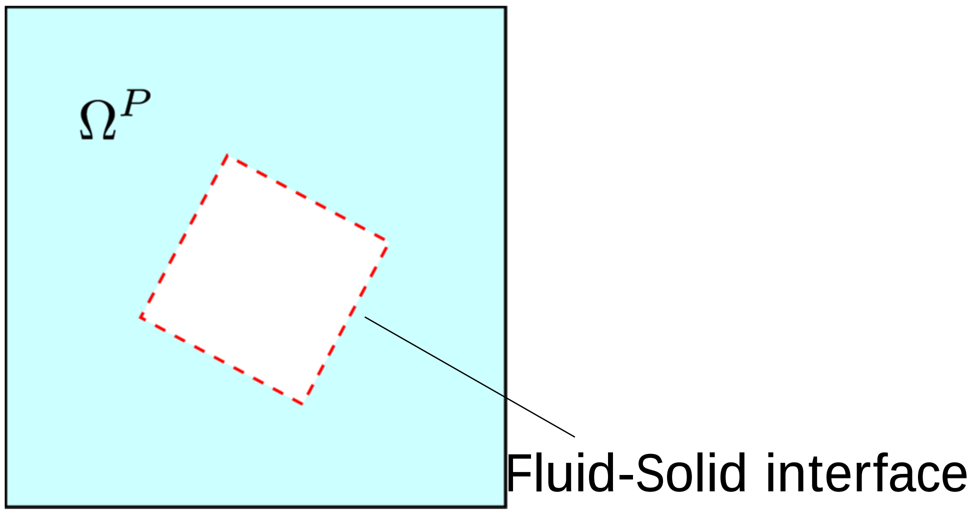
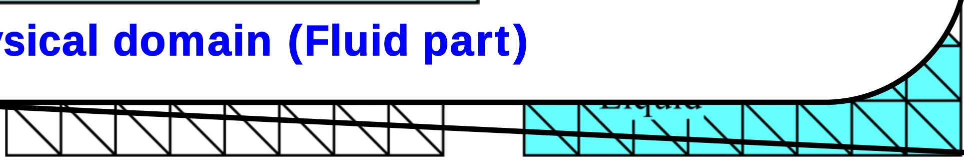
03; 58: 1321-1346.

tly of mathematical one.

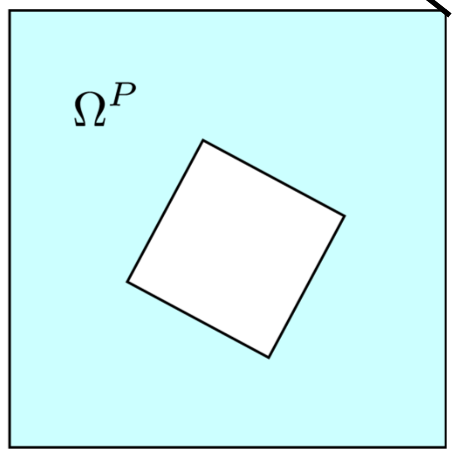
It is possible to impose the boundary condition on the Fluid-Solid interface accurately.



physical domain (Fluid part)



mathematical domain



physical domain (Fluid part)

Stabilized Finite Element Method

Weak form based on SUPG/PSPG method for Navier-Stokes equation

$$\rho \int_{\Omega^P} \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - \mathbf{f} \right) \cdot \mathbf{u}^* \, d\Omega$$

$$- \int_{\Omega^P} p \nabla \cdot \mathbf{u}^* d\Omega + \mu \int_{\Omega^P} \left(\nabla \mathbf{u} : \nabla \mathbf{u}^* + \nabla \mathbf{u} : (\nabla \mathbf{u}^*)^T \right) d\Omega$$

$$+ \int_{\Omega^P} q^* \nabla \cdot \mathbf{u} \, d\Omega + \sum_{P=1}^{n_{el}} \int_{\Omega^P} \{ \tau_{\mathrm{supg}} \mathbf{u} \cdot \nabla \mathbf{u}^* + \tau_{\mathrm{pspg}} \frac{1}{\rho} \nabla q^* \}$$

SUPG term PSPG term

$$\cdot \{ \rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} - \mathbf{f} \right) - \nabla \cdot \sigma \} \, d\Omega$$

$$+ \int_{\Gamma_g} \bar{p} (\mathbf{u} - \bar{\mathbf{u}}) d\Gamma$$

Penalty term

$$+ \sum_{e=1}^{n_{\mathrm{el}}} \int_{\Omega^e} \tau_{\mathrm{cont}} \nabla \cdot \boldsymbol{w}^h \rho \nabla \cdot \boldsymbol{u}^h \, d\Omega = 0$$

Shock-Capturing term

M. Nakamura, S. Takase, K. Kashiyama, K. Terada, M. Kurumatani, A Simulation method for fluid-structure interaction problems with free surface based on the finite cover method, J. JSCE, Ser. A2, Vol. 67, No. 2 P I_199-I_208, 2011

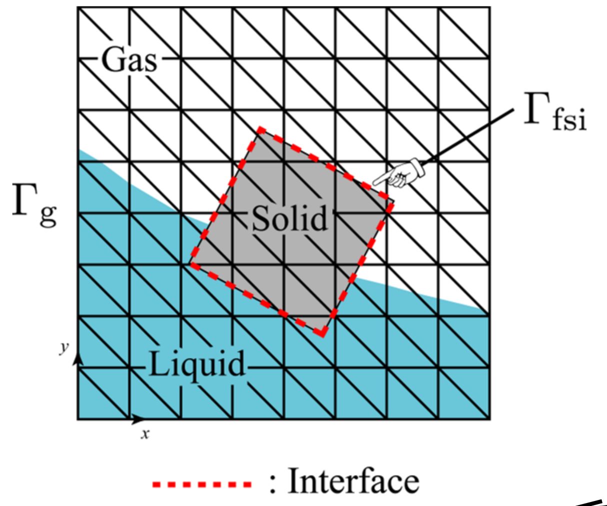
Stabilized Finite Element Method

The penalty method is applied to impose the Dirichlet boundary condition on the fluid-solid interface.

Boundary condition

$$\int_{\Gamma_{\mathrm{fsi}}} \bar{p}(\mathbf{u} - \bar{\mathbf{u}})d\Gamma$$

Penalty parameter



$$\cdot\left\{\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u} - \mathbf{f}\right) - \nabla\cdot\sigma\right\} d\Omega$$

SUPG term

PSPG term

$$+\int_{\Gamma_g} \bar{p}(\mathbf{u} - \bar{\mathbf{u}})d\Gamma$$

Penalty term

Penalty term

$$+\sum_{e=1}^{n_{\mathrm{el}}}\int_{\Omega^e} \tau_{\mathrm{cont}}\nabla\cdot\boldsymbol{w}^h\rho\nabla\cdot\boldsymbol{u}^h\, d\Omega = 0$$

Shock-Capturing term

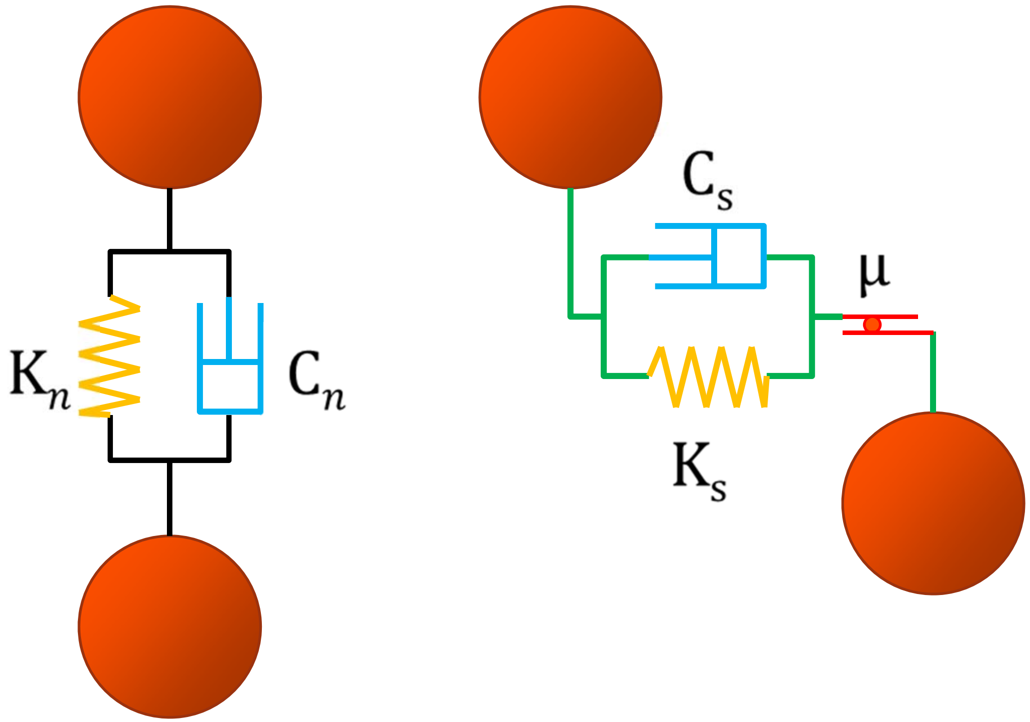
M. Nakamura, S. Takase, K. Kashiyama, K. Terada, M. Kurumatani, A Simulation method for fluid-structure interaction problems with free surface based on the finite cover method, J. JSCE, Ser. A2, Vol. 67, No. 2 P I_199-I_208, 2011

Discrete Element Method (DEM)

Movement of the structure is computed by the Discrete element method

$$\mathbf{F}_n + C_n \dot{\mathbf{u}} + K_n \mathbf{u} = 0$$

$$\mathbf{F}_s + C_s \dot{\mathbf{v}} + K_s \mathbf{v} = 0$$



K : **Spring coefficient** C : **Viscosity coefficient**
μ : **Friction coefficient**

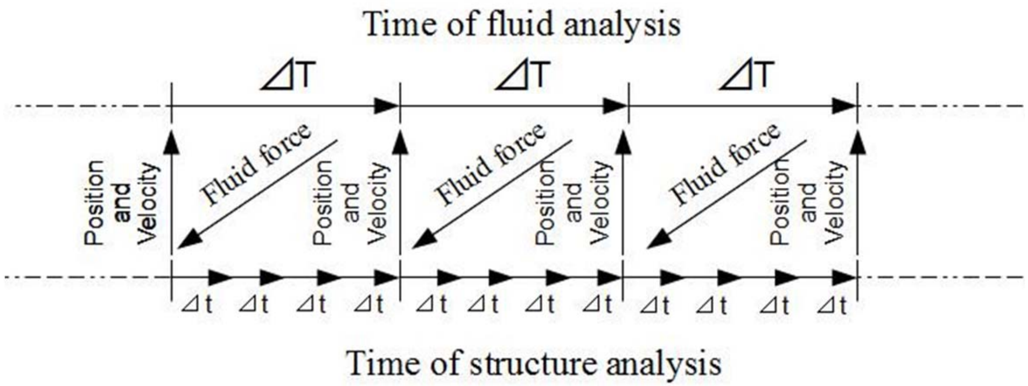
Algorithm of Fluid-Structure Interaction

Fluid force that acts on rigid body

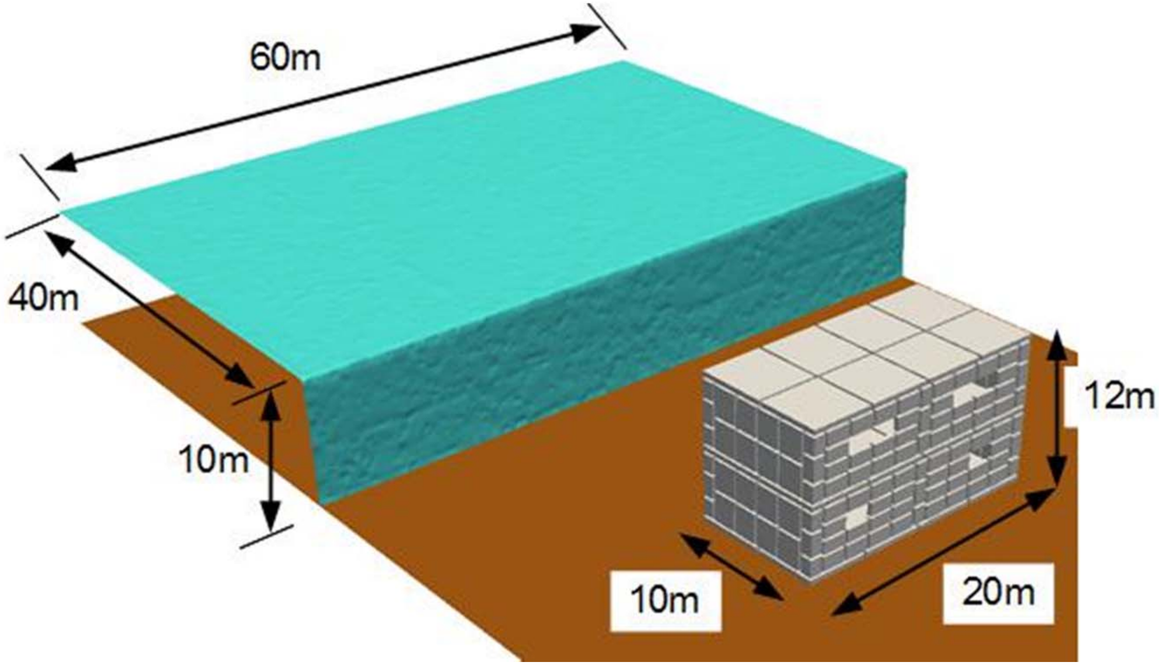
Fluid analysis
FCM using VOF method

Structural analysis
DEM using
rigid bodies model

Position of rigid body and velocity on surface of rigid body



Tsunami impact loading simulation

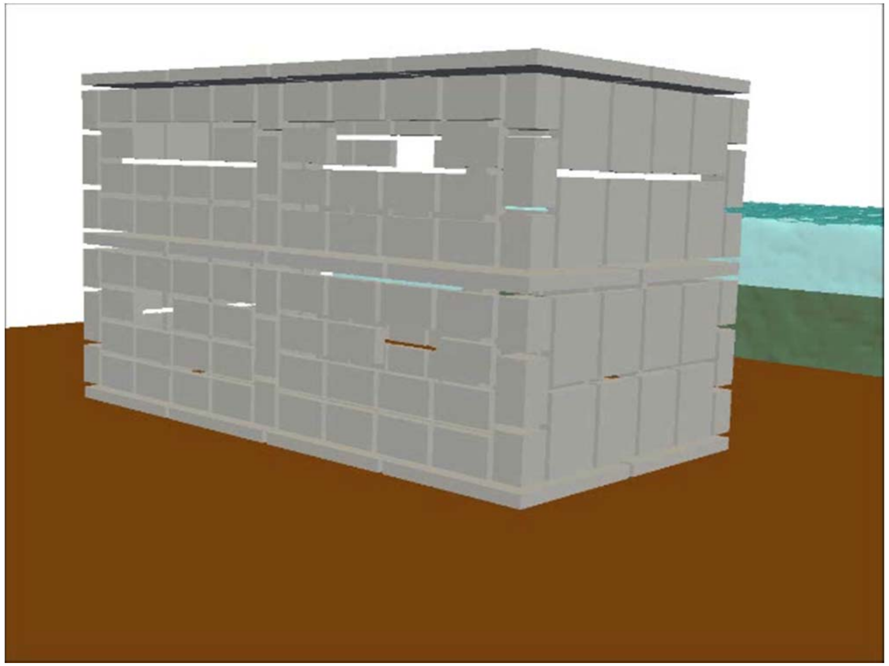


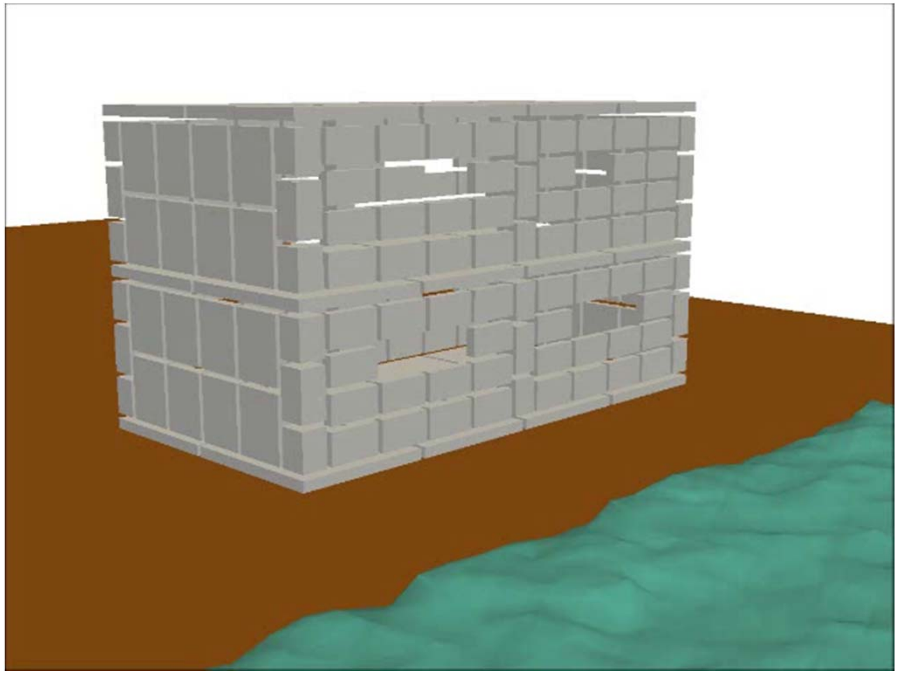
FCM
3185117 nodes
18757346 elements

DEM
26838 particle

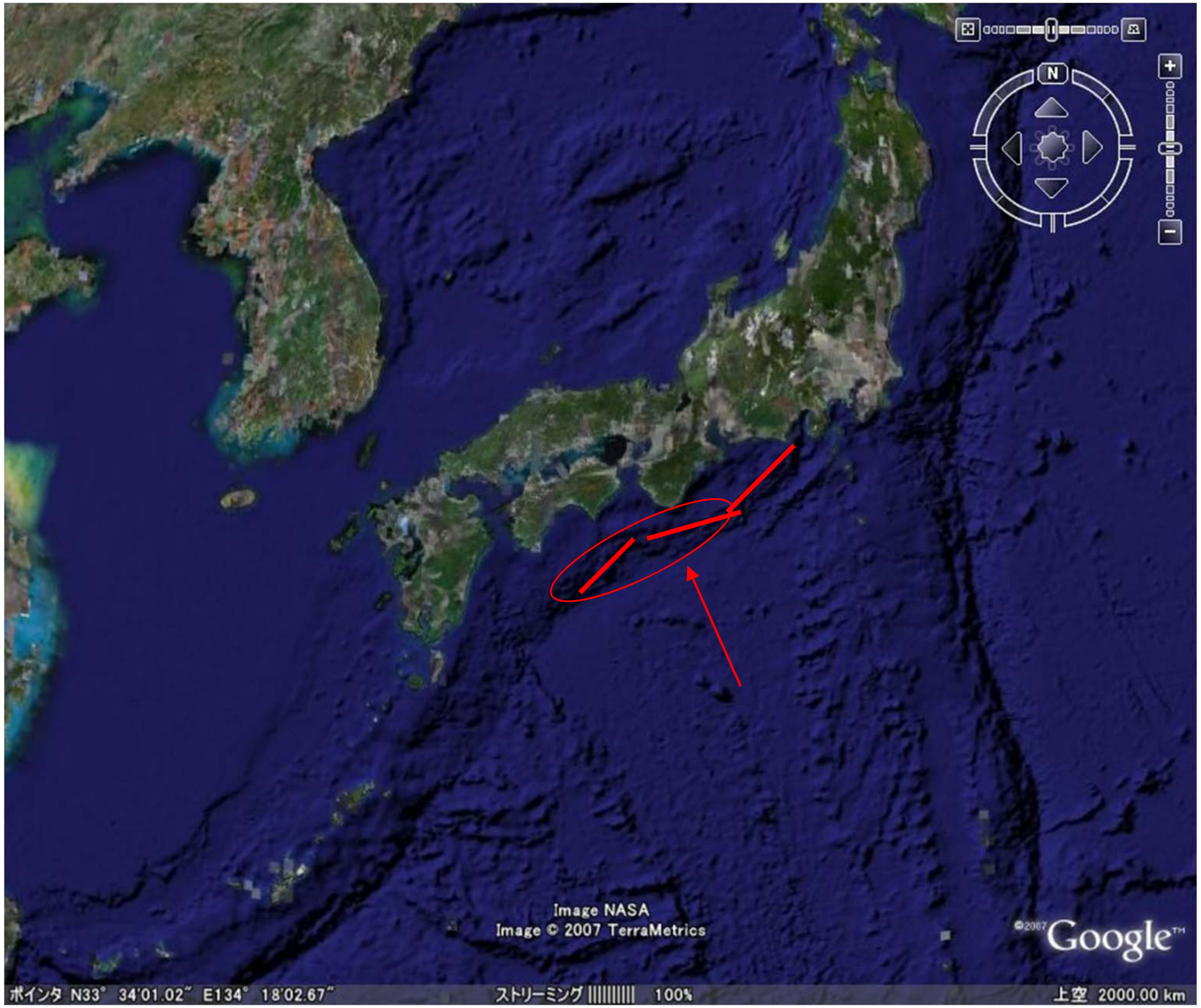
FCM : Dt = 2e-2
DEM : Dt = 1e-5

Tsunami impact loading simulation





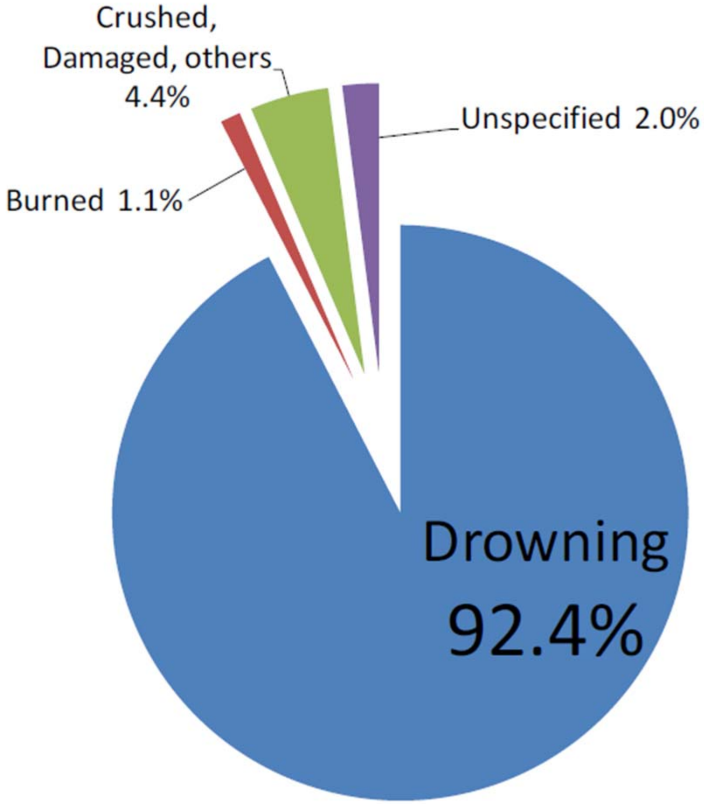
Tsunami Wave (Ansei-Nankai earthquake : 1854)



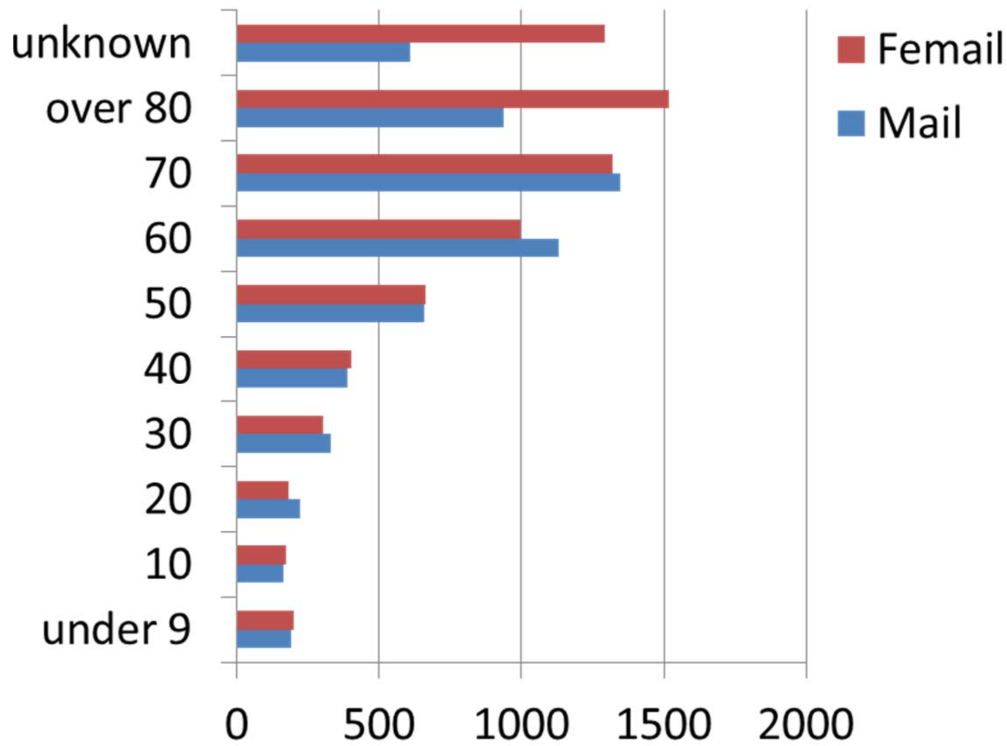
Tsunami Wave (Ansei-Nankai earthquake : 1854)

Cause of death in the great east Japan earthquake

More than 90% of deaths were caused by drowning and 65% of the dead were over 60



Data provided by National Police Agency



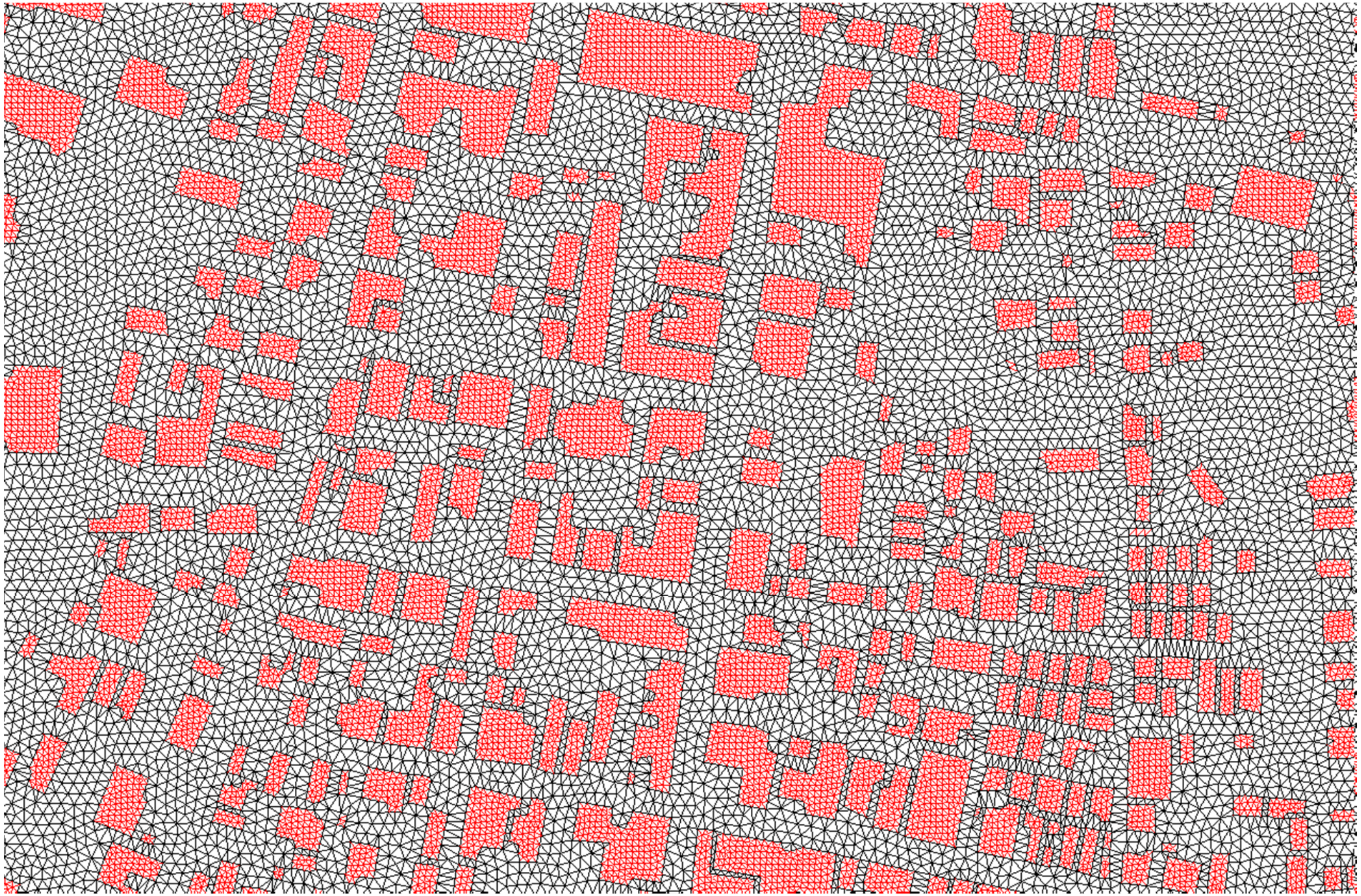
The disaster prevention education to promote a refuge action is very important

Numerical Example

: Wood

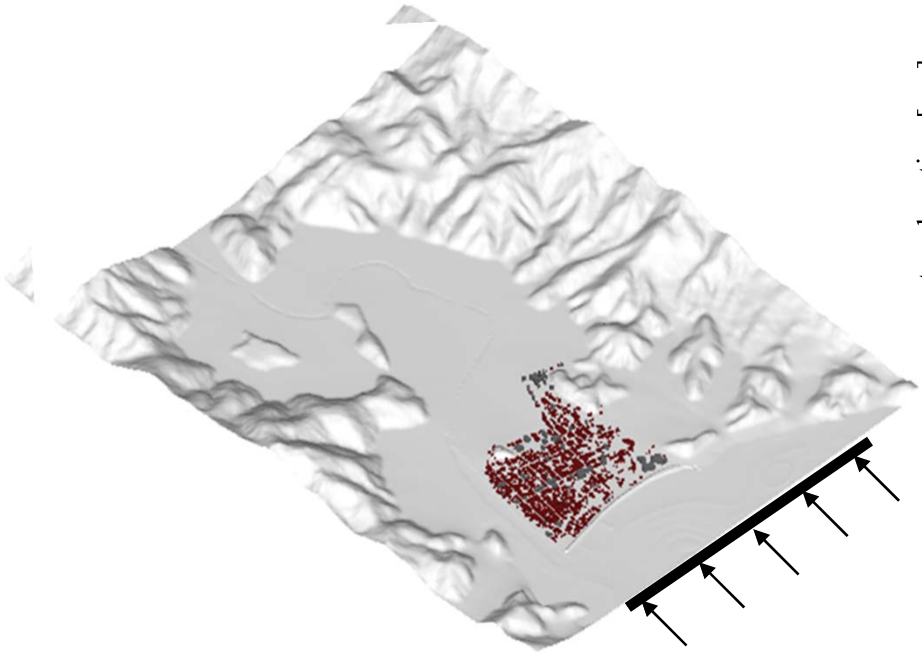
: Concrete

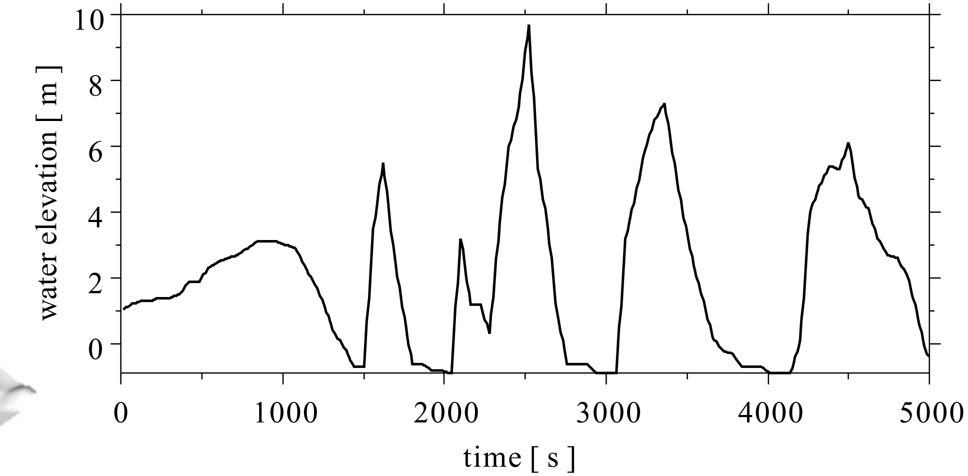
Finite Element Mesh



Numerical Example

Tsunami run-up problems





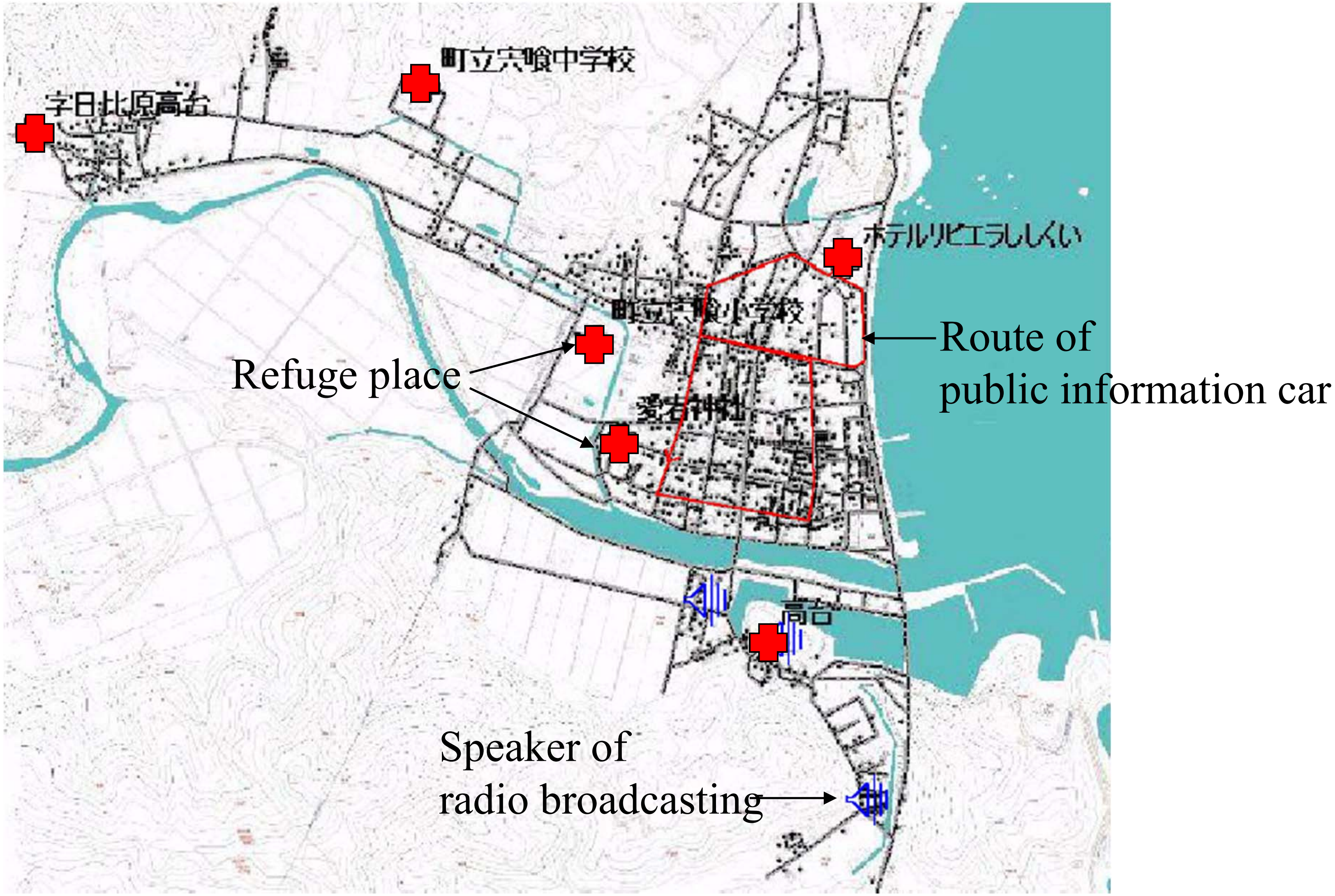
Incident wave

Criterion for collapse
（Iizuka and Matsutomi 2000)

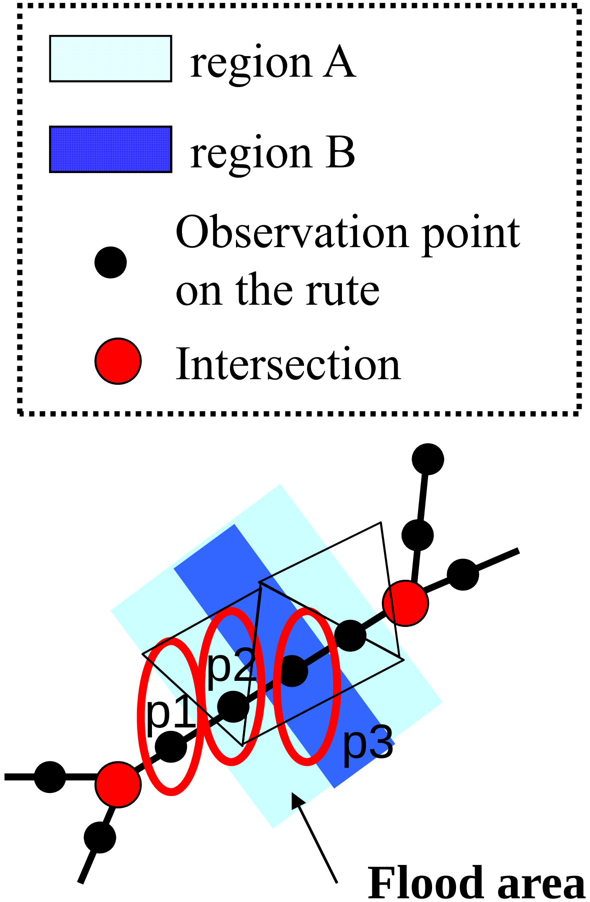
	Concrete building	Wooden building
Case A	332kN/m	27.4kN/m
Case B	603kN/m	49.0kN/m

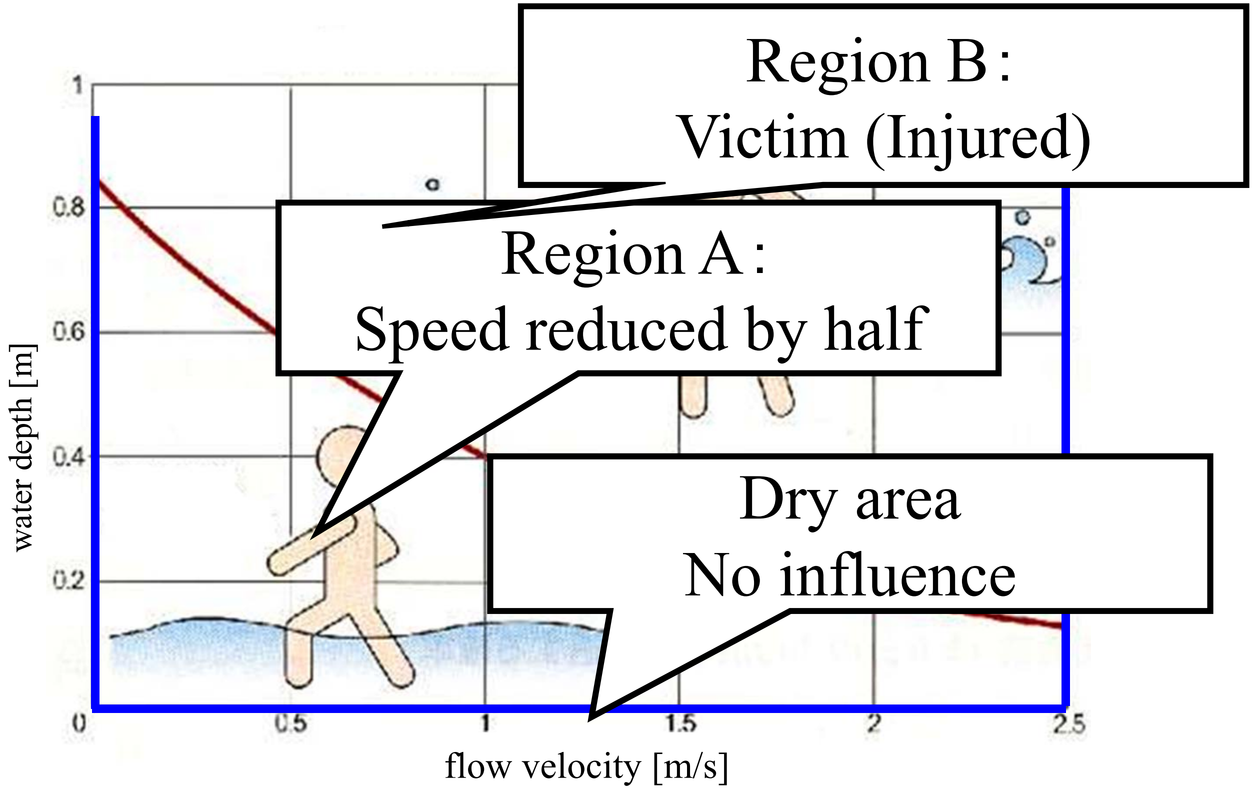
Manning's coefficient   Water area : $0.025 s/m^{1/3}$ Dry bed area : $0.040 s/m^{1/3}$

Evacuation Analysis



Evacuation Analysis





Relationship between flow velocity, water depth and refugee's status

Suga, et al. (2000)

Power of Tsunami

Largest wave tank (Port and Airport Research Institute, Japan)

Tsunami evacuation simulation

CaseA

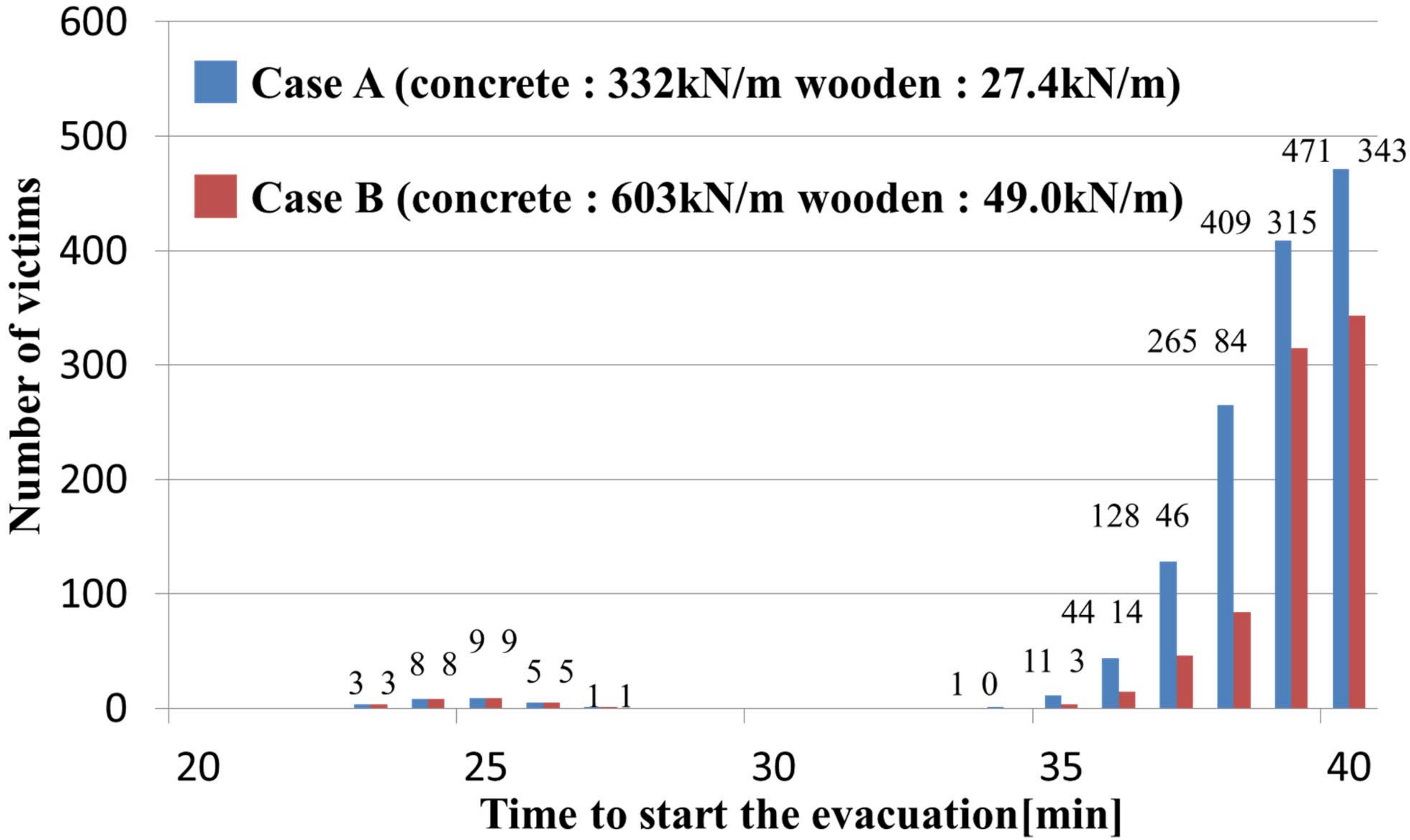
0 min

CaseB (High strength building)

0 min

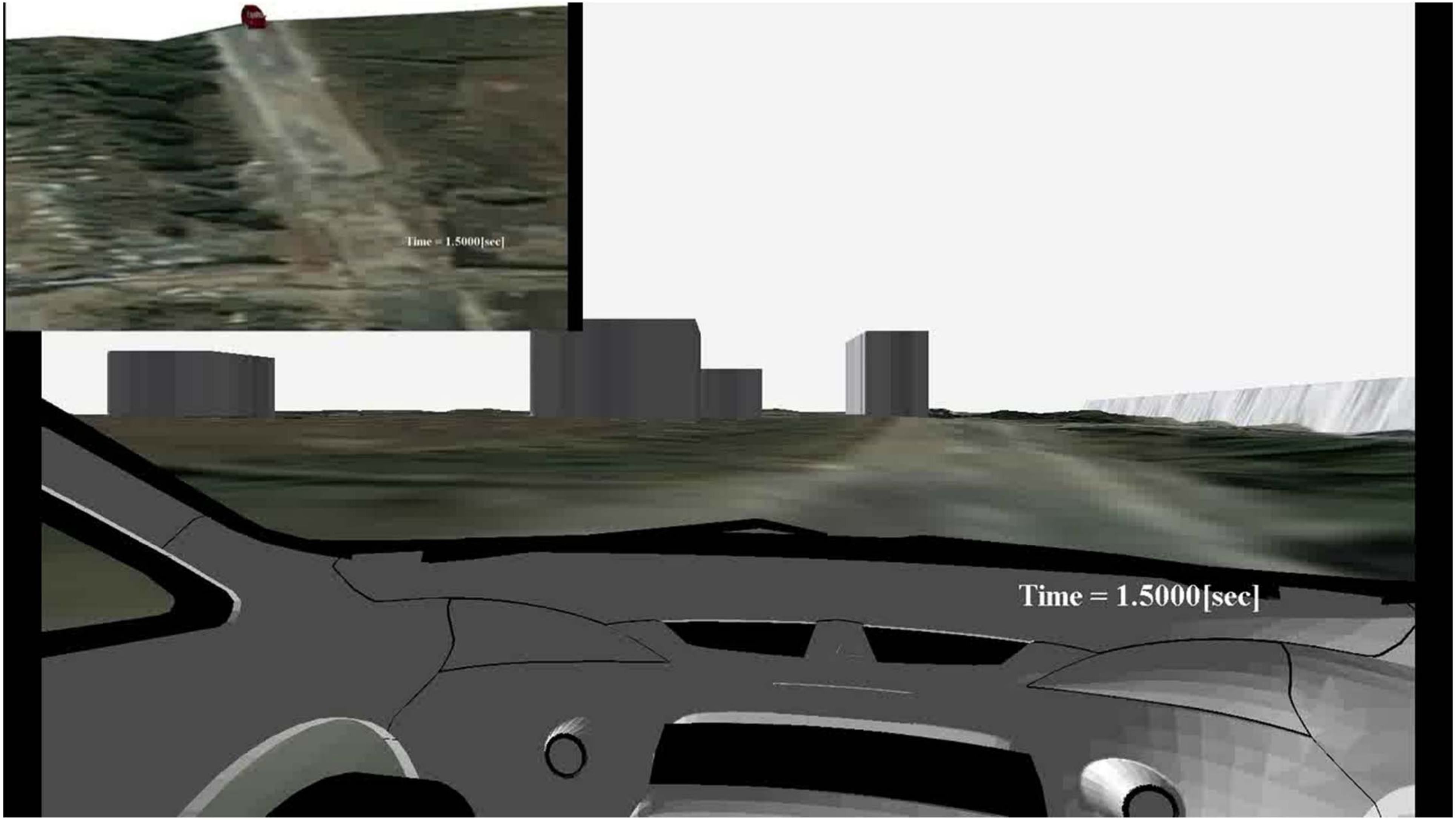
The time to start of the information car : 36 minutes

Tsunami evacuation simulation



High strength building is effective in delaying the inundation time for tsunami

View from a refugee in car



Coupled Problem 2015

Modeling and Simulation of Tsunami Using Virtual Reality Technology

Kazuo Kashiyama, Guoming Ling, Taiki Fumuro, Takeshi Kawabe (Chuo University)
Junichi Matsumoto (AIST)、Masaaki Sakuraba (Nippon Koei Co. Ltd.)
Shinsuke Takase, Kenjiro Terada (Tohoku University)

- Introduction
- VR Technology
- Modeling and Simulation of Tsunami
- Visualization and Auralization using VR technology
- Conclusions

Large scale visualization system

HMD
Head Mounted Display

(Wikipedia)

Merit: space-saving

Demerit: difficult for
bodily sensation with full scale

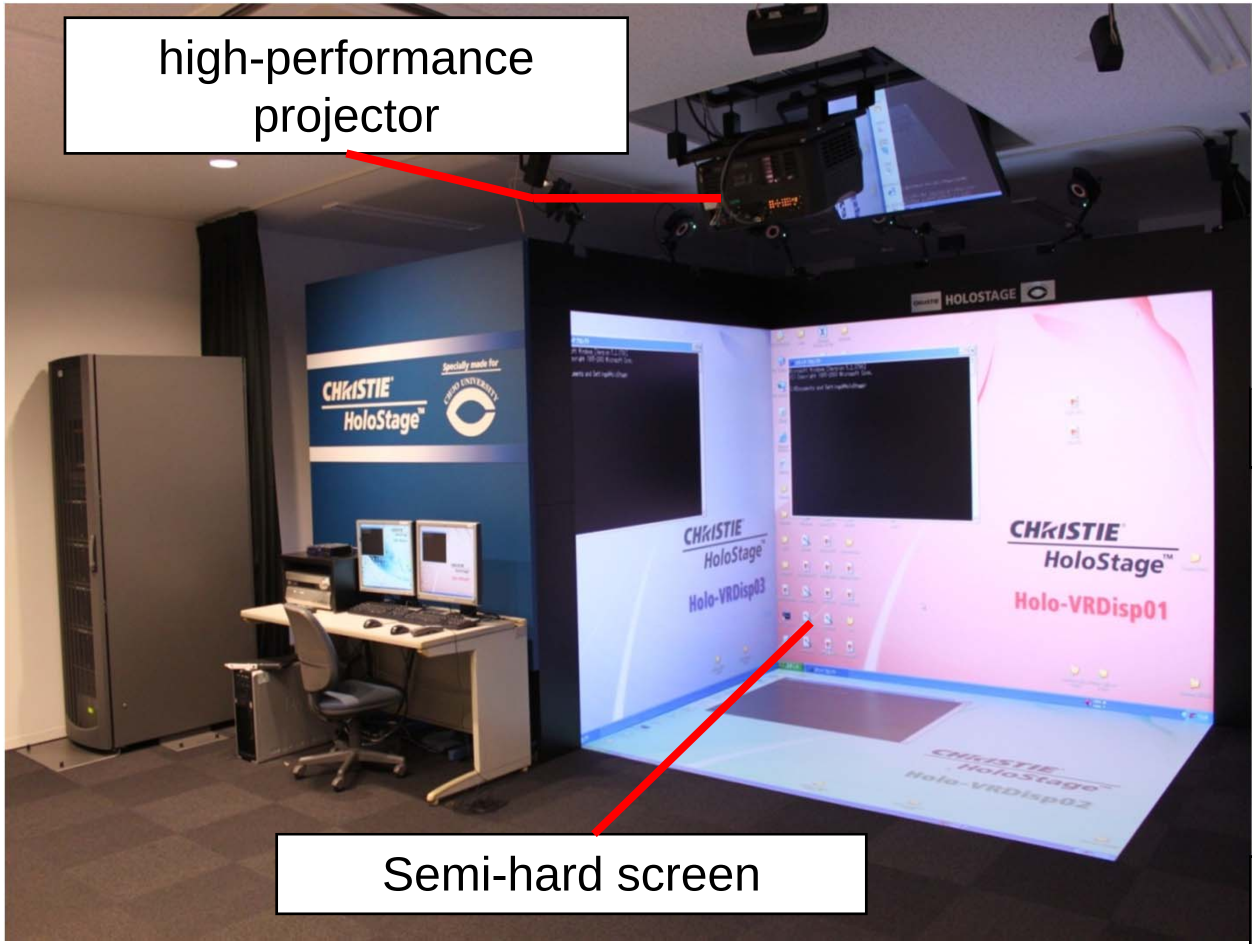
CAVE
CAVE Automatic Virtual Environment

CAVE（Univ. Illinoi，1993; Wikipedia）

Merit:
- easy for bodily sensation with full scale
- easy to share the common VR space with multiple people

Demerit: wide-space

CAVE System (HoloStage)

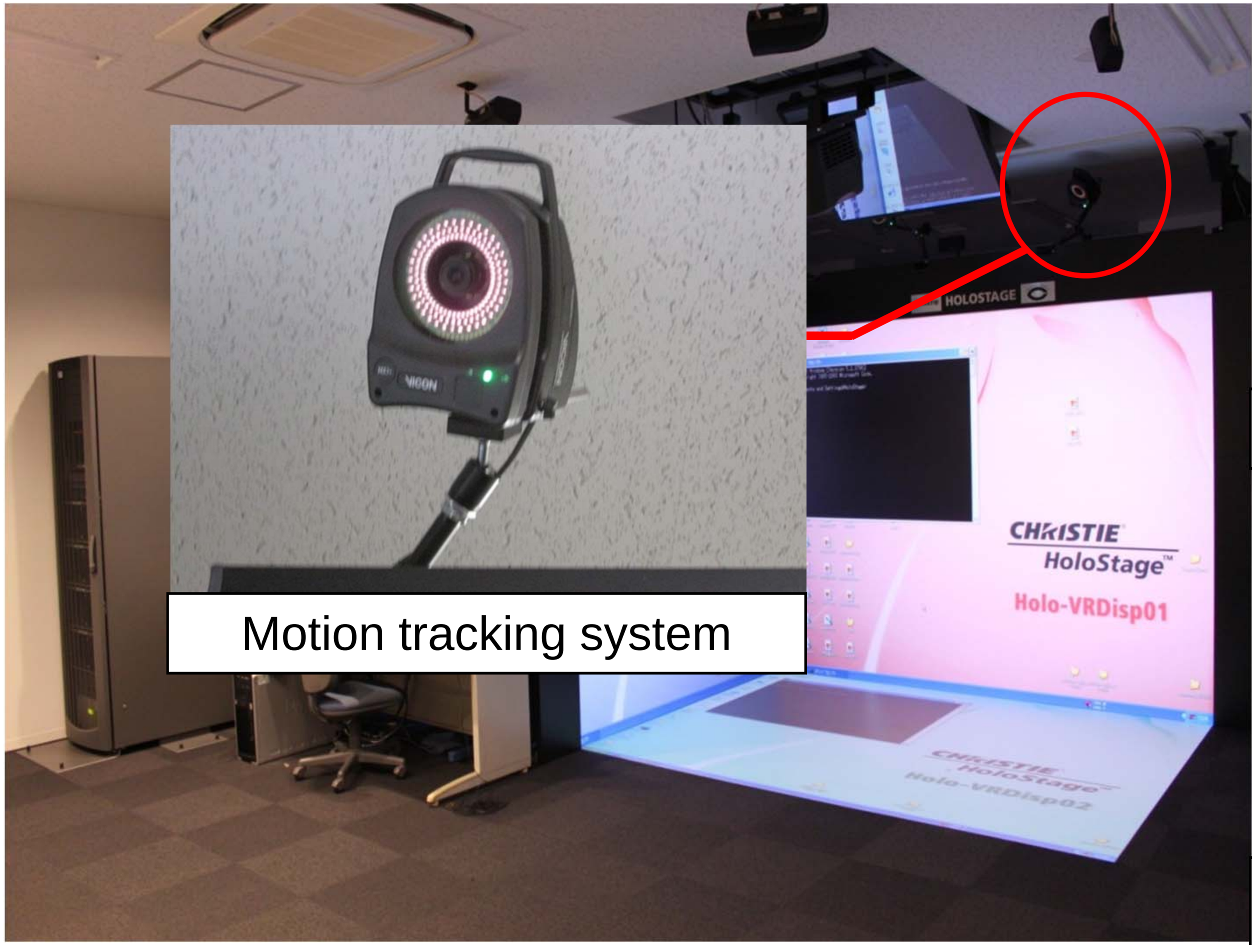


Controller

liquid crystal shutter glasses

Since 2007 September

CAVE System (HoloStage)



Motion tracking system

Controller

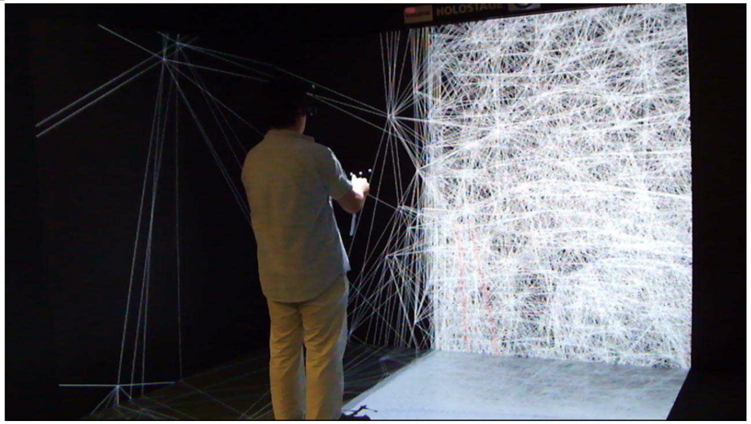
liquid crystal shutter glasses

Since 2007 September

CAVE System (HoloStage)

Application of VR Technique

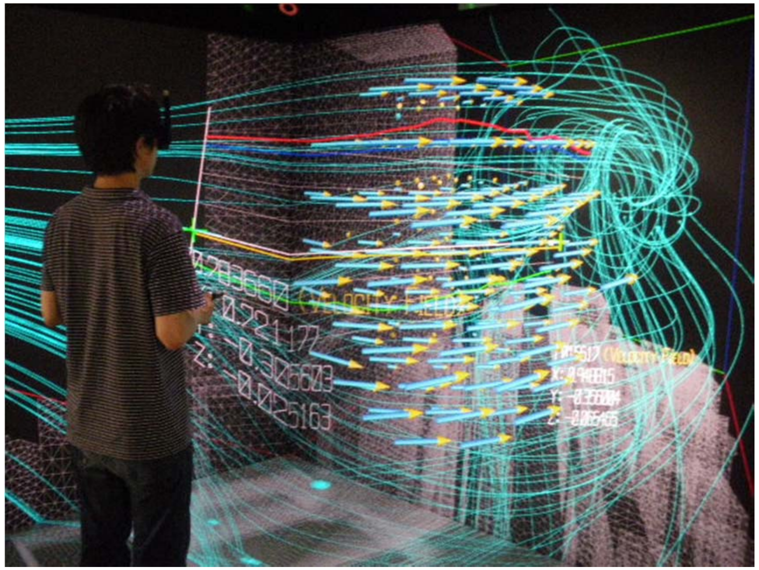
Pre-Process（Modeling）



・Quality of shape model and mesh
・Modification of mesh idealization

Main-Process（Simulation）

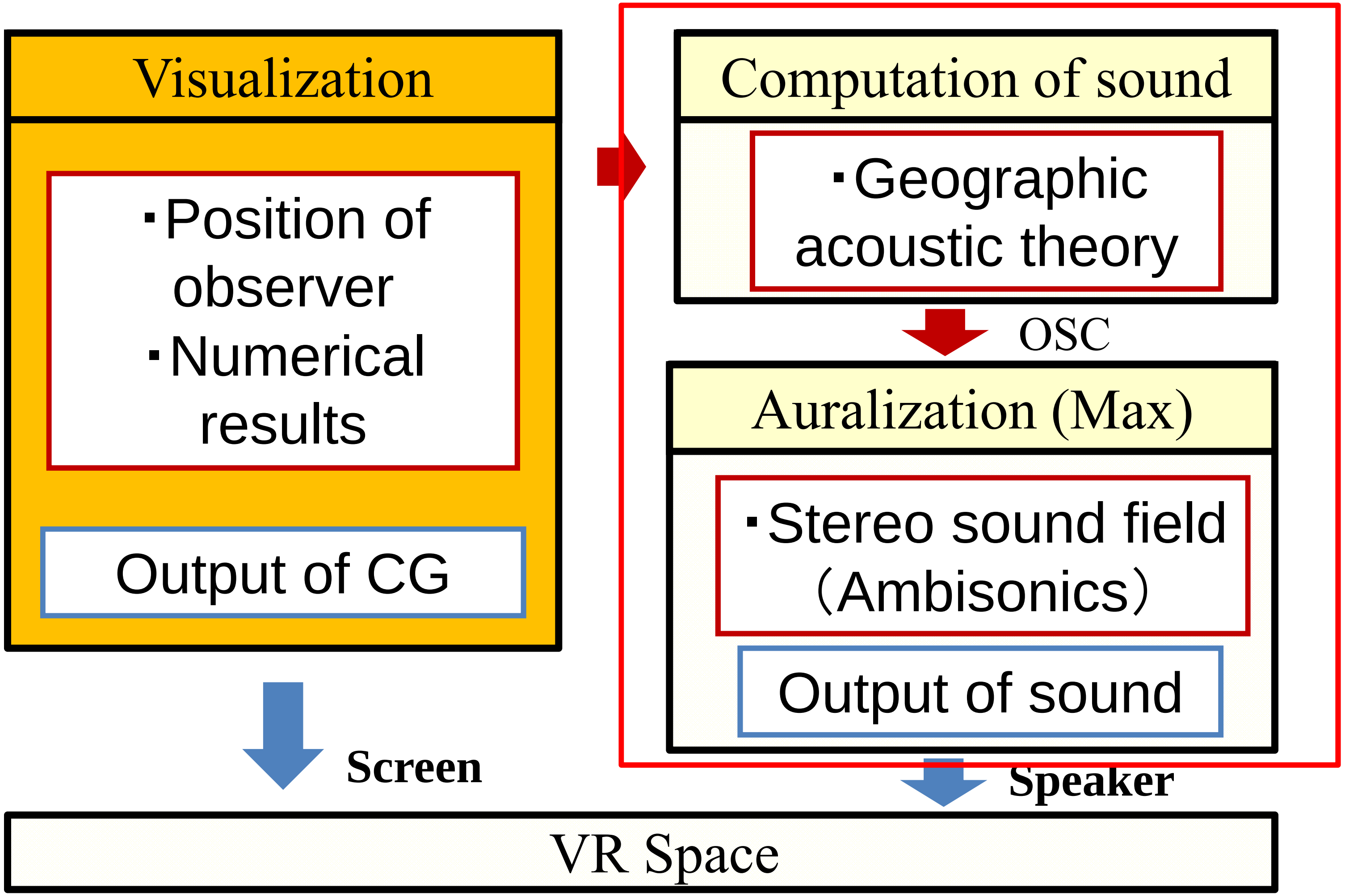
Post-Process（Visualization）



・Understanding for details of three dimensional phenomena

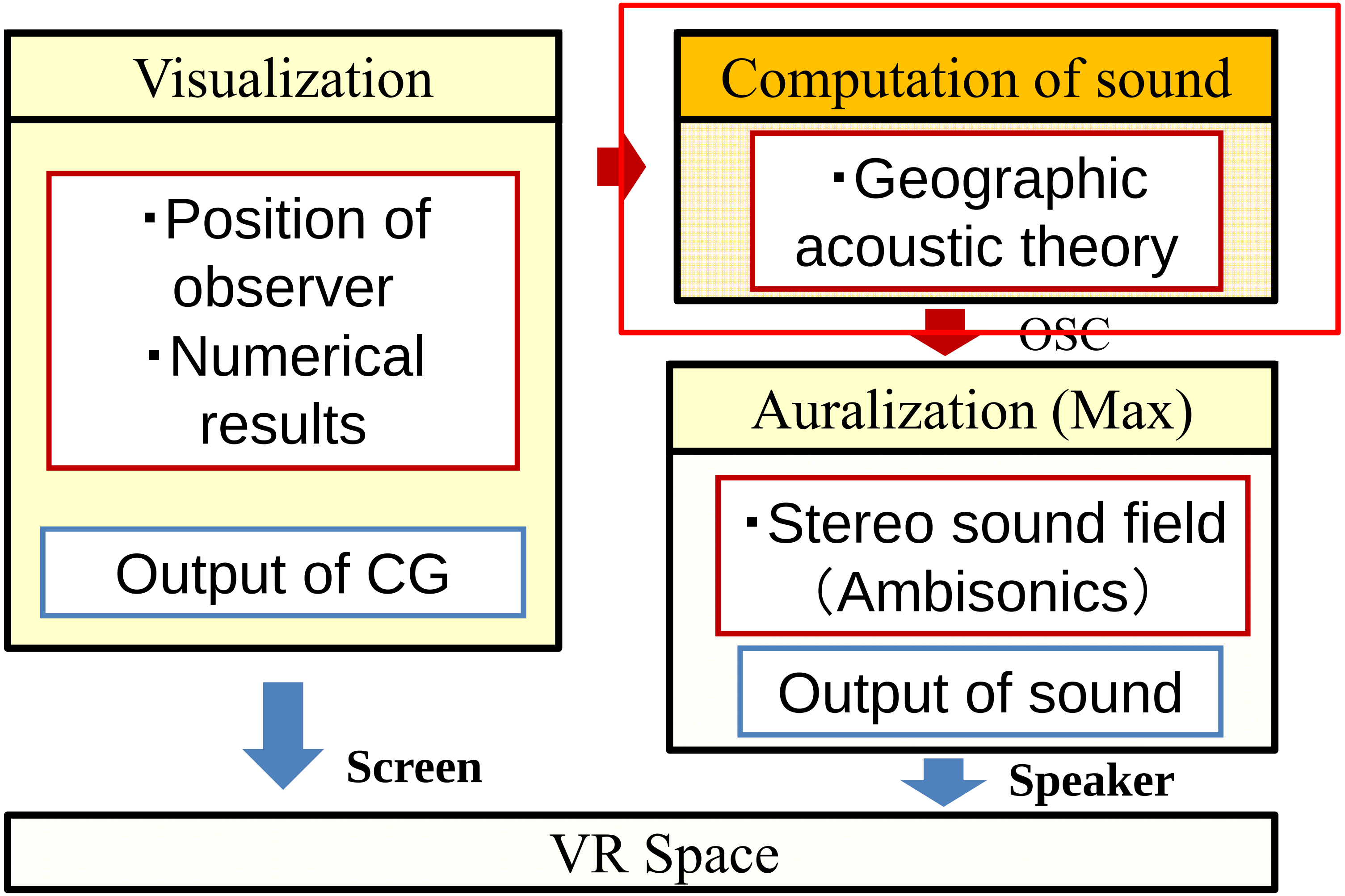
Visualization and Auralization

The system consists of three parts; visualization, computation of sound pressure level and auralization parts.



Visualization and Auralization

The system consists of three parts; visualization, computation of sound pressure level and auralization parts.



Visualization and Auralization

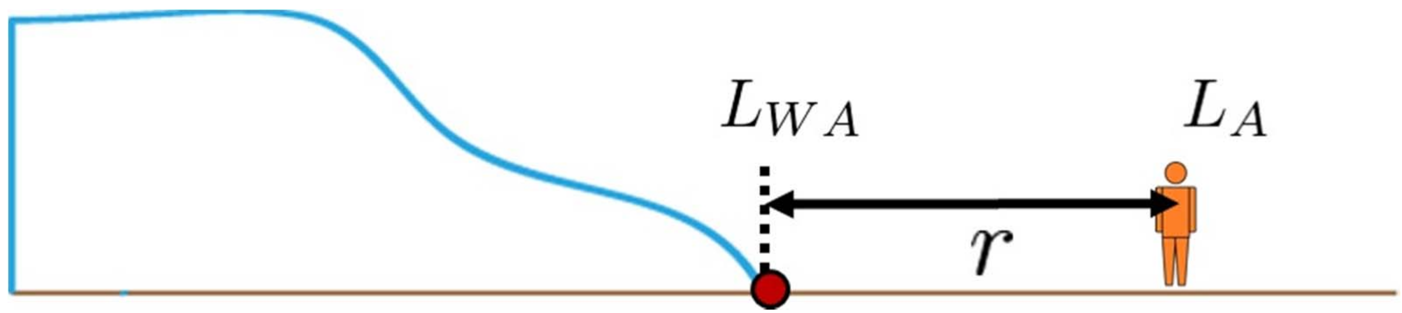
Geometric acoustic theory

$$L_A = L_{WA} - 8 - 20\log_{10} r$$

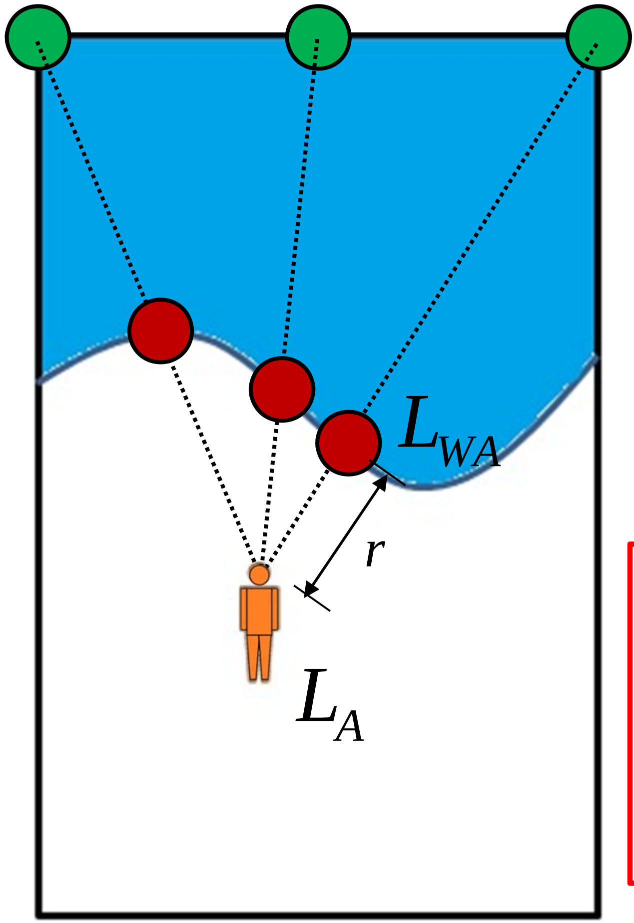
L_A : The Sound pressure level of the observer's position

L_{WA} : The Sound power level of tsunami

r : The distance in a straight line between the observer and the sound source



Computation of sound pressure level



Geographic acoustic theory

$$L_A = L_{WA} - 8 - 20\log_{10} r$$

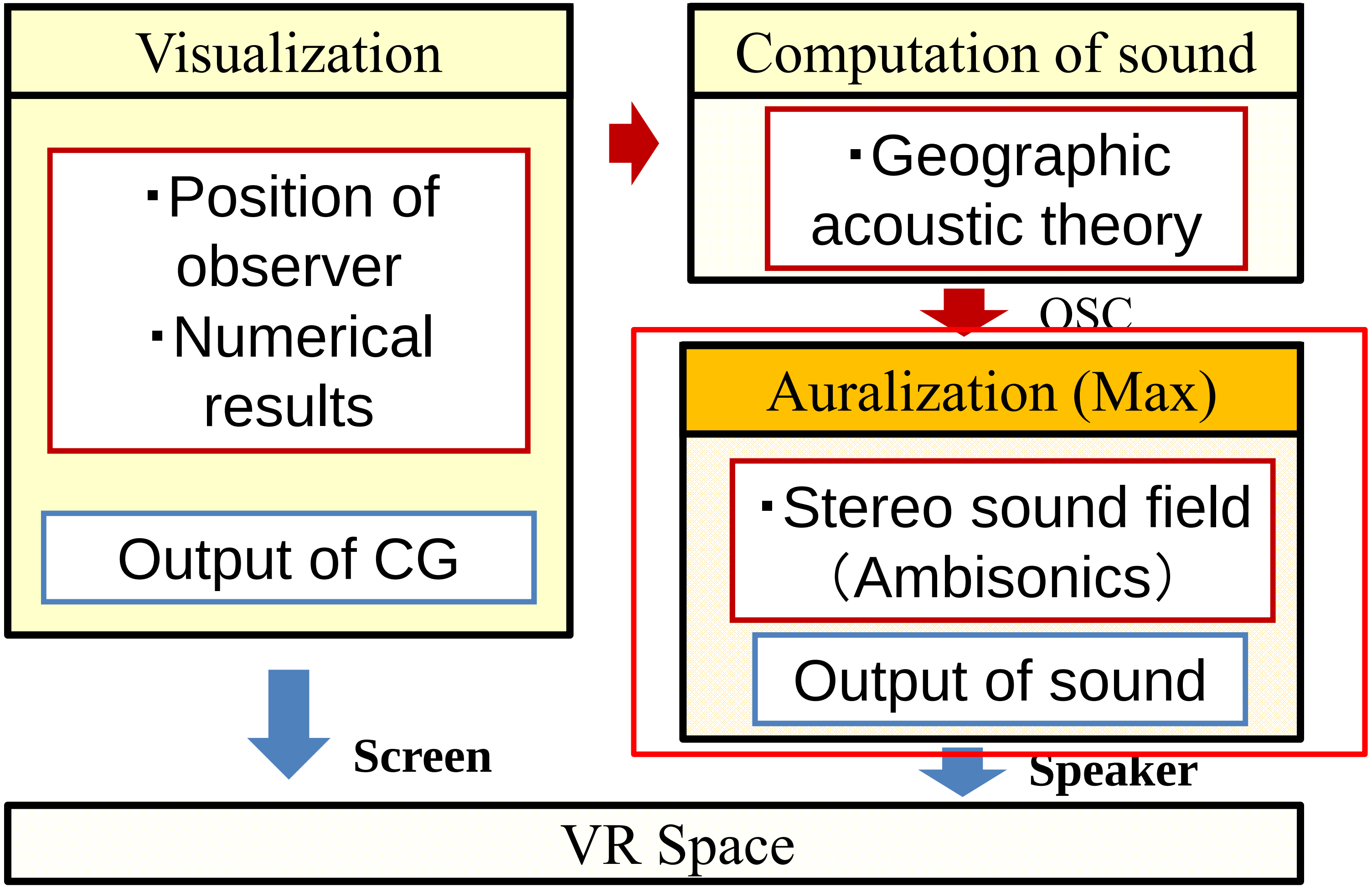
↑
assume

$$L_A = 10\log \sum_{L_{A,i}}^{i_{max}} 10^{\frac{L_{A,i}}{10}}$$

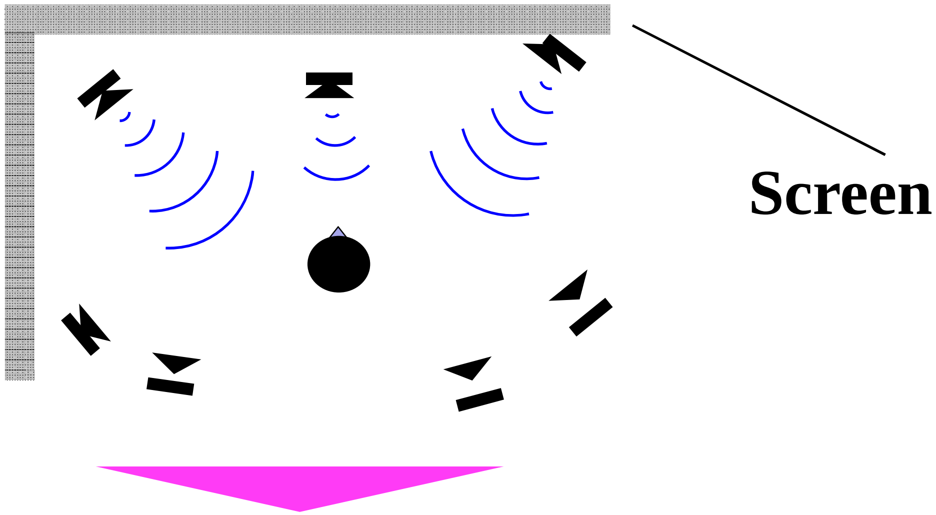
● **Position of sound source**

Visualization and Auralization

The system consists of three parts; visualization, computation of sound pressure level and auralization parts.



Stereoscopic sound system

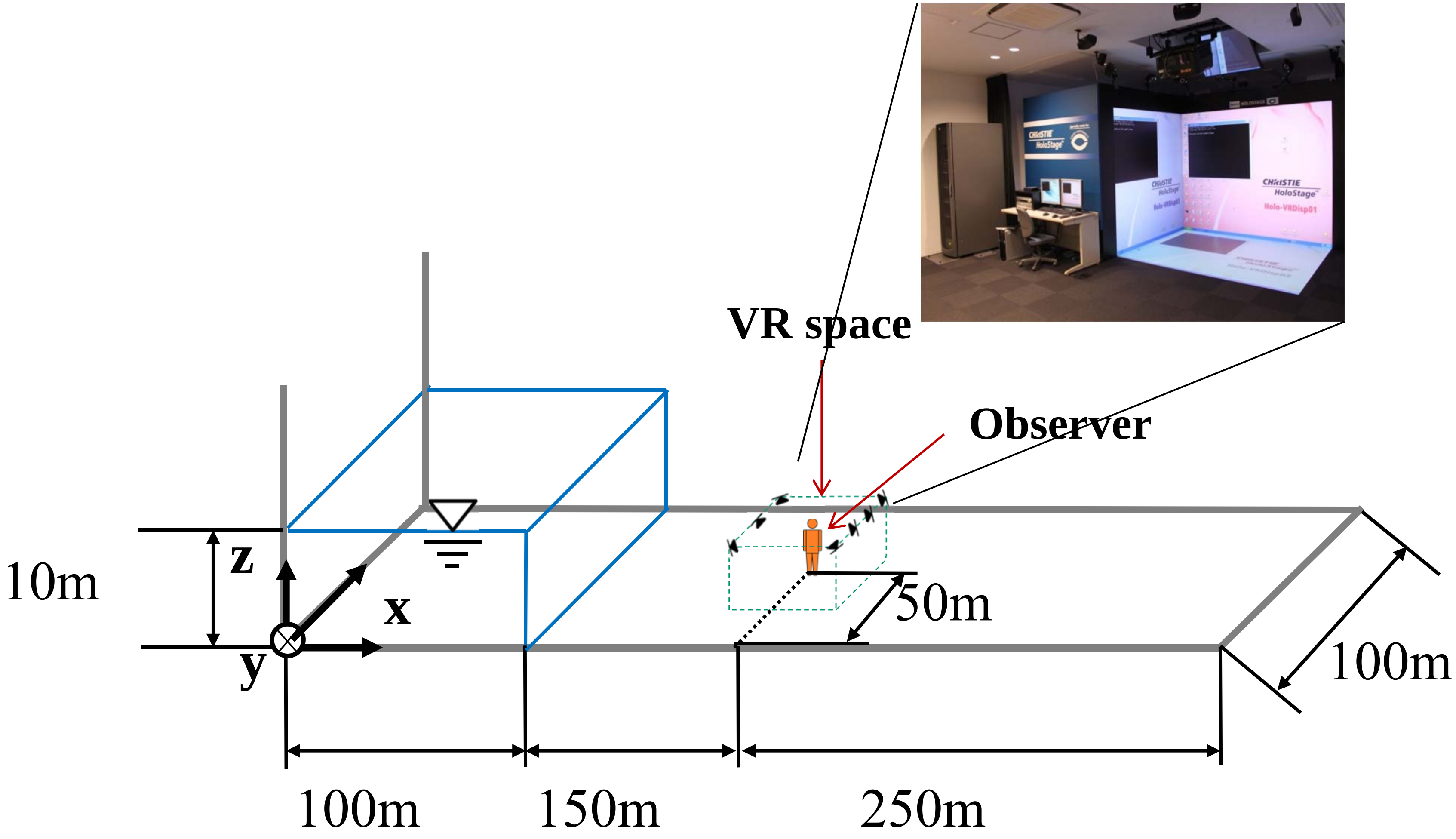


Ambisonics

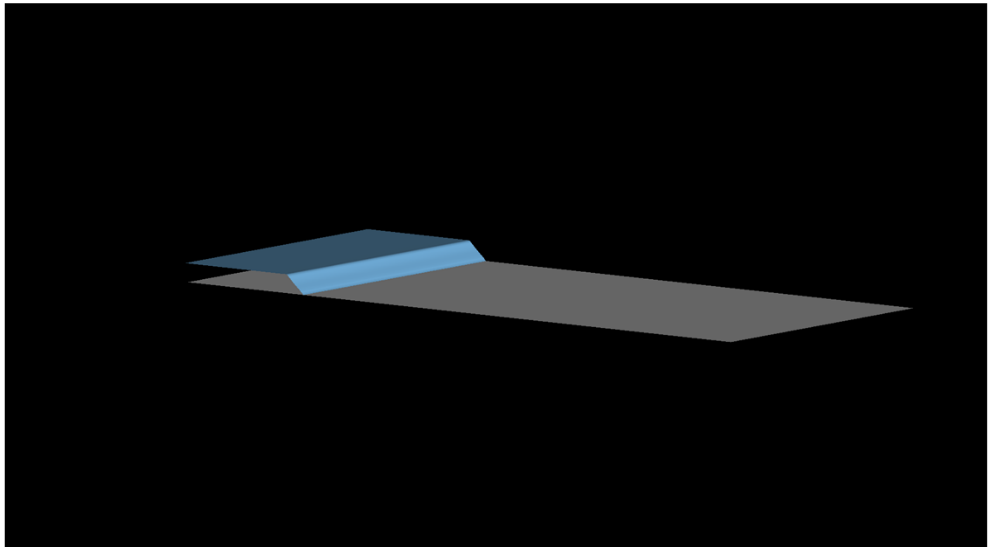
Ambisonics is based on the spherical surface function expansion, using computational results and sound source data.

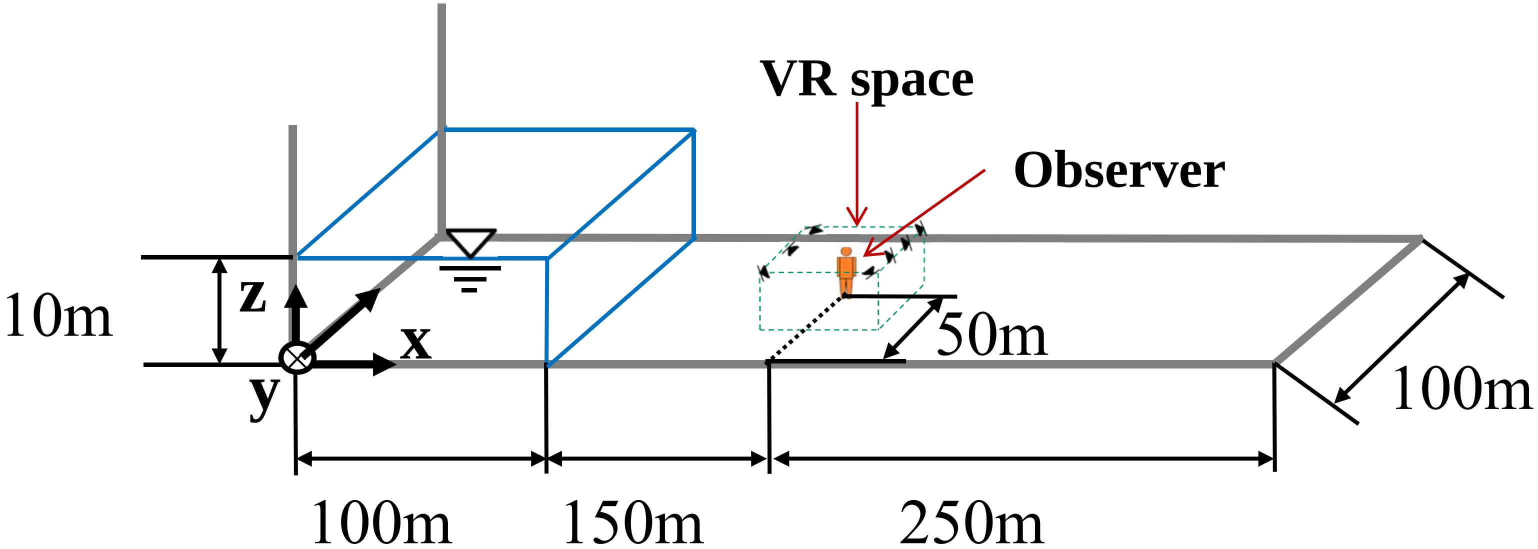
Ward, D.B. and Abhayapala, T.D.: Reproduction of a plane-wave sound field using an array of loudspeakers, Speech and Audio Processing, IEEE Transactions on, vol.9 pp.697–707, 2001.

Test Example

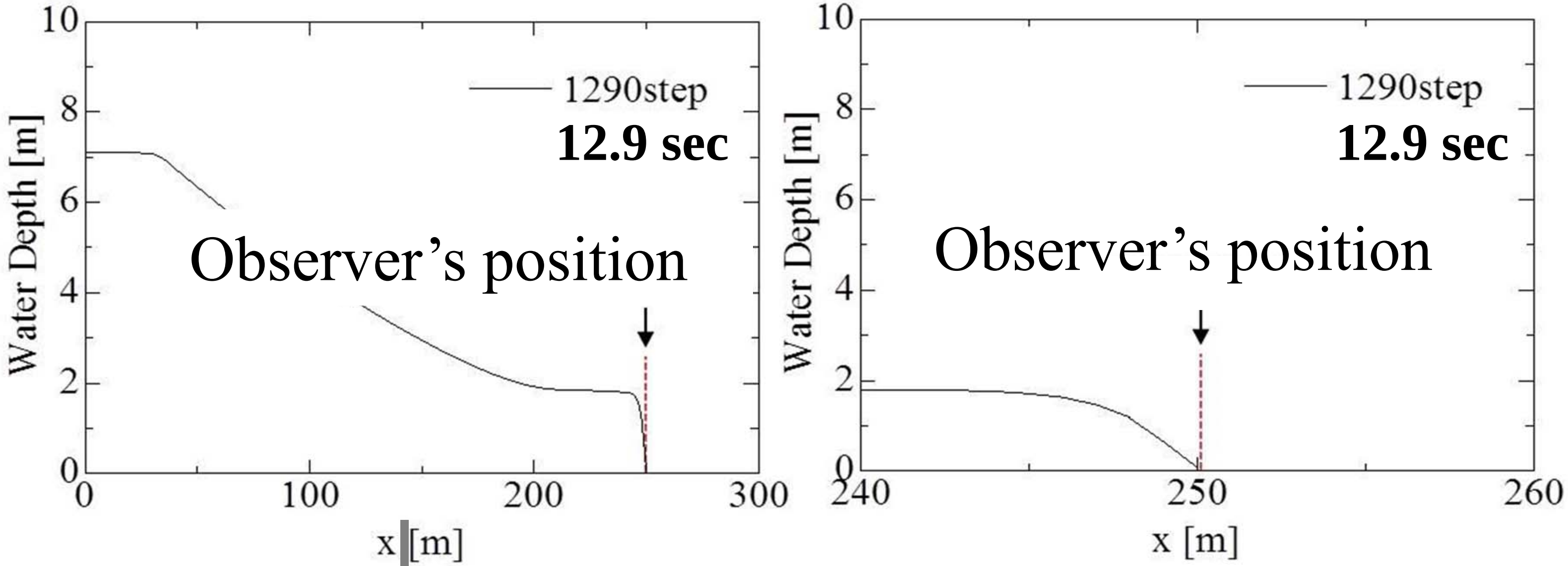


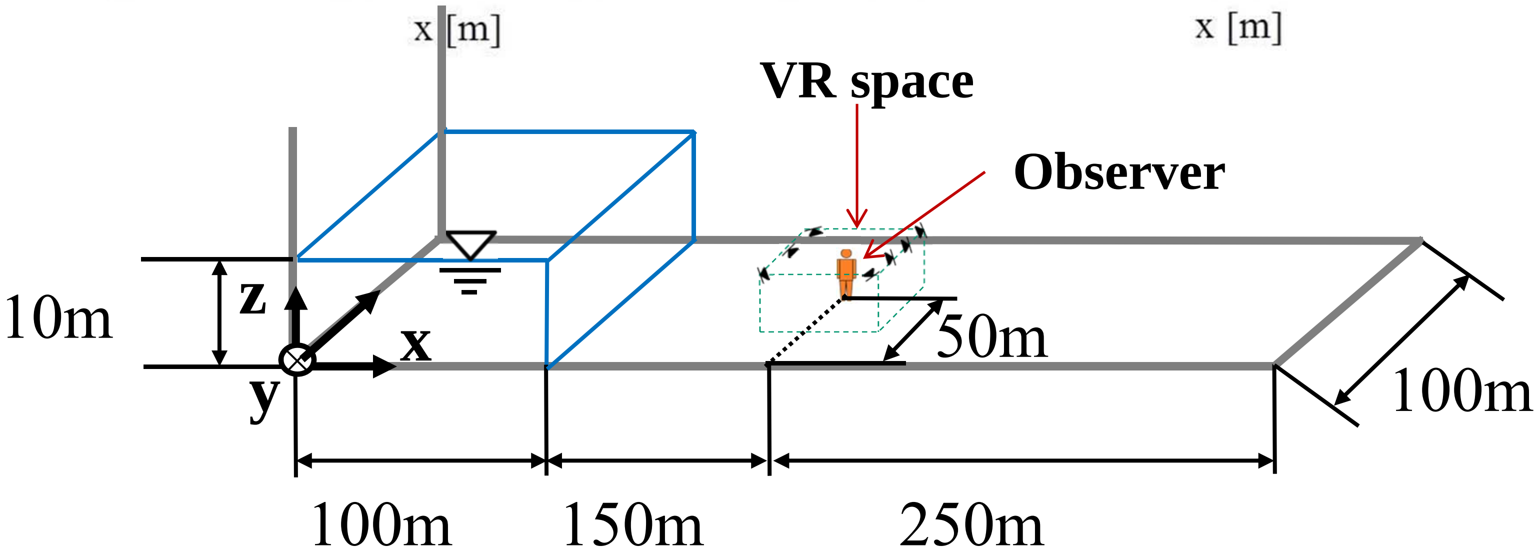
Test Example



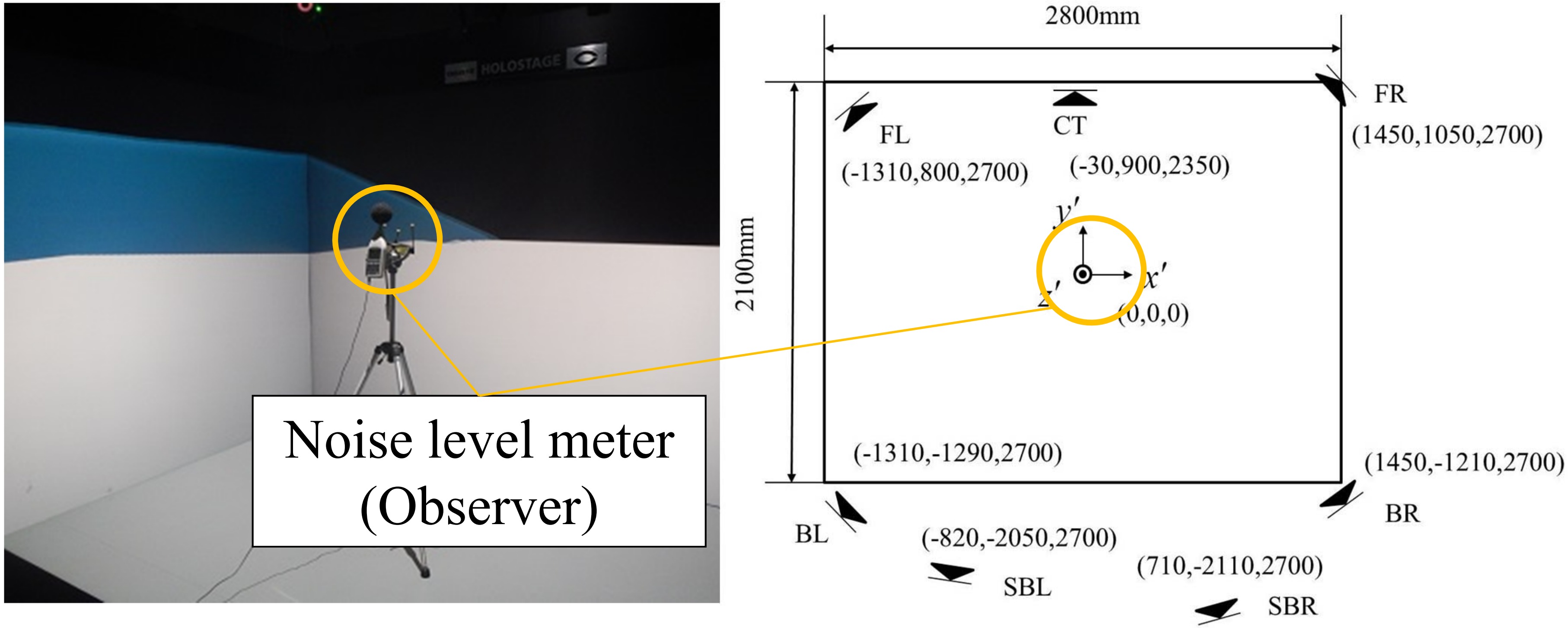


Verification of stereoscopic sound system

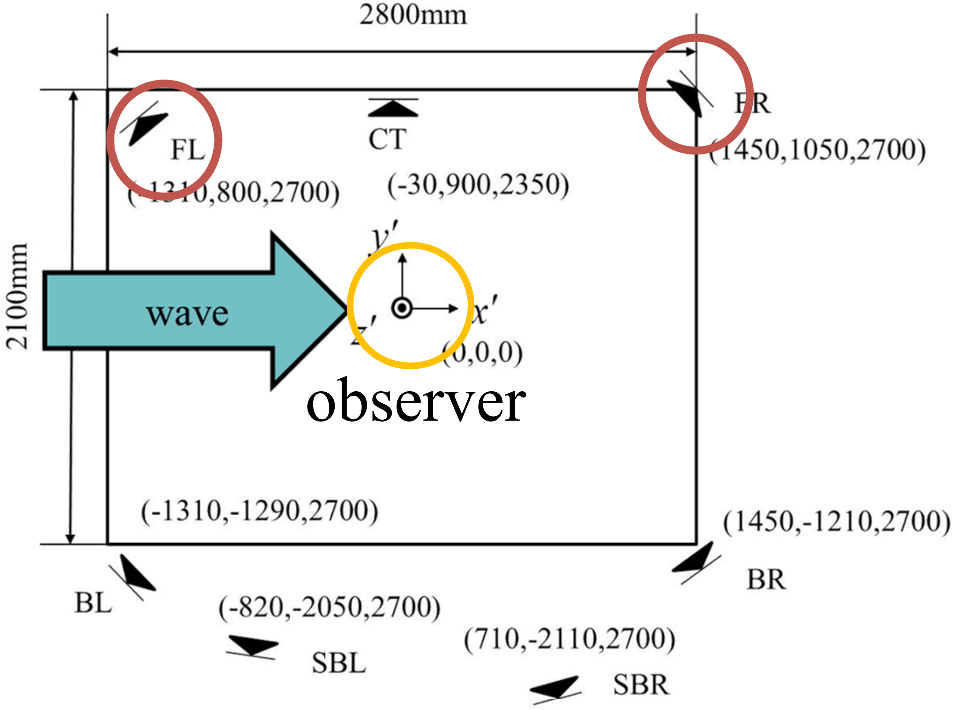


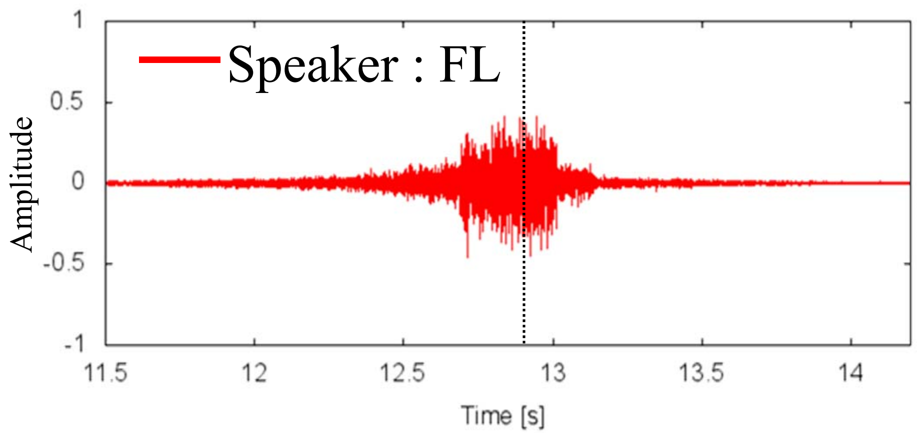


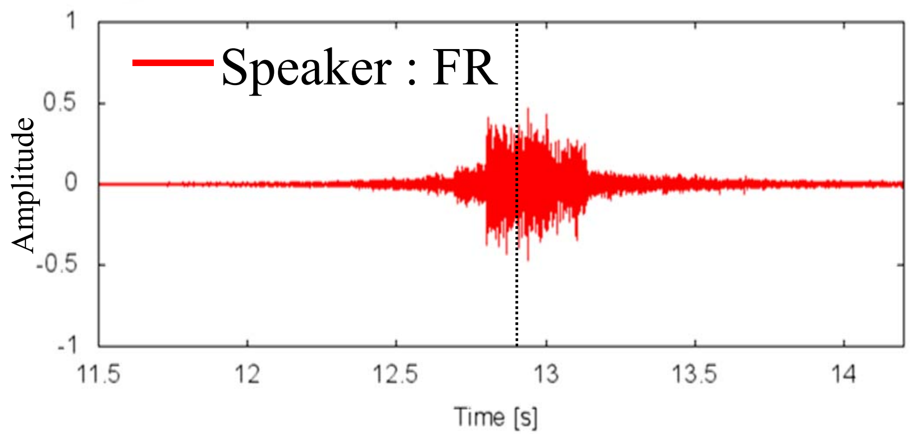
Verification of stereoscopic sound system



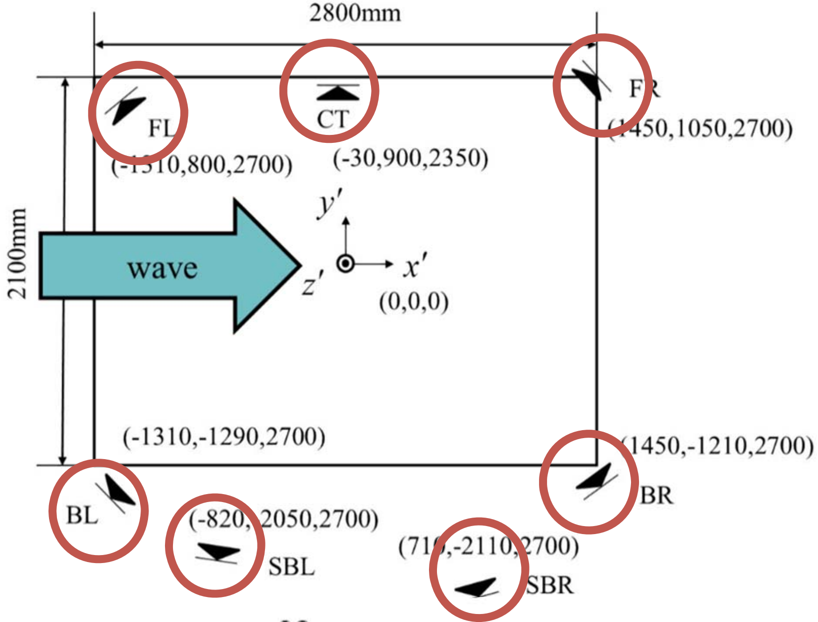
Comparison of the sound signals from speakers

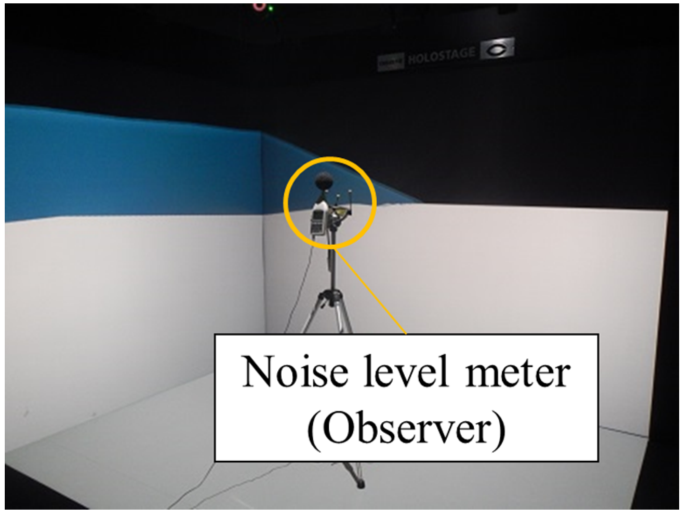


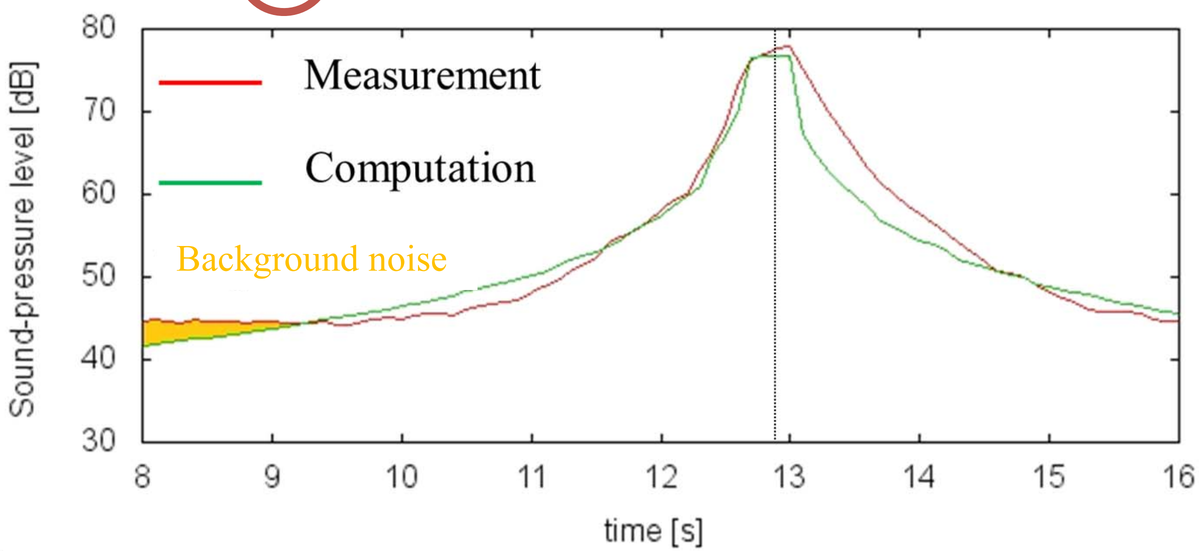




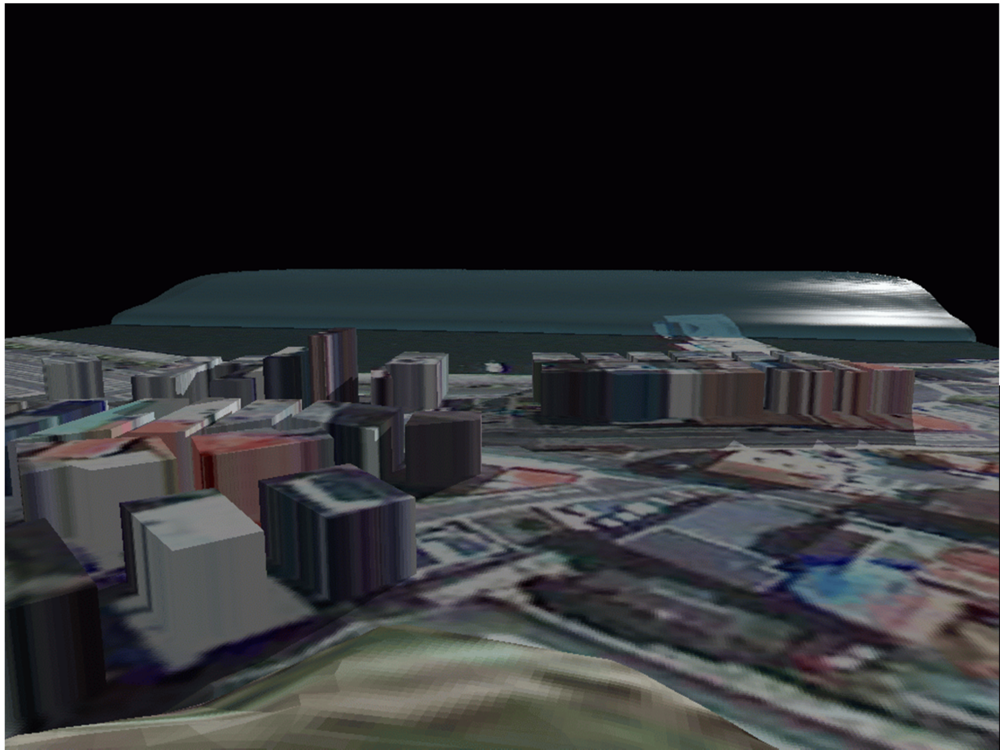
Comparison of the measured and the computed results



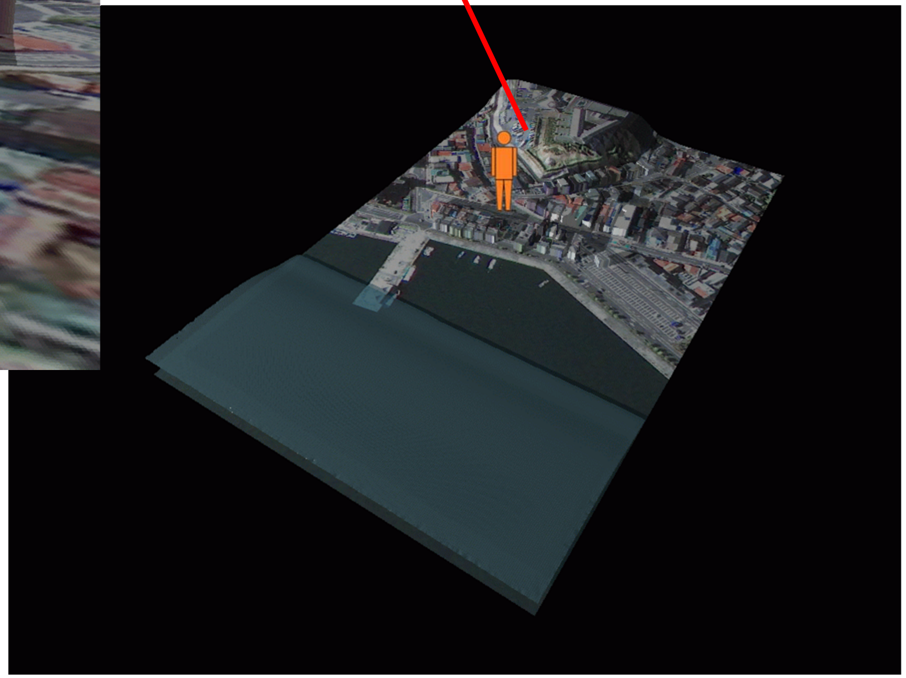




Application example

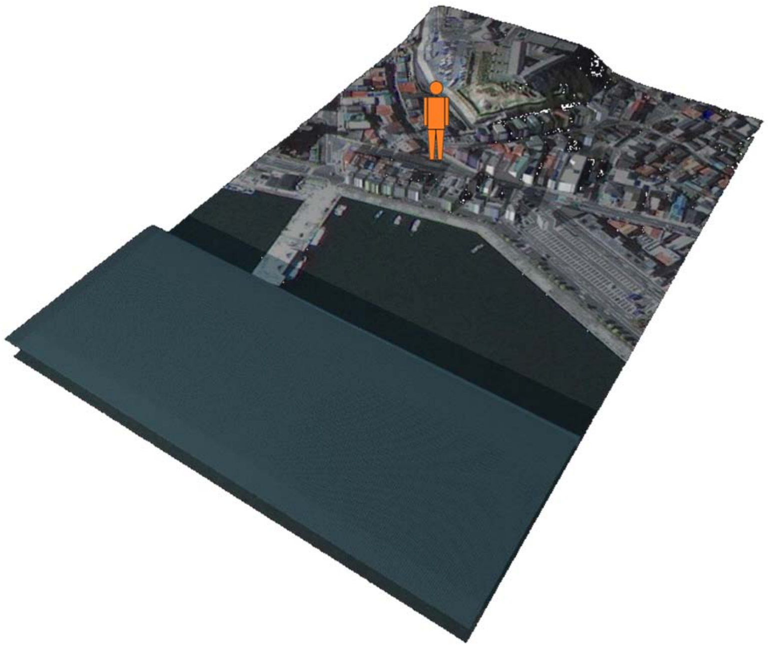


View from this point



Applicatioan example

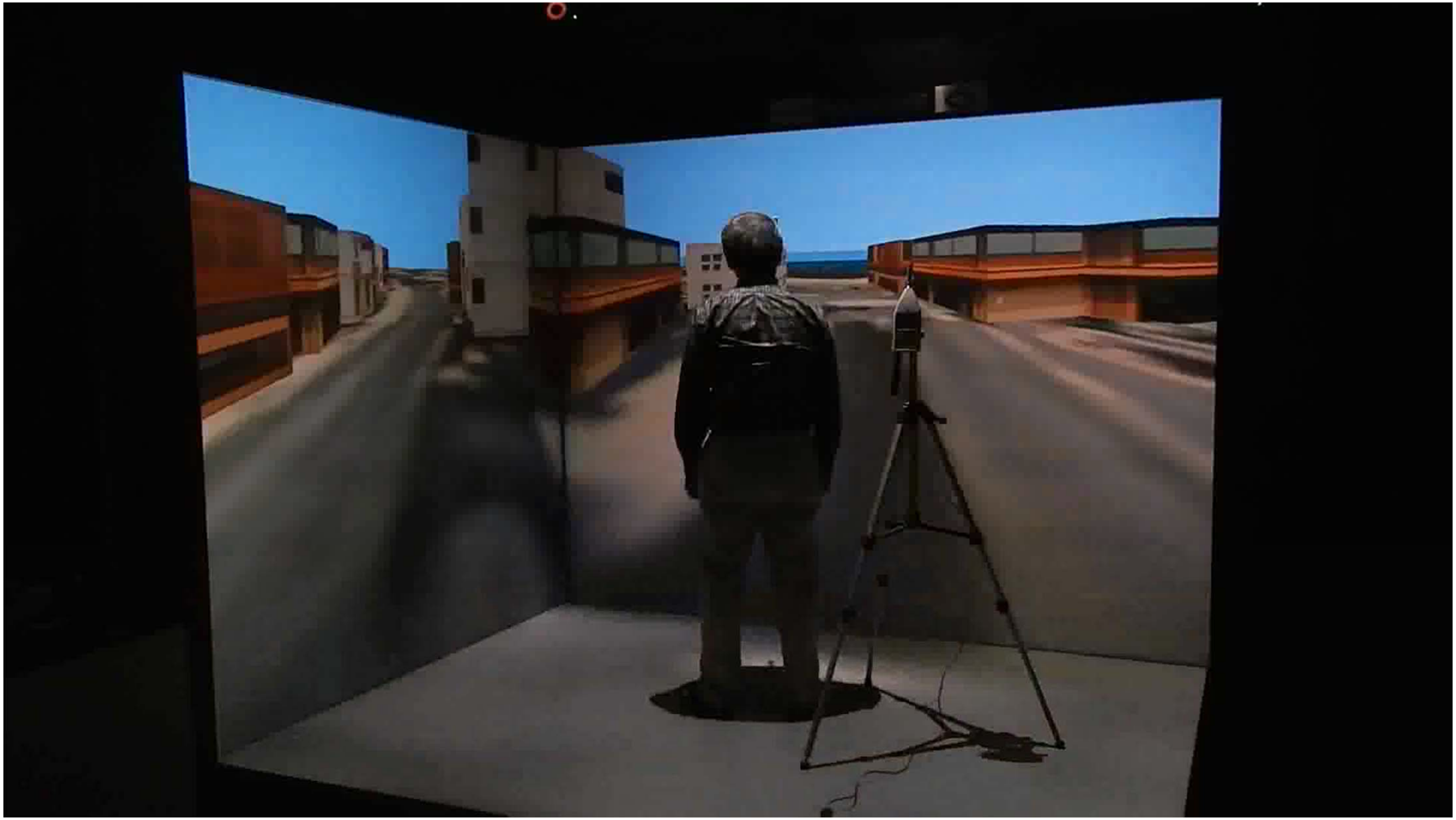
User's position



The position of the user

The CG image from the refugee's eye

Application example



Conclusions

Modelimg, simulation and visualization methods for Tsunami has been presented.

⇒ Modeling and simulation of Tsunami
    2D/3D coupling simulation
    FSI simulation
    Evacuation simulation
⇒ Visualization and auralization using VR/AR technology

The present system is useful for planning, designing and educational tool for disaster prevention for Tsunami.

The application of VR technology is useful to make the overall computational tool set a high-quality simulation environment, especially for safety problems.

“A natural disaster strikes when people lose their memory of the previous one.”

Torahiko Terada (1878-1935)

"Thank you very much for your attention!"