ICCE 2018

36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018

Baltimore, Maryland | July 30 – August 3, 2018

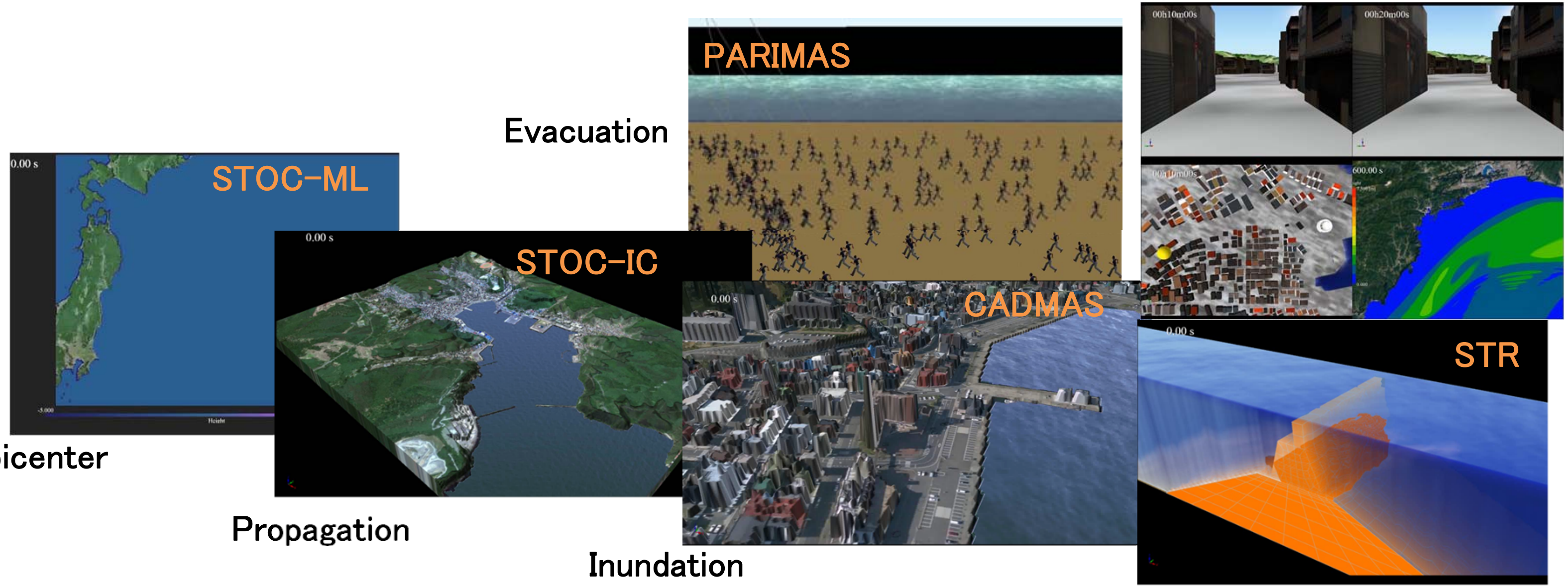
The State of the Art and Science of Coastal Engineering

DEVELOPMENT OF MULTISCALE MULTIPHYSICS INTEGRATED SIMULATOR FOR TSUNAMI RUNUP CALCULATION COUPLED WITH STRUCTURE ANALYSIS

Taro Arikawa[1], Katsumi Seki[1], Yu Chida[2], Tomohiro Takagawa[2], Kenichiro Shimosako[2]
[1]Chuo University, Japan
[2]Port and Airport Research Institute, Japan




Total system of Multiscale Multiphysics Integrated simulator



STOC-ML ⟷ STOC-IC ⟷ CADMAS ⟷ CADMAS-2F ⟷ STR

STOC-ML: Nonlinear Long wave equations

STOC-IC: Three dimensional NS equations with continuity surface model

CADMAS: Three dimensional NS equations with VOF model

CADMAS-2F: Three dimensional two phase NS equations with VOF model

STR: Structure and geo analysis by FEM or DEM

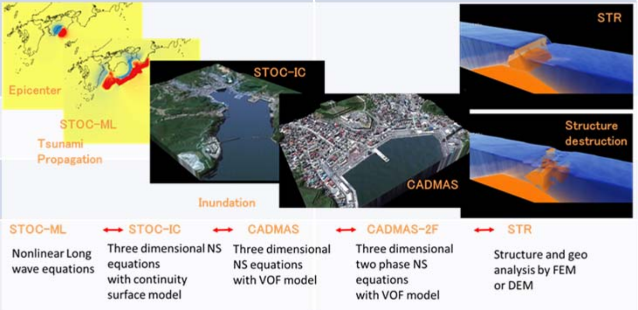
PARIMAS: Multi-agent simulator for evacuation analysis

CHUO UNIVERSITY

ICCE 2018

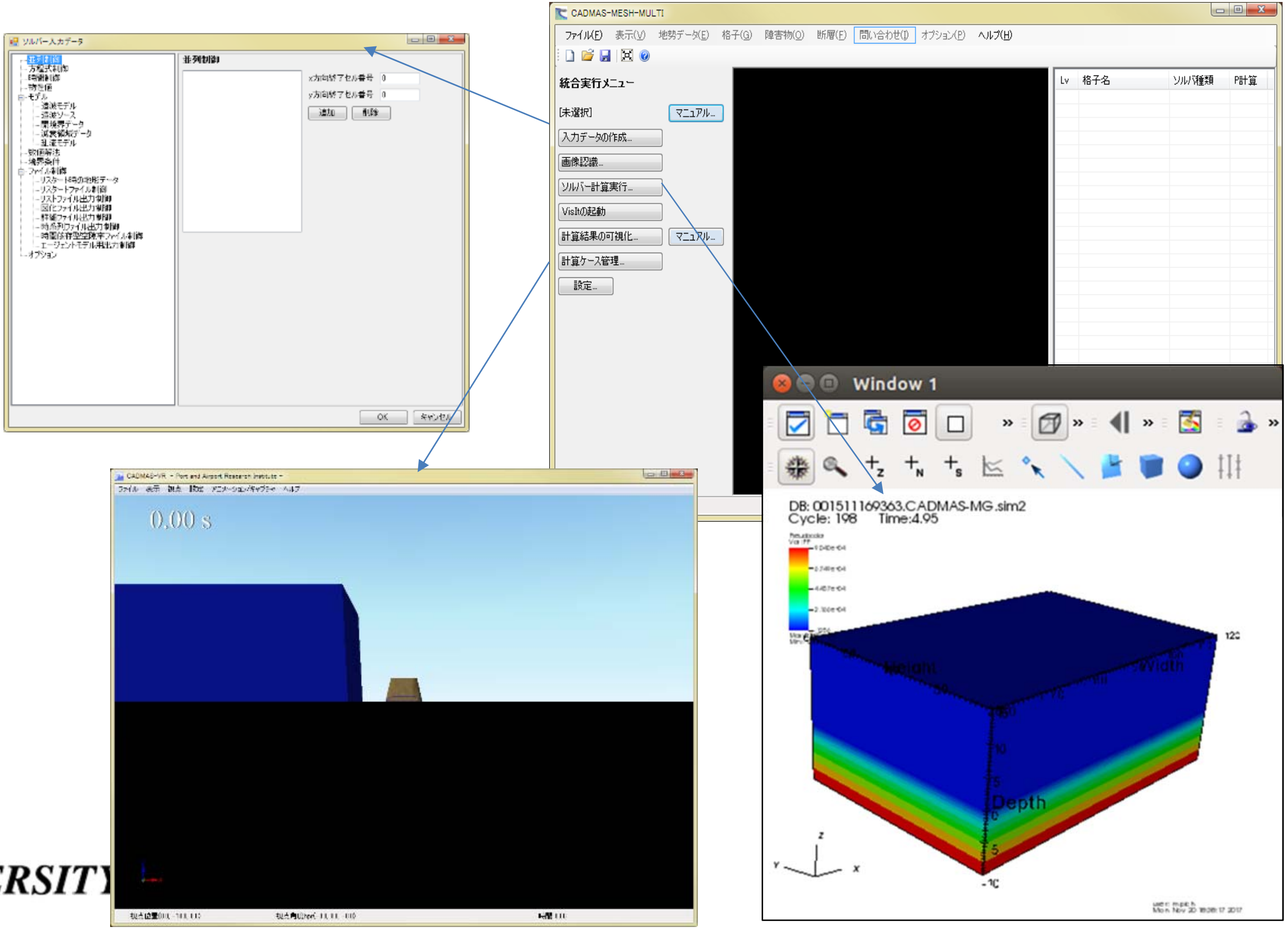
South China Sea Tsunami Workshop
https://sites.google.com/view/nuscoastalgroup/scstw10

History of Development

	STOC-ML	STOC-IC	CADMAS-SURF/3D	CADMAS-2F	STR
1998			Starting of 2 Dimensional Code		
2001			Code Open for 2D		
2003			Starting 3D		
2005	Tomita & Kakinuma, ARI report (STOC)		Arikawa et al., JSCE		
2009					Arikawa et al.,JSCE (Coupling with 3D)
2010			Code Open for 3D		
2011				Arikawa et al.,JSCE (Coupling with DEM)	
2014	Arikawa & Tomita, PARI Report (STOC-CADMAS)				
2017	Arikawa et al.,JSCE (Coupling with Foundation)				
2018	Open all of codes				

How about GUI? For MMI

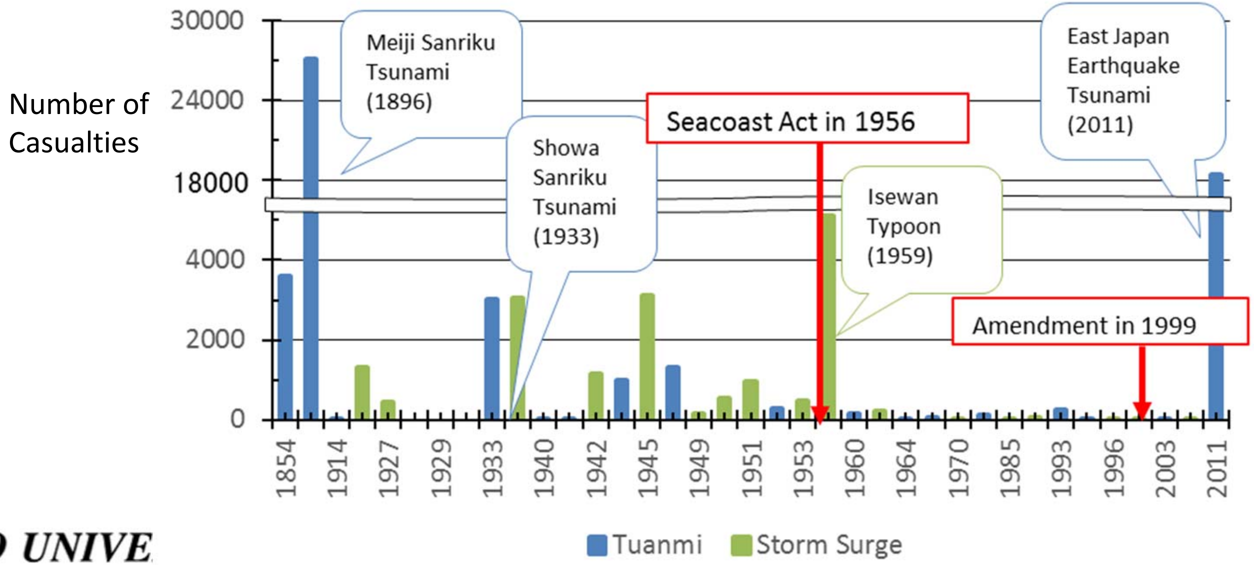
The manual and software is available in English



CHUO UNIVERSITY

History of Coastal Protection Policy in Japan

- 1956; Seacoast Act
  - Prevention by using seawalls / sea dikes (Line Protection system)
- 1999; Seacoast Act was amended
  - The purpose of the amendment was not only prevention but also environmental consideration and utilization in the coastal zone
  - Protection system changed from the line system to the multiple defense system.



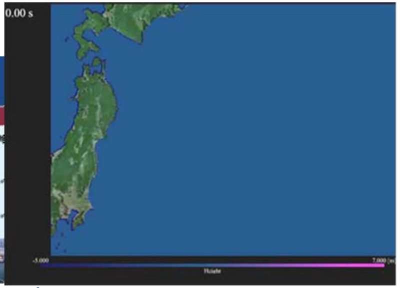
CHUO UNIVE

Motivation of our development

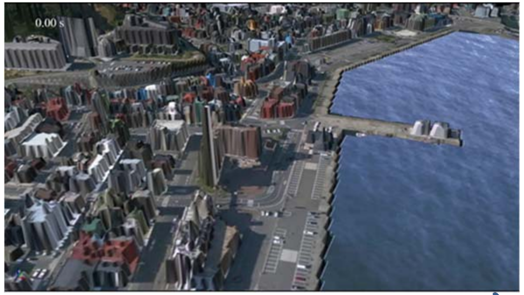
- The Japan government changed the coastal protection policy after 2011.
- Before 2011 the hinterland had been protected by seawall basically, but the government recognized the limitation of protective facilities after 2011.
- So, they declared that inhabitants survive the maximum level of the tsunami not only by protective facilities but also by evacuation.
- It is necessary to develop a tsunami evacuation planning tool based on actual damage as much as possible.

STOC-ML

Nonlinear wave equation



Navier Stokes equations



For considering more concrete measures

Probabilistic approach ⟷ Deterministic approach

CHUO UNIVERSITY

Coastal Protective Facilities

Ref: Regarding how to maintain and manage coastal conservation facilities ,MLIT, Oct, 2015

The way of destruction and easiness of destruction are different

Coastal Dike

Seawall

Parapet wall

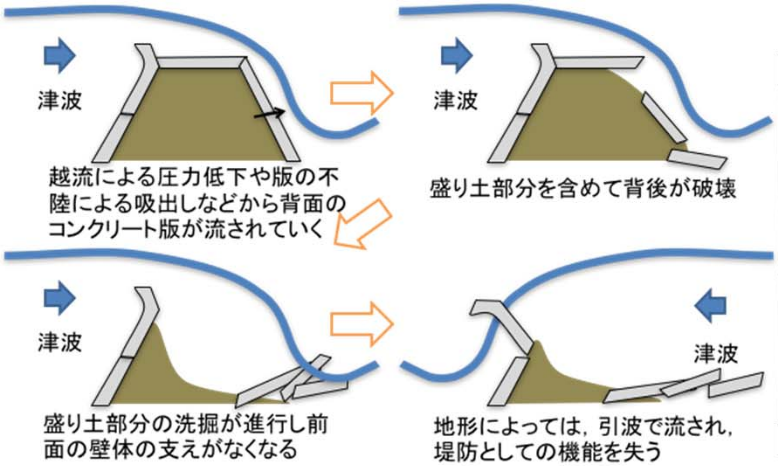
Groins

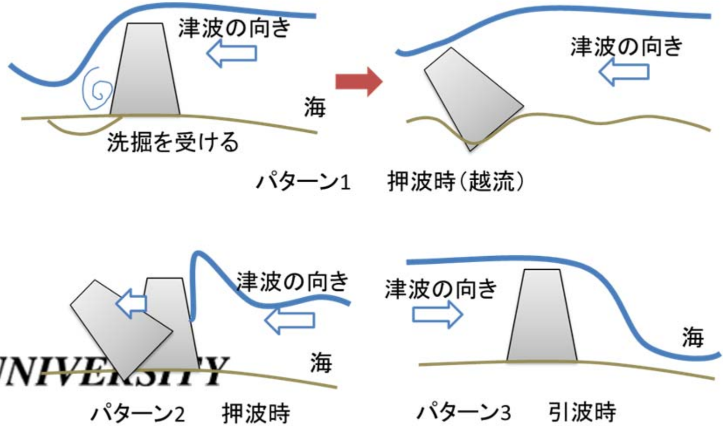
Detached Breakwaters

CHUO UNIVERSITY

ICCE 2018

Embankment (Slope Revetment / Parapet wall)





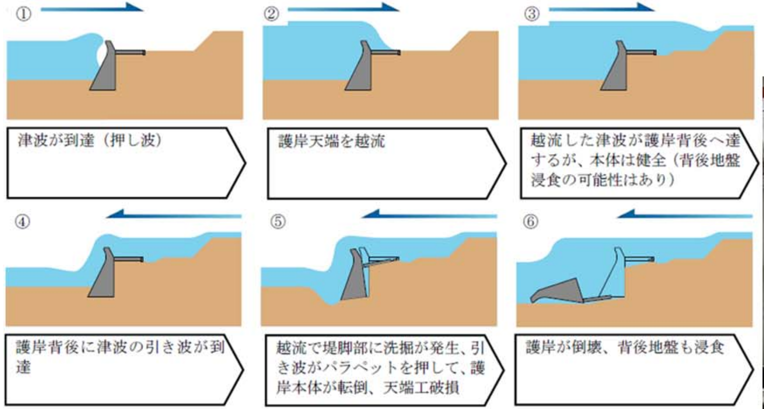
Slope Revetment

Parapet wall

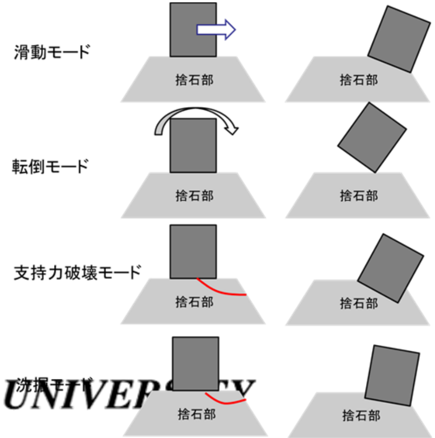
CHUO UNIVERSITY

ICCE 2018

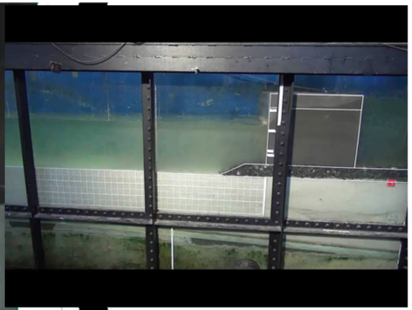
Sea Wall / Breakwater



Seawall



Breakwater

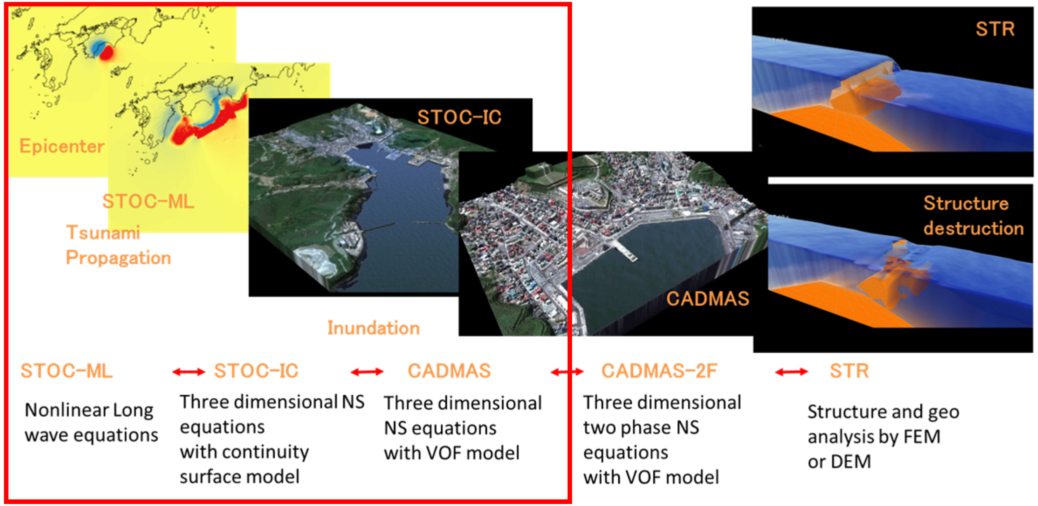


CHUO UNIVERSITY

ICCE 2018

Multiscale analysis

Coupled with wave propagation simulation



The STOC-CADMAS system

(Arikawa and Tomita, 2016)

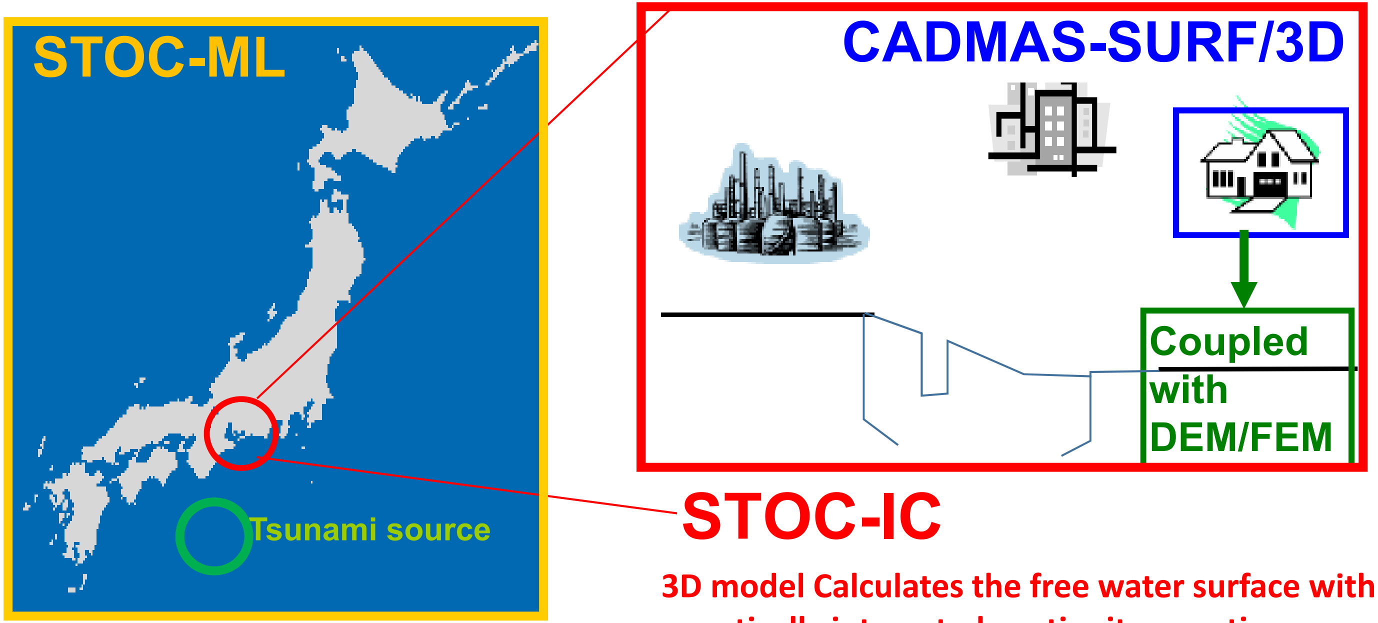
Quasi-3D model (multi-level model)

Assumes hydrostatic pressures at each level

Computation load: light

3D model Estimates the free water surface with the VOF method

Computation load: heavy



3D model Calculates the free water surface with a vertically integrated continuity equation

Computation load: moderate

STOC system (Tomita et. al., 2005)
CADMAS system (Arikawa et. al., 2005)

STOC(Storm surge and Tsunami simulator in Oceans and Coastal areas)

STOC-ML 3-d Multi-Level constant density RANS model with Eddy Viscosity and hydro-static pressure $p=\rho g(\eta - z)$ (Tomita et. al.,2005)

STOC-IC 3-d variable density RANS model with Eddy Viscosity closure and Integrated Continuity eq. for free-surface tracking

Equation of Motions

$$\gamma_v \frac{\partial u}{\partial t} + \frac{\partial}{\partial x}(\gamma_x uu) + \frac{\partial}{\partial y}(\gamma_y vu) + \frac{\partial}{\partial z}(\gamma_z wu) =$$
$$fv - \gamma_v \frac{1}{\rho_0}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left(\gamma_x \nu_e 2\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left\{\gamma_y \nu_e\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\}$$

$$\gamma_v \frac{\partial v}{\partial t} + \frac{\partial}{\partial x}(\gamma_x uv) + \frac{\partial}{\partial y}(\gamma_y vv) + \frac{\partial}{\partial z}(\gamma_z wv) =$$
$$-fu - \gamma_v \frac{1}{\rho_0}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right\} + \frac{\partial}{\partial y}\left(\gamma_y \nu_e 2\frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e\left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)\right\}$$

$$\gamma_v \frac{\partial w}{\partial t} + \frac{\partial}{\partial x}(\gamma_x uw) + \frac{\partial}{\partial y}(\gamma_y vw) + \frac{\partial}{\partial z}(\gamma_z ww) =$$
$$-\gamma_v \frac{1}{\rho_0}\frac{\partial p}{\partial z} + \gamma_v \frac{\rho - \rho_0}{\rho_0} g + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)\right\} + \frac{\partial}{\partial y}\left\{\gamma_y \nu_e\left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)\right\} + \frac{\partial}{\partial z}\left(\gamma_z \nu_e 2\frac{\partial w}{\partial z}\right)$$

γ_v : porosity

$\gamma_x \gamma_y \gamma_z$: transmissivity in each direction of "x", "y" and "z"

$$\tau_x = \frac{\rho g n^2 u_b \sqrt{u_b^2 + v_b^2}}{h^{1/3}}$$

Equation of Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Integrate in the z direction

Equation of Free Water Surface

$$\gamma_v \frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\int_{-h}^{\eta} \gamma_x u dz + \frac{\partial}{\partial y}\int_{-h}^{\eta} \gamma_y v dz = 0$$

CADMAS-SURF

(For 3D version, Arikawa et. al.,2005)

(SUper Roller Flume for Computer Aided Design of MAritime Structure)

This numerical code is based on the VOF method, and is applicable to not only wave transformation but also interaction of wave, current, structure and foundation. Namely, this numerical flume is replaceable with the laboratory flume, and applicable to the practical works of maritime structure design against wave action.

Equation of Motions

$$\lambda_v \frac{\partial u}{\partial t} + \frac{\partial \lambda_x uu}{\partial x} + \frac{\partial \lambda_y vu}{\partial y} + \frac{\partial \lambda_z wu}{\partial z} = -\frac{\gamma_v}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e \left(2\frac{\partial u}{\partial x}\right)\right\}$$
$$+ \frac{\partial}{\partial y}\left\{\gamma_y \nu_e \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\} - \gamma_v D_x u - R_x + \gamma_v S_u$$

$$\lambda_v \frac{\partial v}{\partial t} + \frac{\partial \lambda_x uv}{\partial x} + \frac{\partial \lambda_y vv}{\partial y} + \frac{\partial \lambda_z wv}{\partial z} = -\frac{\gamma_v}{\rho}\frac{\partial p}{\partial y} + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\right\}$$
$$+ \frac{\partial}{\partial y}\left\{\gamma_y \nu_e \left(2\frac{\partial v}{\partial y}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)\right\} - \gamma_v D_y v - R_y + \gamma_v S_v$$

$$\lambda_v \frac{\partial w}{\partial t} + \frac{\partial \lambda_x uw}{\partial x} + \frac{\partial \lambda_y vw}{\partial y} + \frac{\partial \lambda_z ww}{\partial z} = -\frac{\gamma_v}{\rho}\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)\right\}$$
$$+ \frac{\partial}{\partial y}\left\{\gamma_y \nu_e \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e \left(2\frac{\partial w}{\partial z}\right)\right\} - \gamma_v D_z w - R_z + \gamma_v S_w - \frac{\gamma_v \rho^* g}{\rho}$$

$$\left.\begin{aligned} \lambda_v &= \gamma_v + (1-\gamma_v)C_M \\ \lambda_x &= \gamma_x + (1-\gamma_x)C_M \\ \lambda_z &= \gamma_z + (1-\gamma_z)C_M \end{aligned}\right\} \qquad R_x = \frac{1}{2}\frac{C_D}{\Delta x}(1-\gamma_x)u\sqrt{u^2+w^2}$$

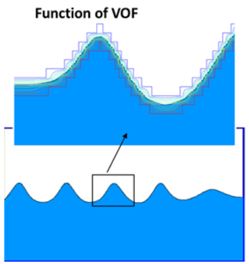
Equation of Continuity

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

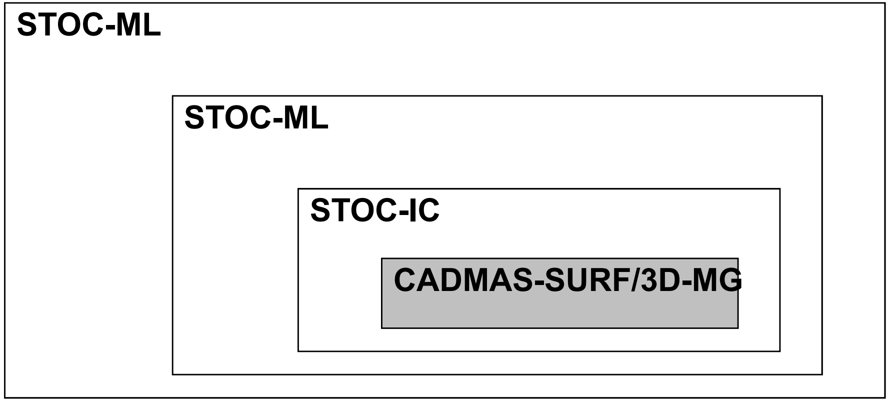
Equation of Free Water Surface (VOF Method)

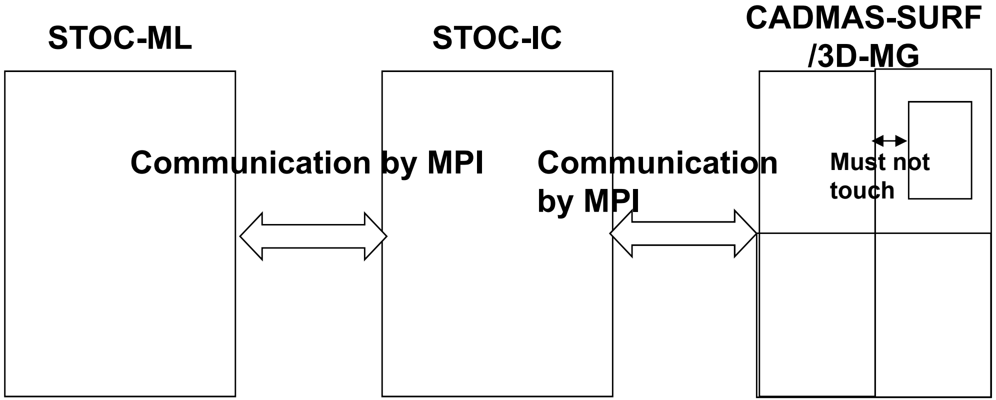
$$\gamma_v \frac{\partial F}{\partial t} + \frac{\partial \gamma_x uF}{\partial x} + \frac{\partial \gamma_y vF}{\partial y} + \frac{\partial \gamma_z wF}{\partial z} = \gamma_v S_F$$

Volume of Fluid implies the ratio of fluid volume to cell volume



Connections between simulator calculations





All connections are made using MPI communications.

Although all three models are capable of segmenting their respective areas of interest, when different calculation methods are used in the same area (for example, STOC-IC calculations are used in an STOC-ML area), the parent area containing the different calculation methods is regulated to prevent segmentation.

Consequently, when a CS3D area is made sufficiently large, the STOC-IC area that contains it ultimately becomes larger as well, as a single area.

Verification of Accuracy of the system

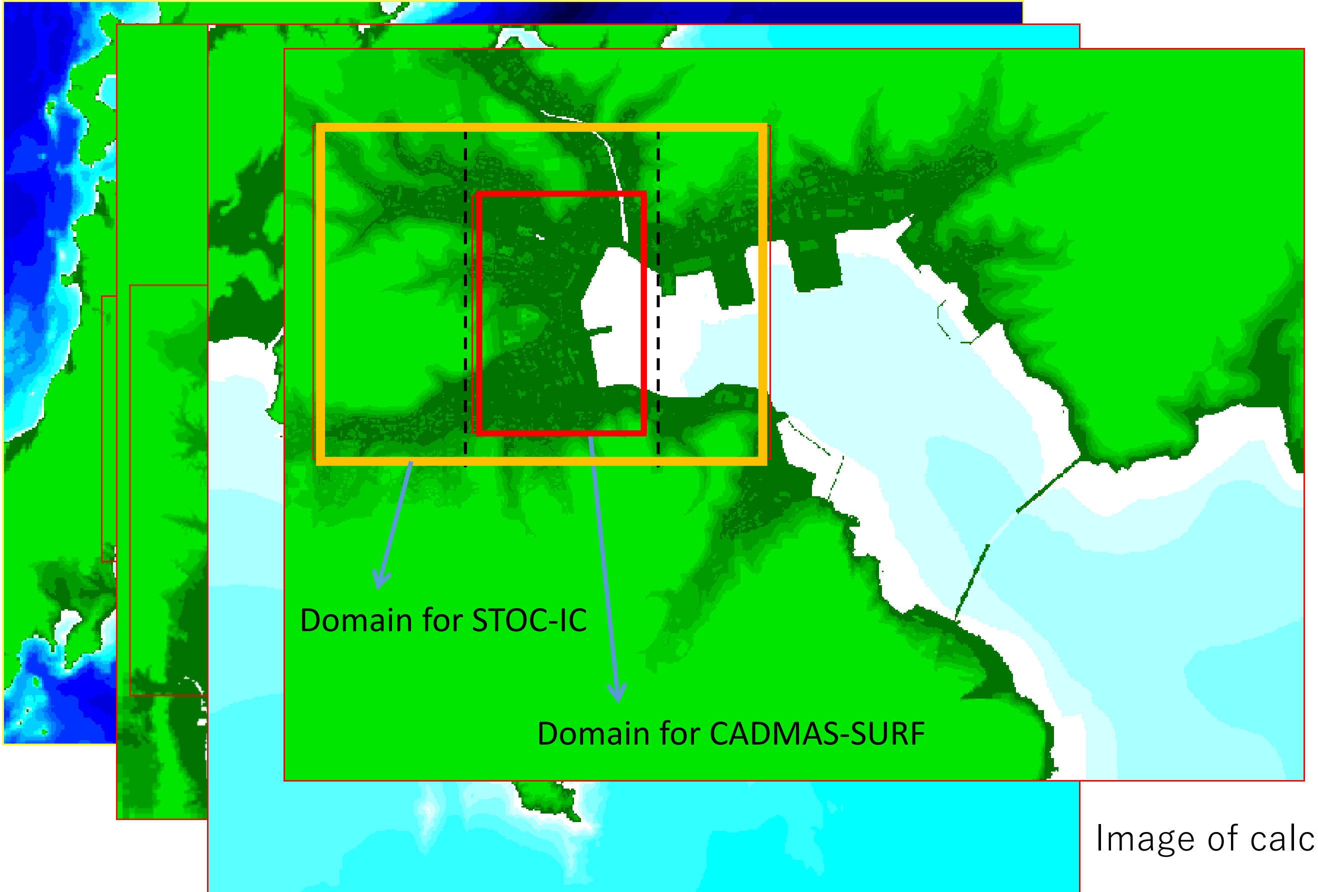


Image of calculation at Onagawa

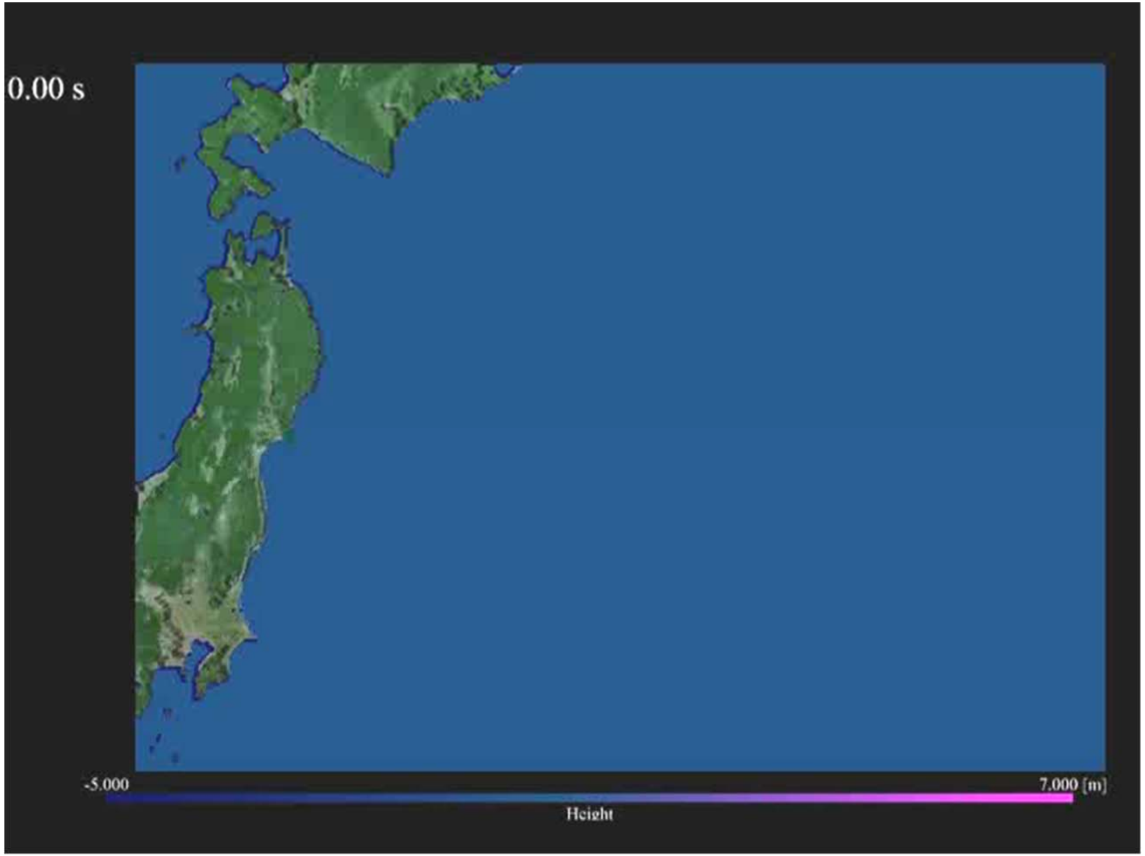
Information of each domain

No. Layer	Grid Size(m)	Ratio of Grid size	Number of grid (X)	Number of grid (Y)	Number of grid (Z)	Number of grid	Code Name	Number of Core
1	2,916.0	–	500	365	1	182,500	STOC-ML	1
2	972.0	3	510	390	1	198,900	STOC-ML	1
3	324.0	3	405	387	1	156,735	STOC-ML	1
4	108.0	3	900	600	1	540,000	STOC-ML	1
5	36.0	3	930	930	1	864,900	STOC-ML	1
6	12.0	3	1,020	780	1	795,600	STOC-ML	1
7	4.0	3	870	627	1	545,490	STOC-ML	1
8	4.0	1	390	285	13	1,444,950	STOC-IC	3
9	1.0	4	600	800	32	15,360,000	CADMAS-SURF/3D	32

Tsunami Source:

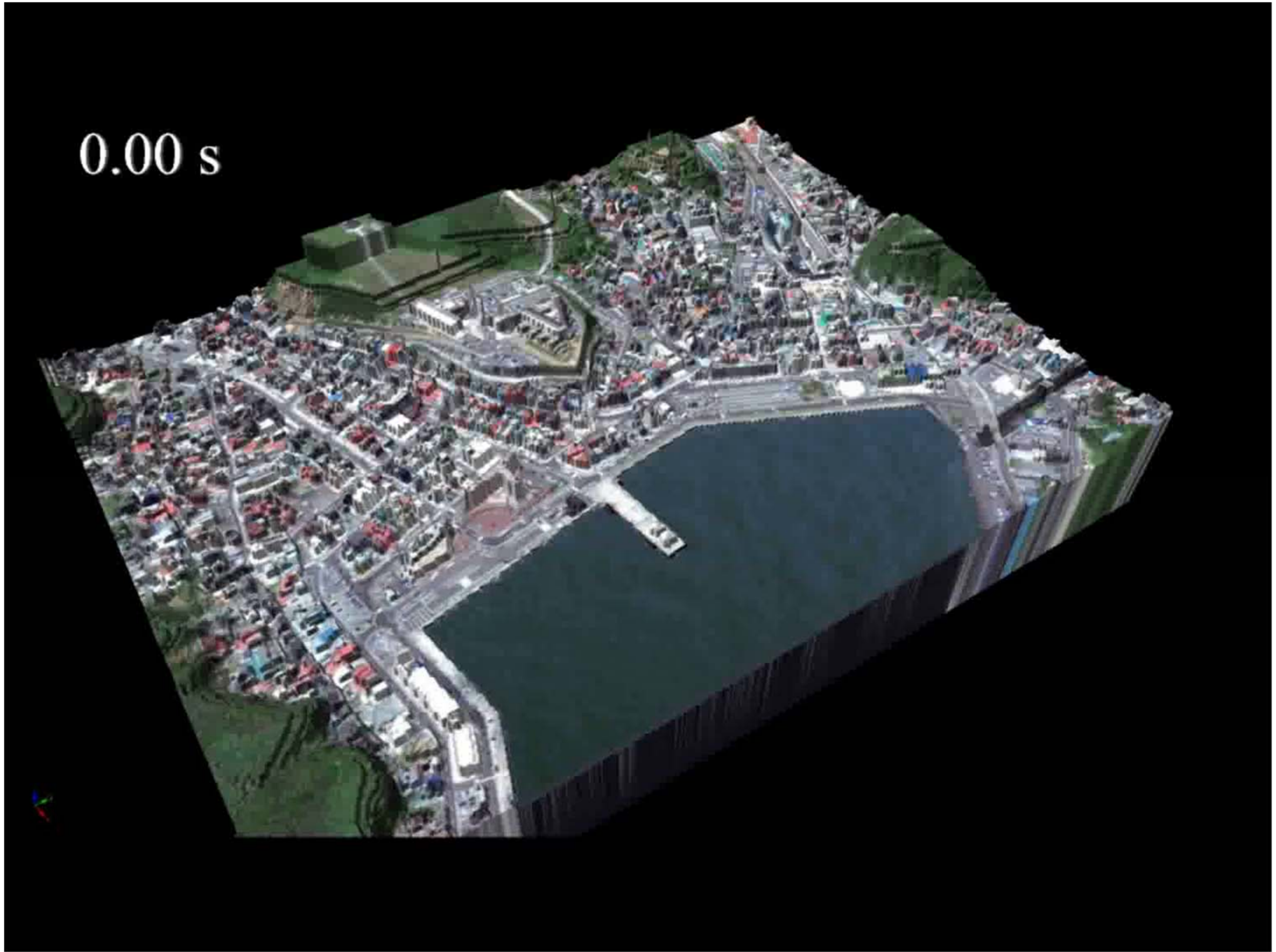
1) Fujii-Satake ver. 4.0 model with scaling adjustments to match the tsunami waveform obtained with GPS wave sensors off the southern Iwate coast.
2) Fujii-Satake ver. 8.0
3) Central Disaster Prevention Council(2011)
4) Takagawa and Tomita (2012)

Domain 01, ML

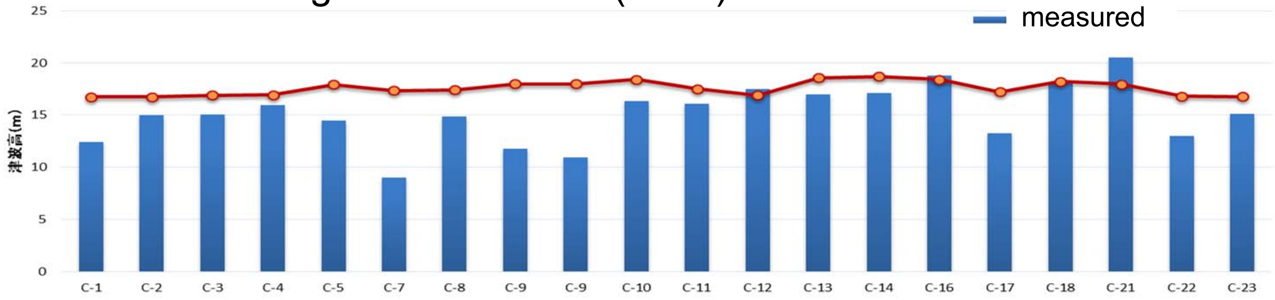


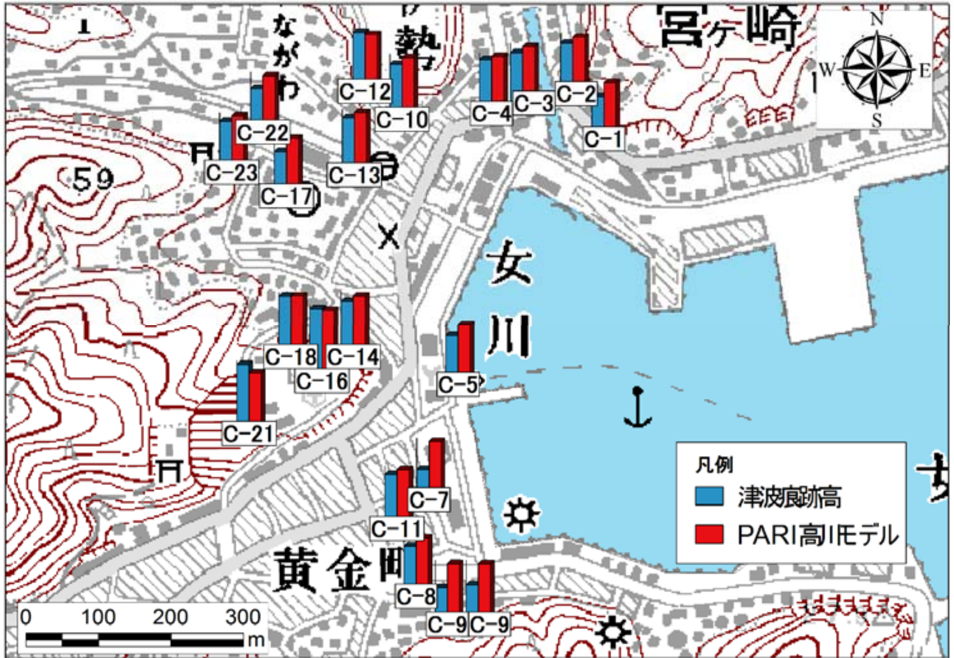
Tsunami Source; Takagawa and Tomita 2012

Domain 08, CADMAS-SURF/3D



Comparison of Maximum Inundation height
(Tsunami Source: Takagawa andTomita (2012)

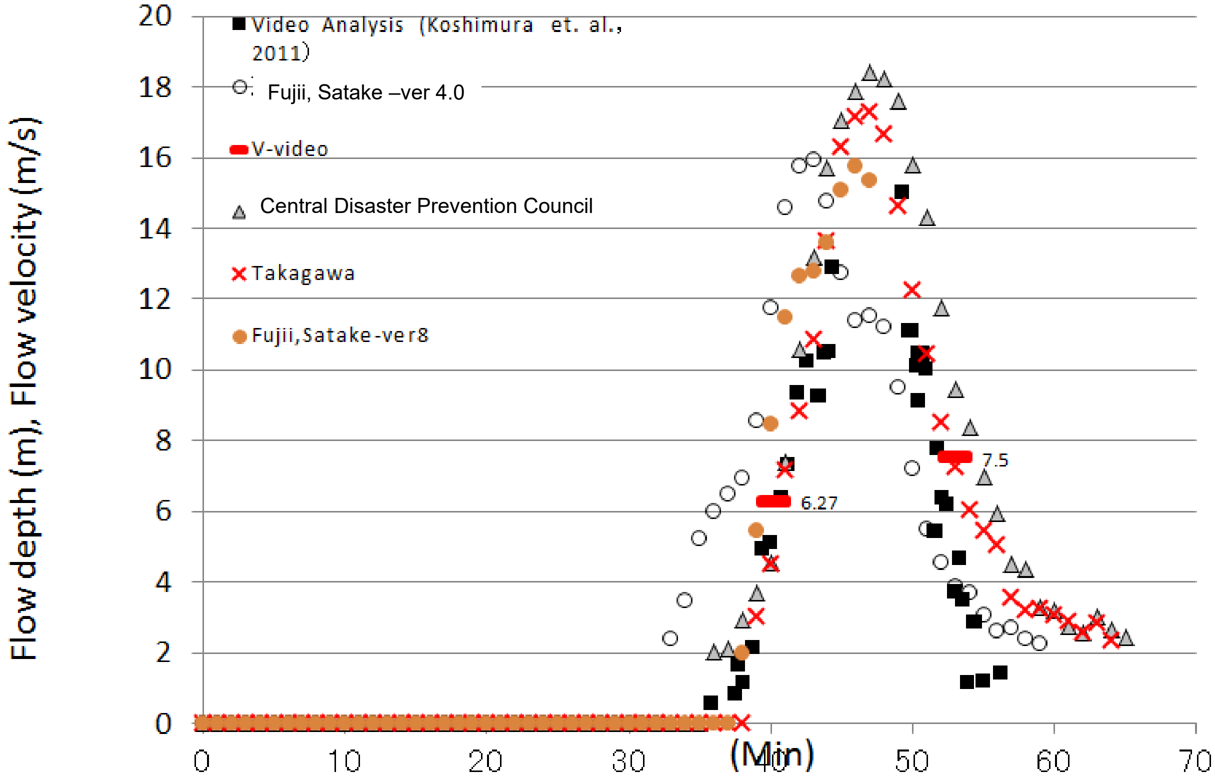




計算領域上のポイ	痕跡データID	痕跡値	計算値	In	In**2
C-1	FRAx-0075	12.445	16.7528	-0.12909	0.016665
C-2	FRAx-0076	15	16.7341	-0.04751	0.002257
C-3	FRAx-0079	15.032	16.9046	-0.05099	0.0026
C-4	FRAx-0080	15.966	16.9342	-0.02557	0.000654
C-5	PARI-0370	14.472	17.917	-0.09274	0.0086
C-7	FRAx-0082	9.033	17.3689	-0.28394	0.080622
C-8	FRAx-0083	14.86	17.4152	-0.06891	0.004749
C-9	THKE-0224	11.756	18.0068	-0.18518	0.034291
C-9	THKE-0225	10.937	18.0068	-0.21654	0.046889
C-10	THKE-0124	16.36	18.3998	-0.05103	0.002604
C-11	SHKK-0054	16.073	17.5081	-0.03714	0.00138
C-12	THKE-0228	17.475	16.8948	0.014664	0.000215
C-13	FRAx-0081	17.0092	18.5854	-0.03849	0.001481
C-14	WSDU-0008	17.12	18.7152	-0.03869	0.001497
C-16	MLIT-0343	18.801	18.4122	0.009075	8.24E-05
C-17	WSDU-0006	13.246	17.2138	-0.11379	0.012949
C-18	PARI-0347	18.068	18.223	-0.00371	1.38E-05
C-21	THKE-0220	20.49	17.9766	0.056834	0.00323
C-22	WSDU-0007	12.996	16.8013	-0.11153	0.01244
C-23	THKE-0230	15.105	16.7881	-0.04588	0.002105

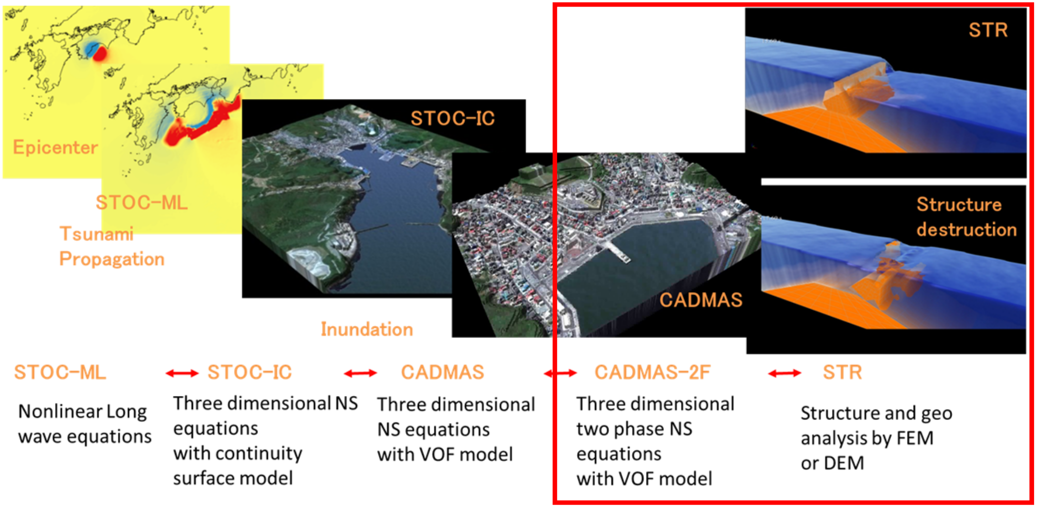
K=	0.845	0.08
κ =	1.203	

Comparison of Flow depth



Multiphysics Simulation

Coupled with Structure Analysis



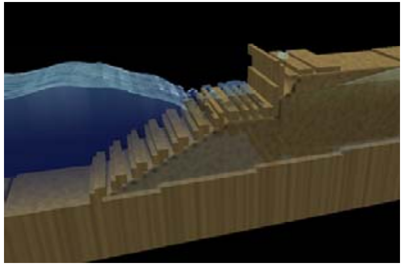
Outline of CADMAS-SURF/3D-STR

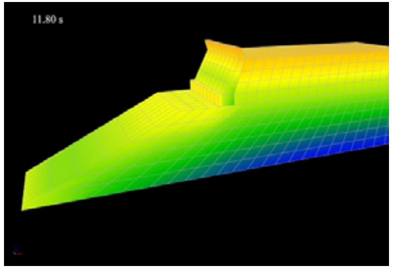
(Arikawa et al., 2009)

Main program

call subroutine

call subroutine



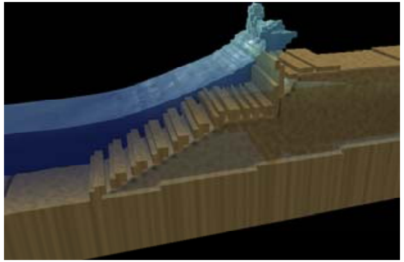


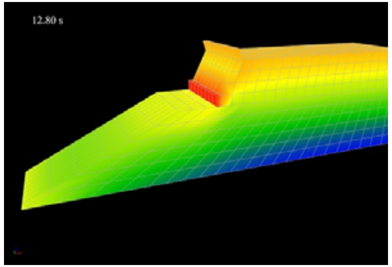
CADMAS-SURF/3D
(VOF method)

STR3D
(FEM)

Data on pressure →

Data on displacement ←





Images of CADCADMAS-SURF/3D

calculation step

calculation step

Basic Equations of STR

$$\rho \frac{\partial^2 u_{si}}{\partial t^2} = \sigma_{ij,j} + \rho g$$

When the object is ground

$$\sigma'_{ij} = \sigma_{ij} + p' I_{ij}$$

$$\rho = (1-n)\rho_s + n\rho_f$$

For Seepage flow analysis

$$\dot{\boldsymbol{w}} = k\left(-\nabla p + \rho_f \boldsymbol{g} - \rho_f \ddot{\mathbf{u}}\right)$$

$$\nabla \cdot \dot{\boldsymbol{w}} = -\nabla \cdot \dot{\mathbf{u}} - C_{Kf}\dot{p}$$

σ_{ij} Stress tensor

u_s Displacement

g Gravitational acceleration

σ'_{ij} Effective stress tensor

p' Pore pressure

I_{ij} Identity matrix

n; Porosity

ρ_s Density of soil

ρ_f Density of water

w; Relative displacement of pore water to ground

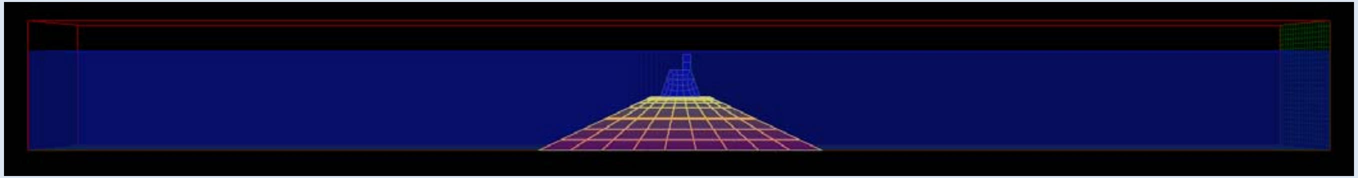
k; Permeability coefficient

$C_{Kf} = n / K_f$

K_f; Bulk modulus of pore water

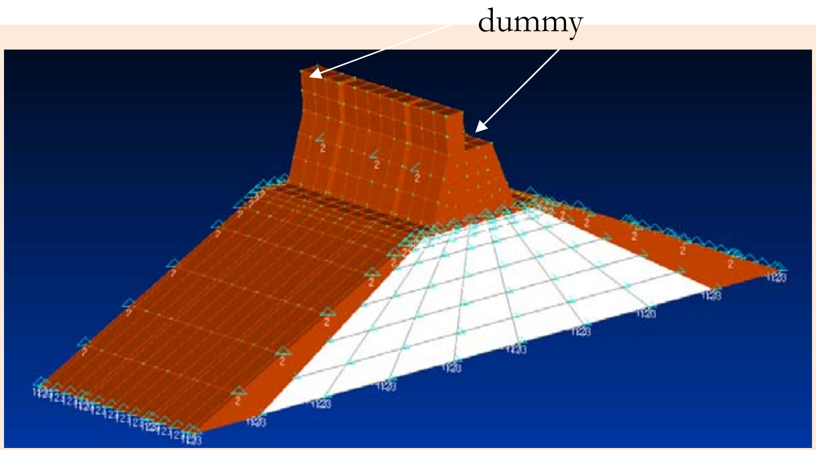
Numerical Conditions

CADMAS dx=dy=dz=0.10 m



STR

Young's modulus : 2.35e11
Poisson's ratio : 0.333
Density
test body : 2135
dummy caisson : 2349
Coefficient of friction
static : 0.6
dynamic : 0.2

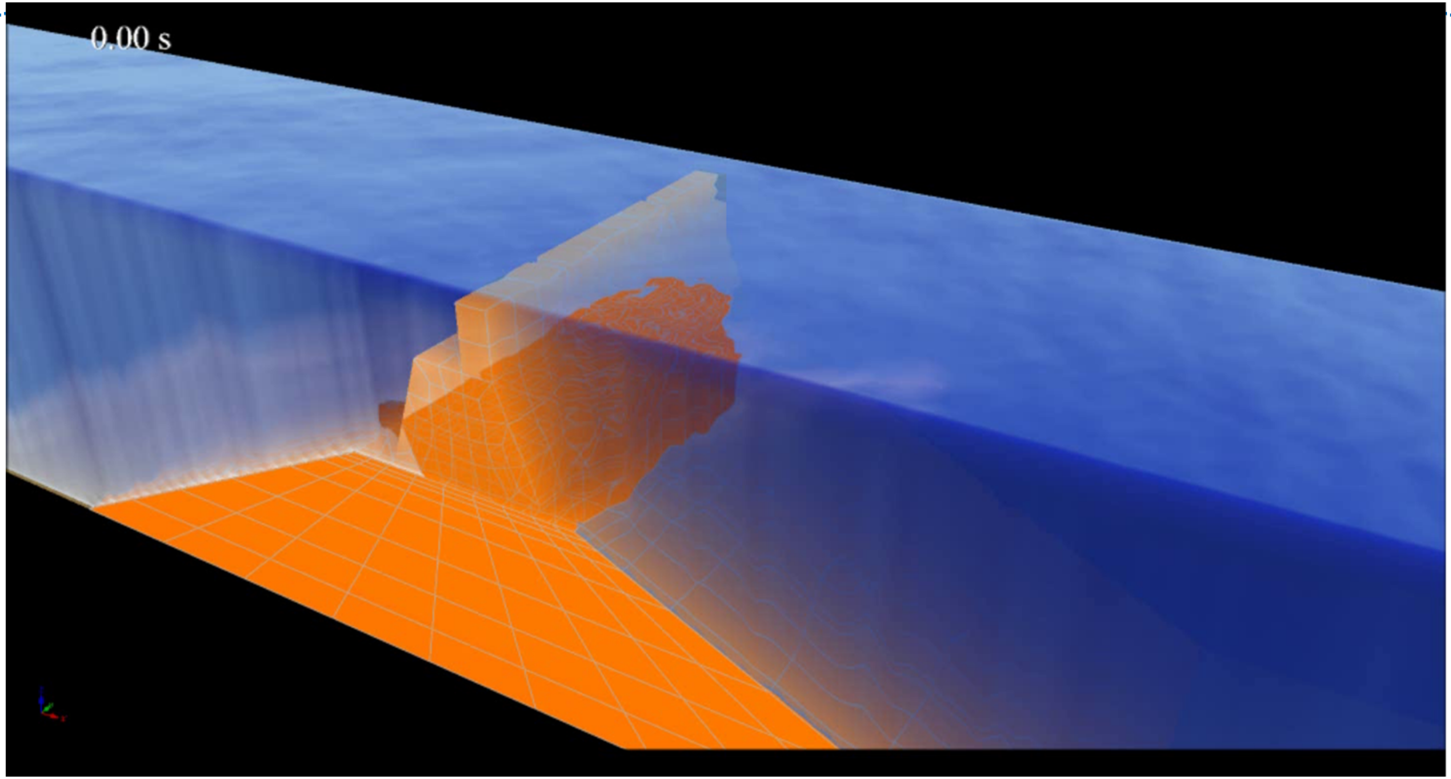


Physical Experiment

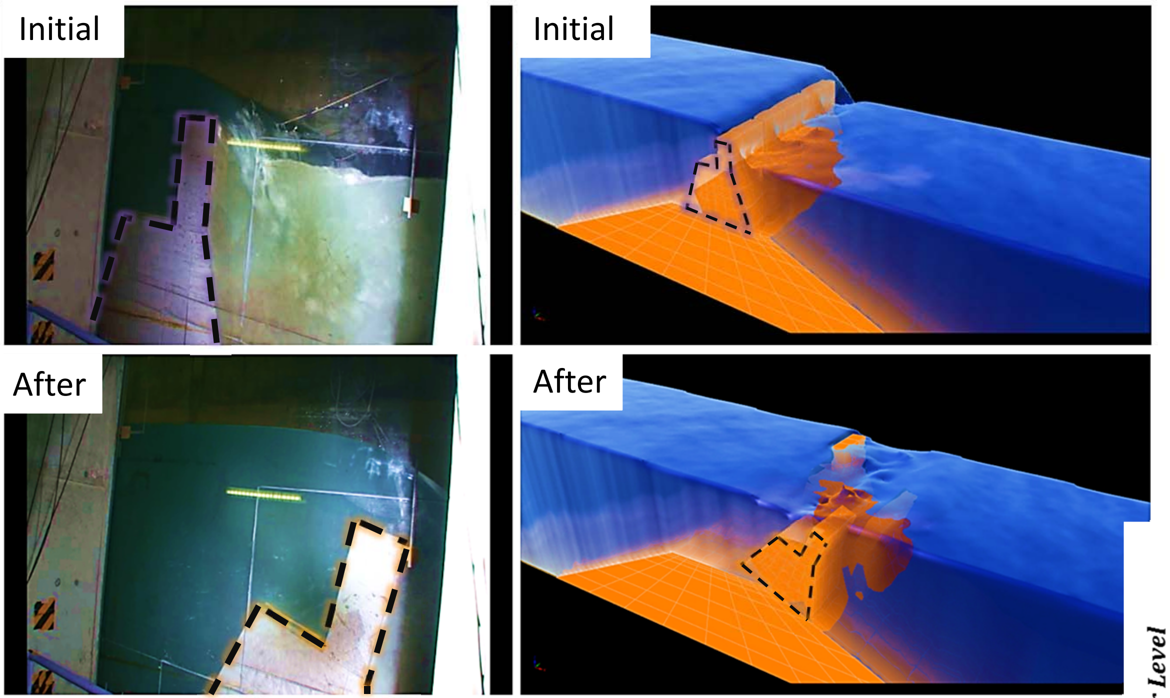
Sea side

Harbor side

Animation



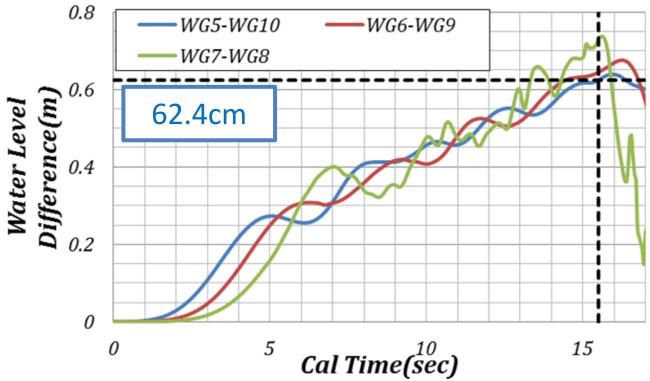
Comparisons



Contour line of caisson at the initial position

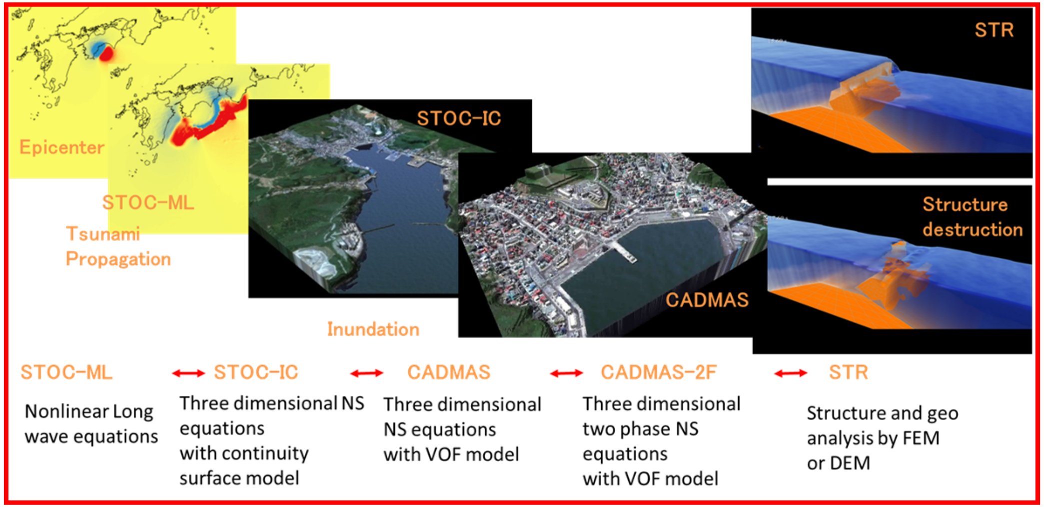
Contour line of caisson after movement

The result of the Water Level Difference of the physical experiment is 60.8cm



Multiscale Multiphysics Simulation

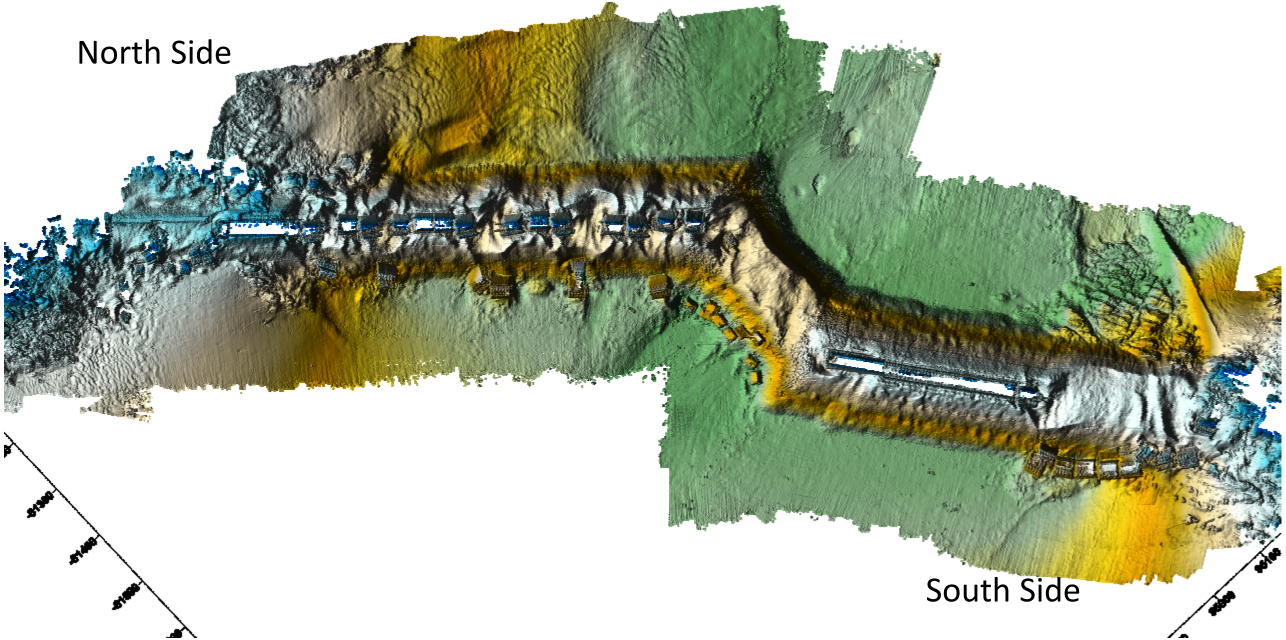
Integrated Analysis



Kamaishi Tsunami Breakwater

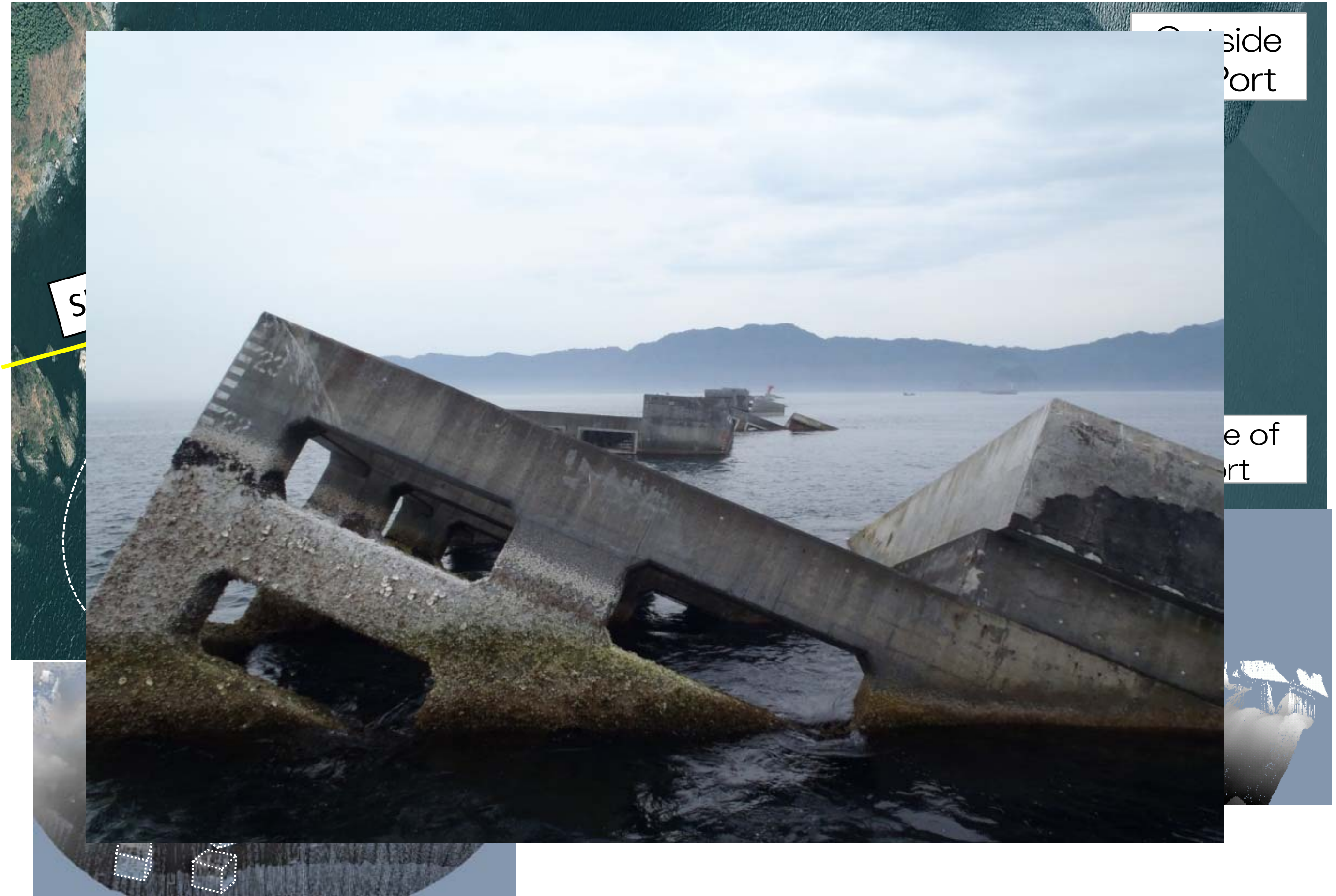
Topography of Sea Bed at Kamaishi after tsunami

25th , March, 2011



Failure of Breakwater at Kamaishi Bay

TOHOKU REGIONAL BUREAU MINISTRY OF LAND , INFRASTRUCTURE AND TRANSPORT

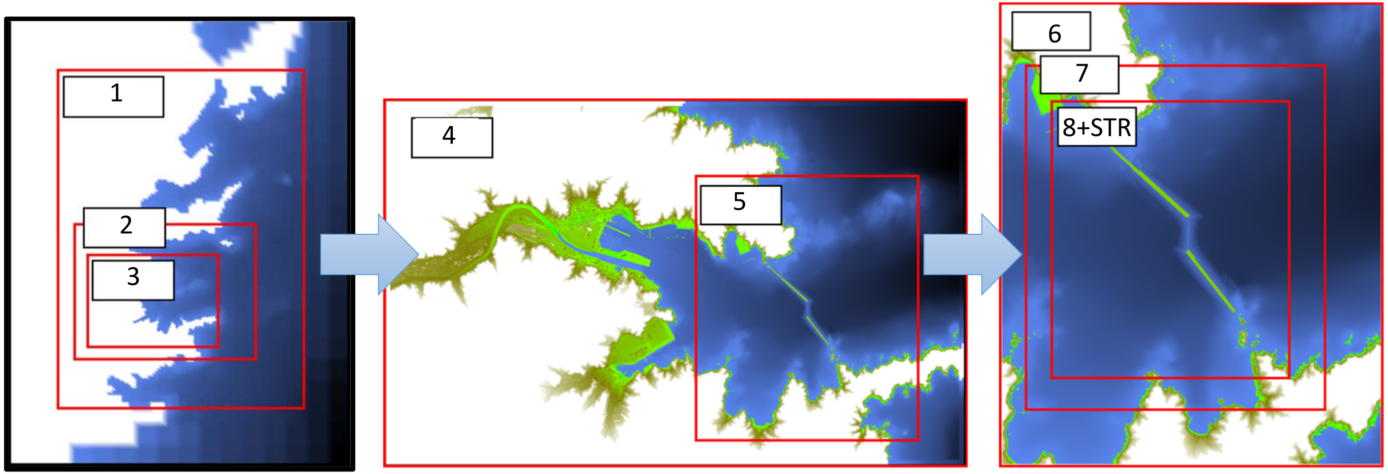


From video by public people

15:18 (1st positive wave, 32 minutes after)

15:28(negative tsunami started, 42 minutes after)

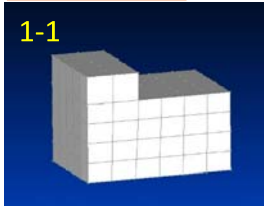
Verification of Damage of Breakwaters at Kamaishi Bay

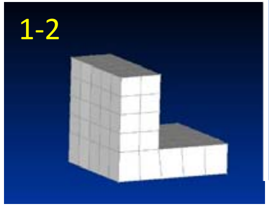


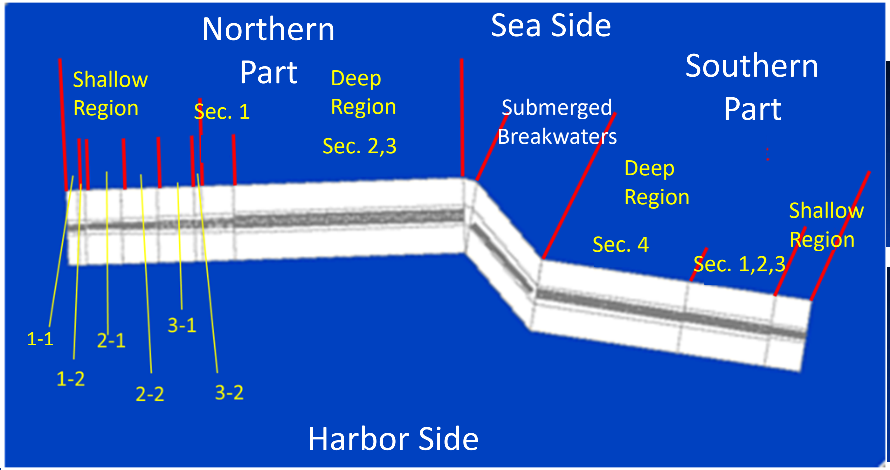
Domain Number	Solver	Grid size(m)	Number of Cells (X)	Number of Cells (Y)	Number of Cells (Z)	Number of CPUs
1	STOC-ML	200	108	141	1	1
2	STOC-ML	100	166	110	1	1
3	STOC-ML	50	240	150	1	1
4	STOC-ML	10	1100	690	1	1
5	STOC-ML	10	410	500	1	1
6	STOC-IC	10	330	400	1	1
7	CADMAS-MG	10	260	300	52	70
8	CADMAS-2FC	5	400	480	52	240
STR	STR	Another slides				

Layout of Breakwaters without slit part

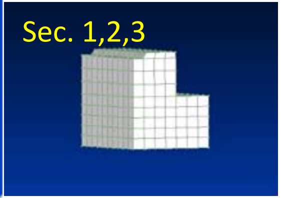
Northern Part

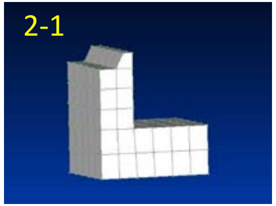


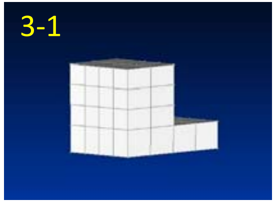


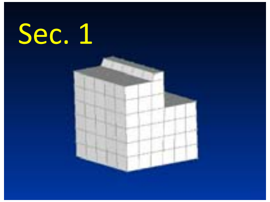


Southern Part

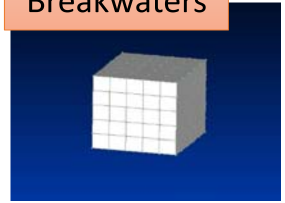


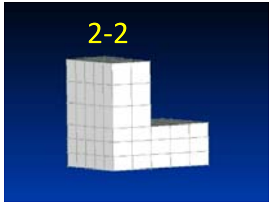


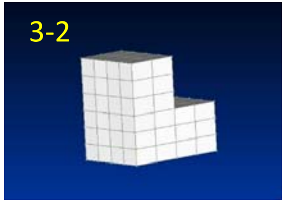


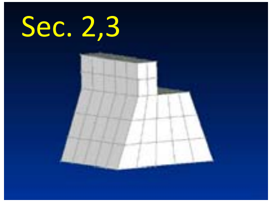


Submerged Breakwaters









Properties for caissons and rubble mound

Type	Position	Depth	Section Name	Number of Caissons	Material	Young Modulus	Shear Modulus	Poisson ratio	Density [N]
Caisson	North	Shallow	1-1	2	Concrete without Porosity	2.35E+10	8.815E+07	0.333	2010
			1-2	1					2040
			2-1	6					2010
			2-2	6					2020
			3-1	6					2030
			3-2	1					2000
		Deep	1	3					1980
			2,3	19					1980
	Submarged			13					1900
	South	Shallow	1,2,3	3					2090
		Deep	1,2,3	7					2030
			4	12					1980
Mound					Foundation with Porosity	2.00E+09	7.692E+08	0.333	1900

Friction coefficient between Caisson and rubble mound

Static 0.6

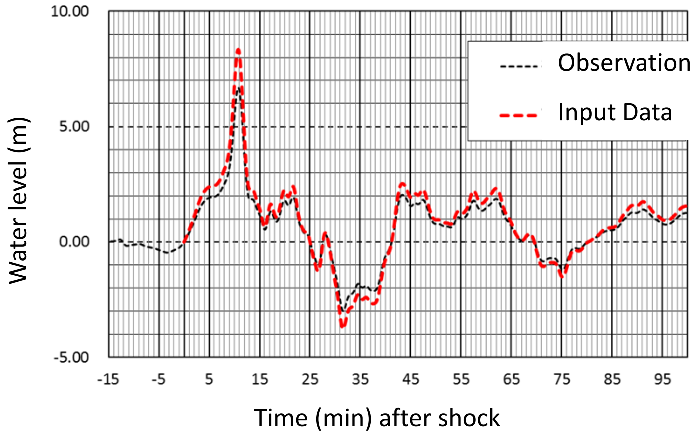
Dynamic 0.4

In the section 3-1 at the Northern shallow region, they used Friction enhancement mat

Static Friction Coefficient 0.8

Dynamic Friction Coefficient 0.6

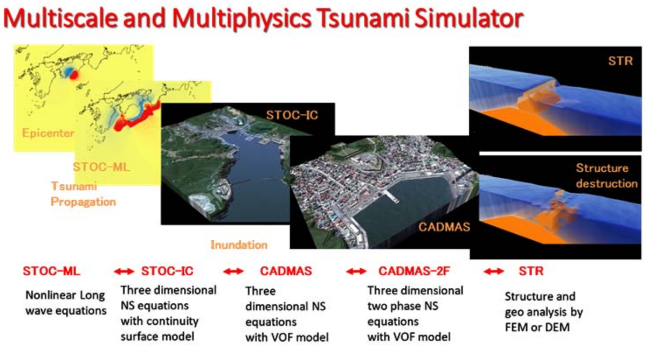
Incident wave and Position of the input boundary

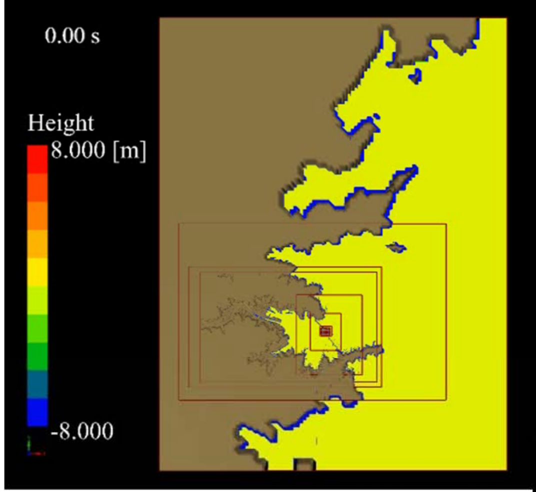


Time series water level of GPS wave gauge off the Kamaishi bay at the time of the Great East Japan Earthquake (39° 15′31″E, 142° 05′49″N) was incident from the east side boundary of the STOC calculation region of the outermost area.

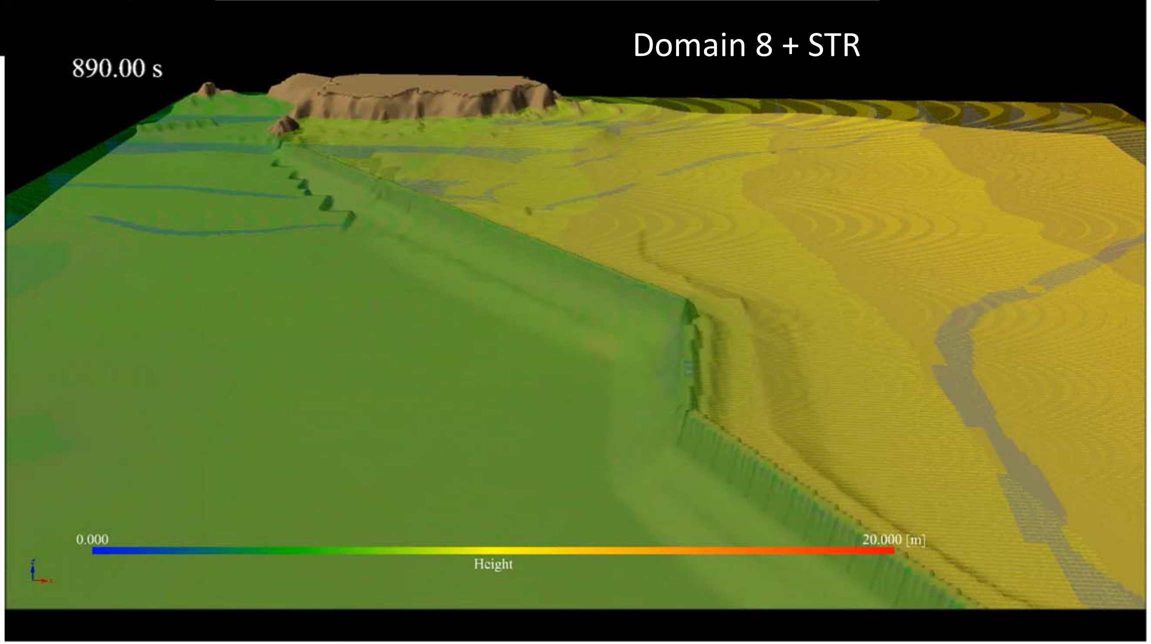
In addition, in order to adjust the calculation time, the receding wave excludes the first 15 minutes
Also because of adjustment of the wave height acting on the STR structure, the water level was made 1.3 times as the observation.

Animation





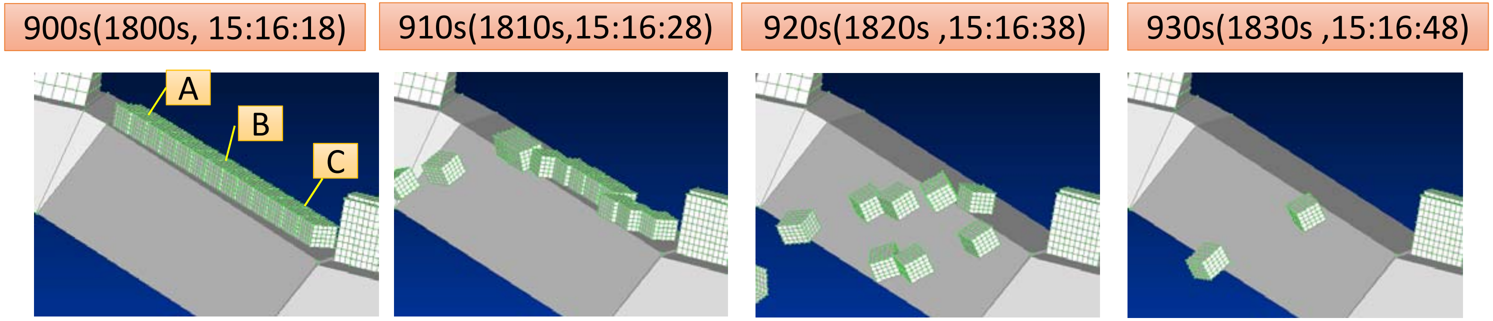
All Domain

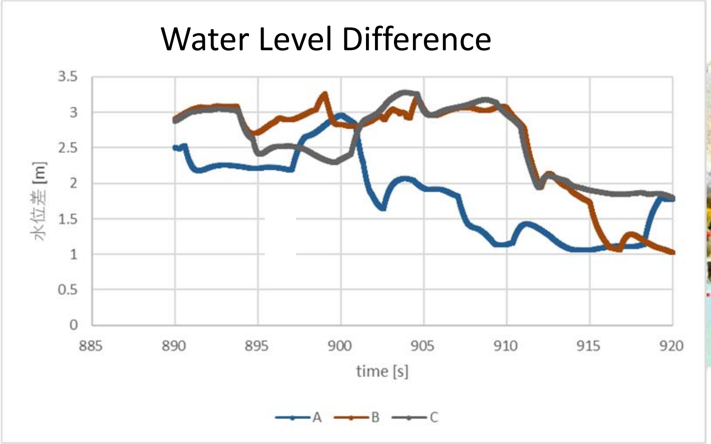


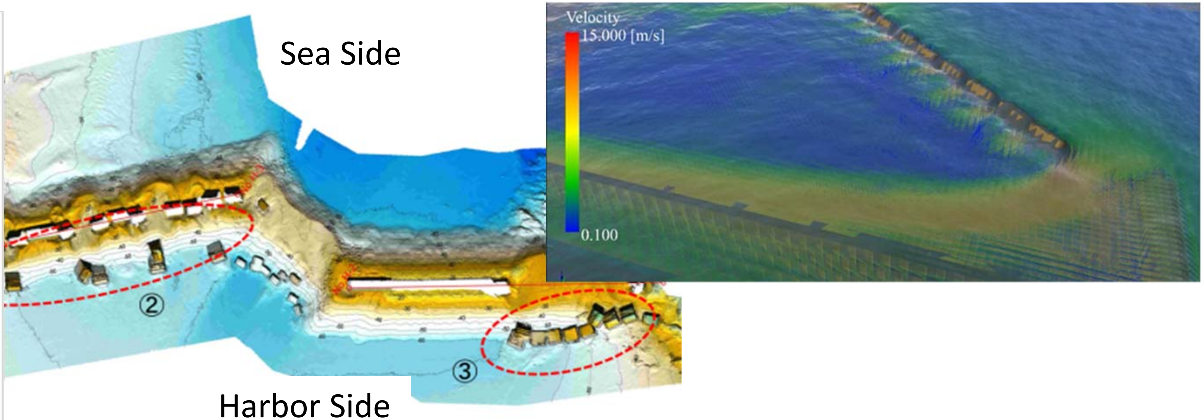
Number of CPUs					
ML	IC	MG	2F	STR	Total
5	1	70	240	8	324
Physical Time			Computational Time		
1015[seconds]			768[hours]		

The calculation time is around 3000 times the physical time

Damage Situation of Submerged Breakwaters

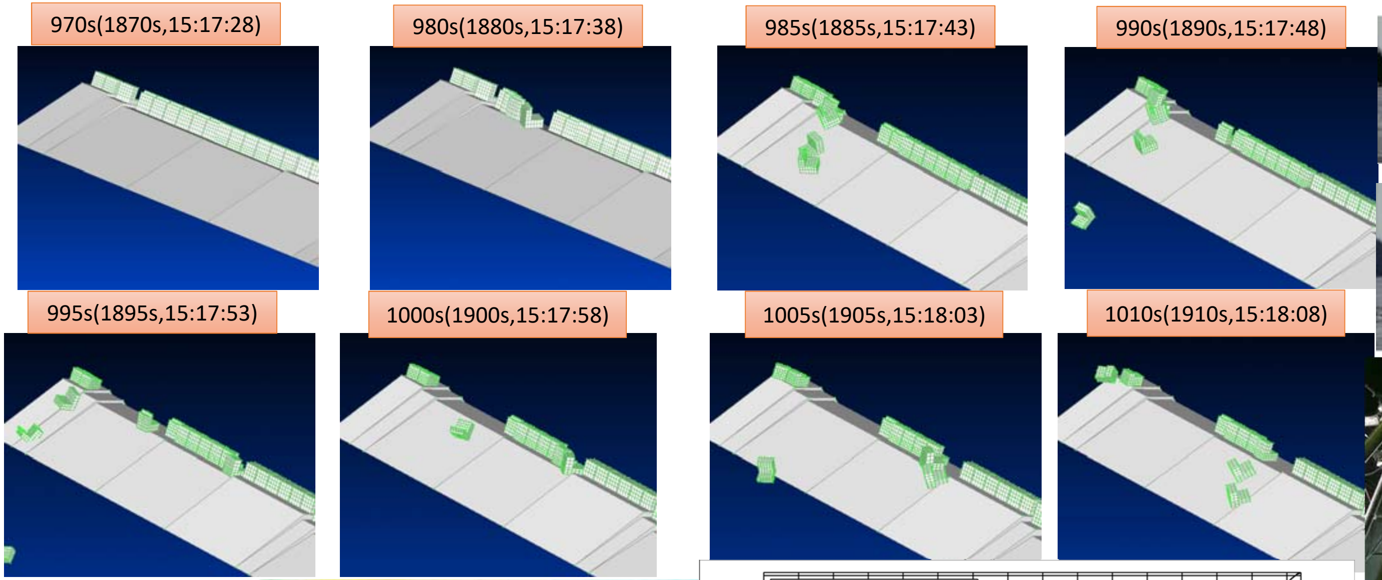






Arikawa et al.(2012)

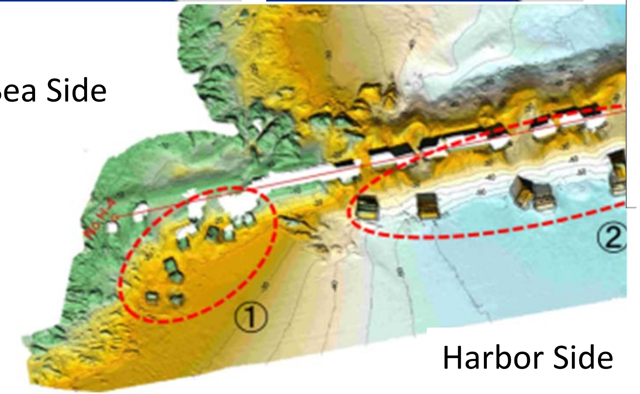
Damage Situation of Breakwaters at Northern part

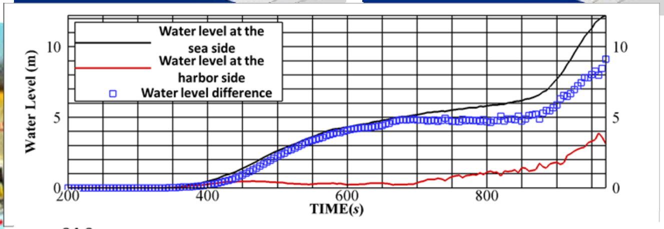


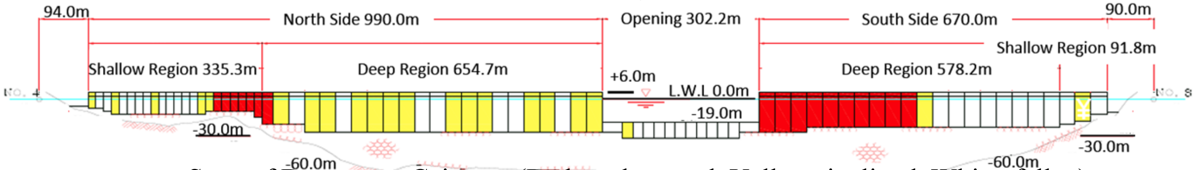
15:18 (1st positive wave, 32 minutes after)

15:28(negative tsunami started, 42 minutes after)

Experimental Scale 1/60



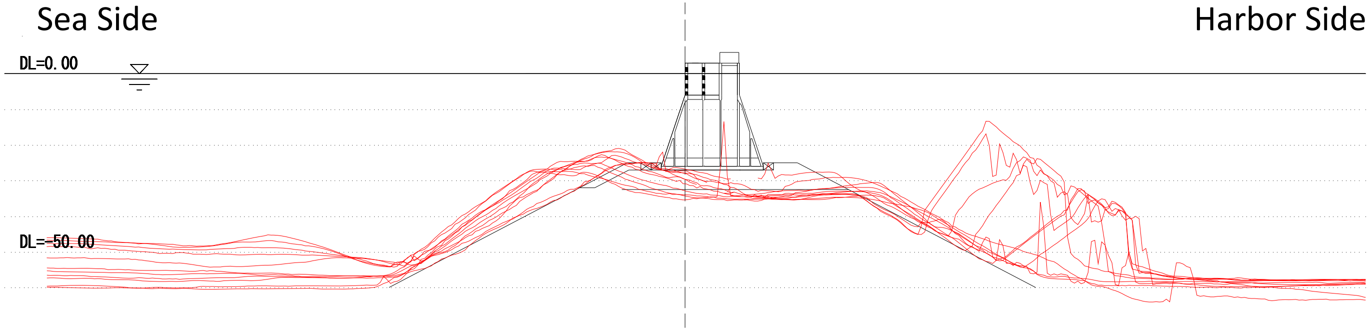


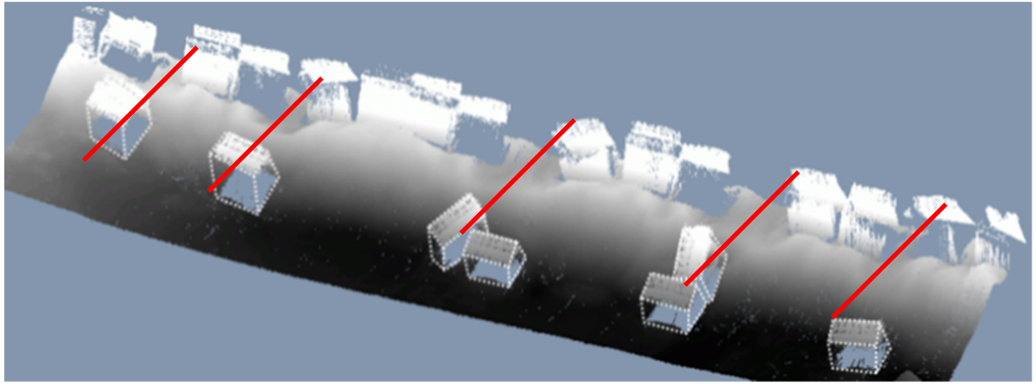


State of Damage to Caissons (Red: undamaged, Yellow: inclined, White: fallen)

For the future task

Cross section of damage of North Breakwater





Coupled with Sediment Transport Simulator

STM

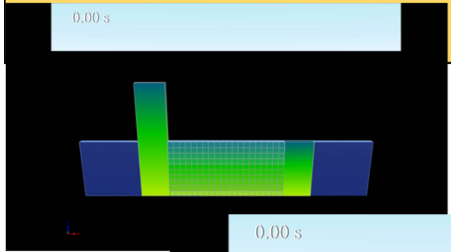
- Continuous equation of bed load

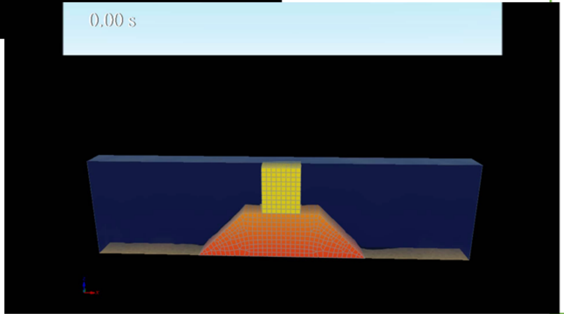
$$\frac{\partial z}{\partial t} + \frac{1}{1-\lambda}\left\{\frac{\partial q_{Bx}}{\partial x} + \frac{\partial q_{By}}{\partial y} + w_{ex}\right\} = 0$$

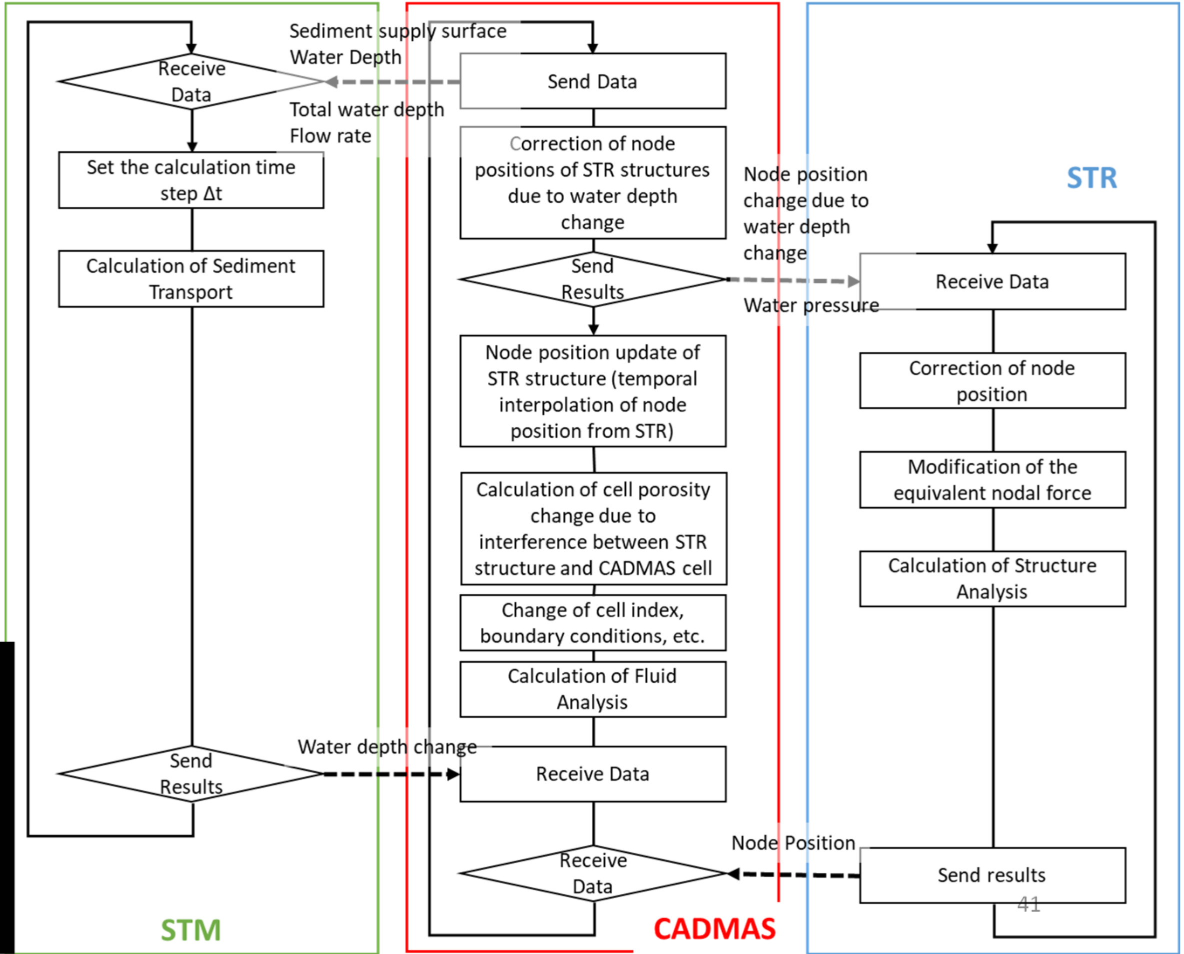
- Continuous equation of suspended layer

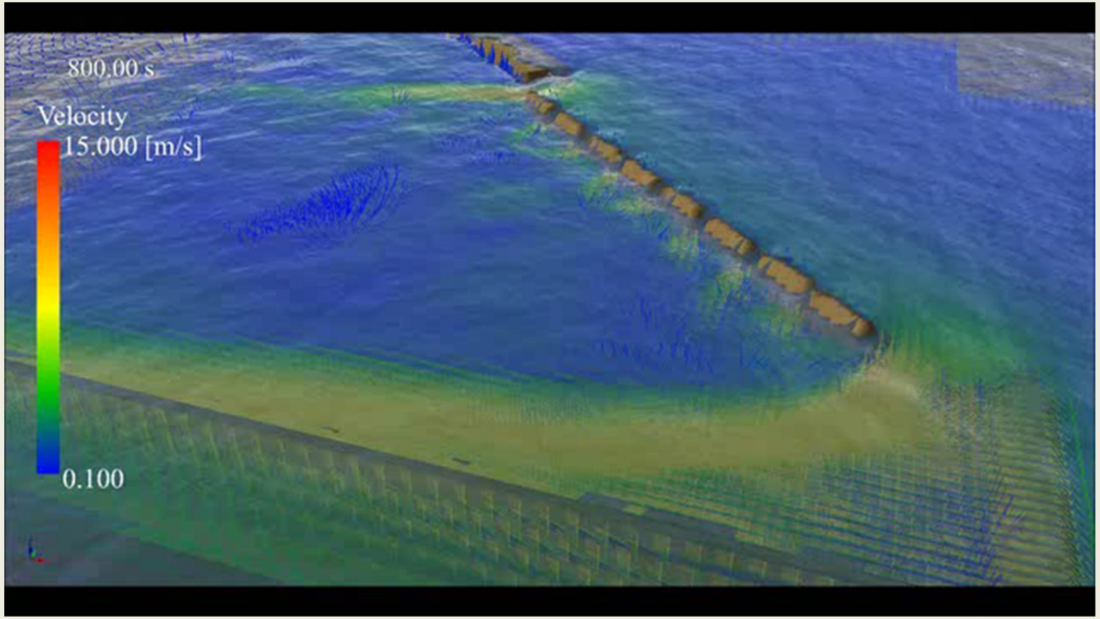
$$\frac{\partial (C_s h_s)}{\partial t} + \frac{\partial (M C_s)}{\partial x} + \frac{\partial (M C_s)}{\partial y} - w_{ex} = 0$$

$$q_B = 2.6 \tau_*^{3/2} \sqrt{sgd^3}$$









Why don't you join this development with us?

Thank you for your Attention!!