Analysis of Tsunami Run-up near Kori Nuclear Power Plant using Tsunami Analysis Code

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ESLAB

Introduction

Background and objective of Research

- Since Fukushima Nuclear power plant accident, there has been an increasing interest in the safety assessment of tsunami at nuclear power plant.
- The safety evaluation and improvement of the tsunami in domestic nuclear power plants was proceeding, and it is essential to understand the characteristics of the tsunami.
- In Korea, a tsunami occurred at a height of 3m at the Im-won port of East Sea in 1983, indicating that **it is not completely safe** from the tsunami.
- The objective of this study is to analyze the wave elevation change and wave behavior near Kori Nuclear Power Plant against Tsunami caused by the ocean and near sea earthquake.

Tsunami at Miyako in Iwate in Japan(2011)

Tsunami at Imwon port, East sea in Korea(1983)

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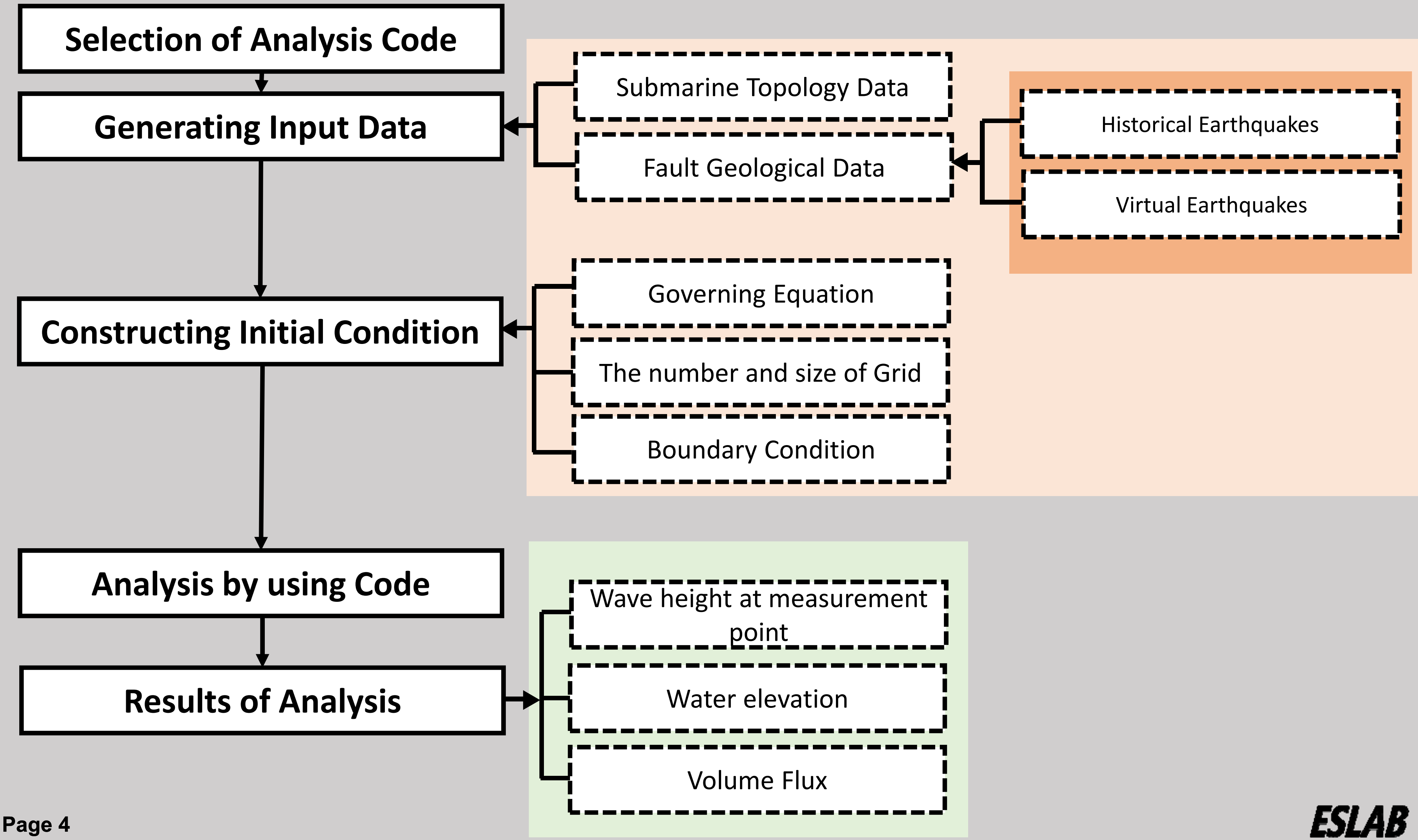
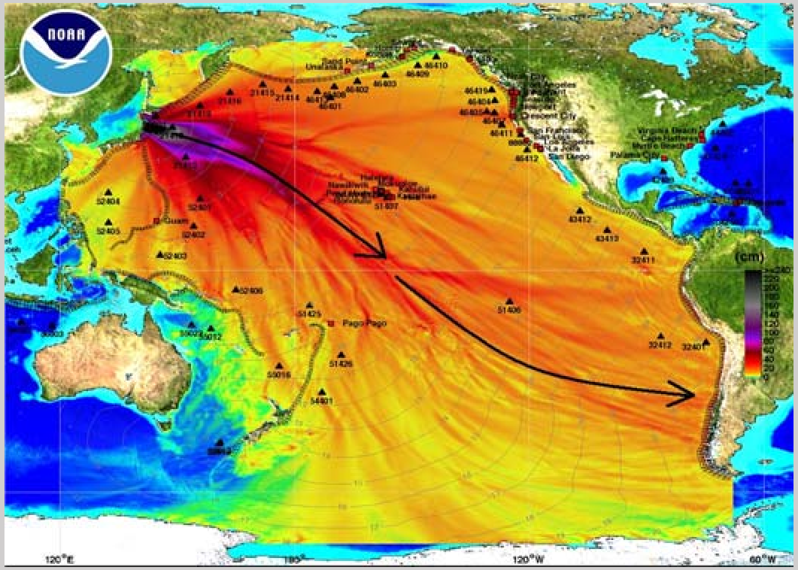
Introduction

- ## Research Outline

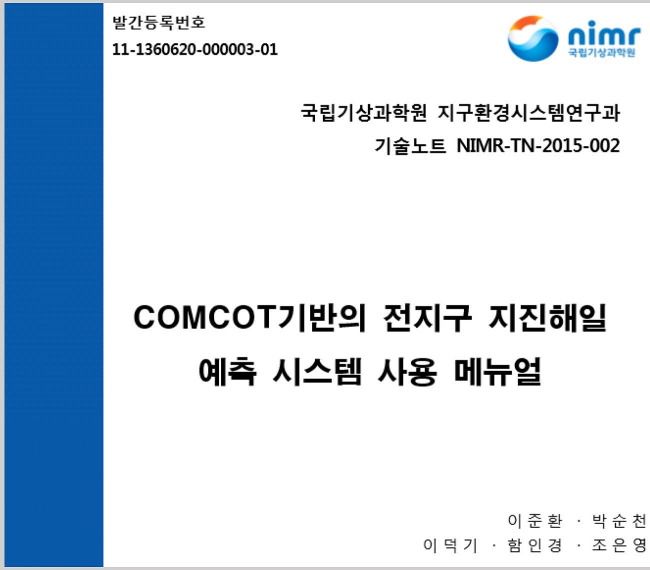


Tsunami Simulation Numerical Code

- **COMCOT v1.7**
  - COMCOT v1.7(**CO**rnell **M**ulti-grid **Co**upled **T**sunami model) was selected as analysis code for Tsunami reaching time and wave height.
  - COMCOT is a suitable code to assume tsunami occurrence in ocean and near sea and multiple fault occurrences.
  - The COMCOT codes were used for the analysis of Singapore, Taiwan, China, Sumatra earthquake and India Ocean earthquake in 2006, and in Korea, NIMR (National Institute of Meteorological Science) was used to build tsunami prediction system.



Coriolis force effect on Tsunami propagation direction.



발간등록번호
11-1360620-000003-01

nimr 국립기상과학원

국립기상과학원 지구환경시스템연구과
기술노트 NIMR-TN-2015-002

COMCOT기반의 전지구 지진해일 예측 시스템 사용 메뉴얼

이준환 · 박순천
이덕기 · 함인경 · 조은영

Usage of Comcot code at Tsunami Prediction system in NIMR, Korea.

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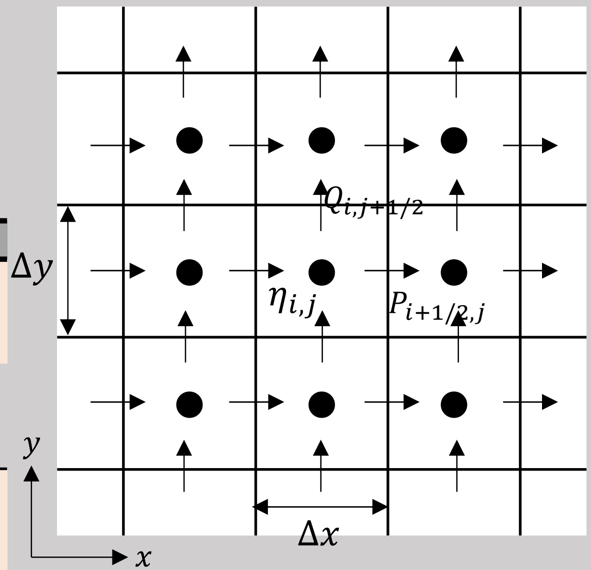
Tsunami Simulation Numerical Code

COMCOT v1.7

- To solve shallow water equation, COMCOT adopts explicit staggered leap-frog finite difference scheme.

Governing Equations in COMCOT

Continuity Equation	$\frac{\partial \eta}{\partial t} + \left\{ \frac{\partial P}{\partial x} + \frac{\partial Q}{\partial y} \right\} = -\frac{\partial h}{\partial t}$
	$\frac{\partial \eta}{\partial t} + \frac{1}{R cos\varphi} \left\{ \frac{\partial P}{\partial \psi} + \frac{\partial}{\partial \varphi}(cos\varphi Q) \right\} = -\frac{\partial h}{\partial t}$
Momentum Equation	$\frac{\partial P}{\partial t} + \boxed{\frac{\partial}{\partial x}\left\{ \frac{P^2}{H} \right\}} + \boxed{\frac{\partial}{\partial y}\left\{ \frac{PQ}{H} \right\}} + gH\frac{\partial \eta}{\partial x} + F_x = 0$ $\frac{\partial Q}{\partial t} + \boxed{\frac{\partial}{\partial x}\left\{ \frac{PQ}{H} \right\}} + \boxed{\frac{\partial}{\partial y}\left\{ \frac{Q^2}{H} \right\}} + gH\frac{\partial \eta}{\partial x} + F_y = 0$
	$\frac{\partial P}{\partial t} + \frac{1}{R cos\varphi}\frac{\partial}{\partial \psi}\left\{ \frac{P^2}{H} \right\} + \frac{1}{R}\frac{\partial}{\partial \varphi}\left\{ \frac{PQ}{H} \right\} + \frac{gH}{R cos\varphi}\frac{\partial \eta}{\partial \psi} - fQ + F_x = 0$ $\frac{\partial Q}{\partial t} + \frac{1}{R cos\varphi}\frac{\partial}{\partial \psi}\left\{ \frac{PQ}{H} \right\} + \frac{1}{R}\frac{\partial}{\partial \varphi}\left\{ \frac{Q^2}{H} \right\} + \frac{gH}{R}\frac{\partial \eta}{\partial \varphi} + fP + y = 0$
Bottom Friction (Manning's Formula)	$F_x = \frac{gn^2}{H^{7/3}} P(P^2 + Q^2)^{1/2}$ $F_y = \frac{gn^2}{H^{7/3}} Q(P^2 + Q^2)^{1/2}$



Sketch of Staggered Grid Setup in COMCOT

η : *Surface elevation*
P : *Volume flux in X(West-East)*
Q : *Volume flux in Y(South–North)*
H : *Total water depth*
φ : *Latitude of the Earth*
ϕ : *Longitude of the Earth*
F_x : *Bottom friction of X direction*
F_y : *Bottom friciton of Y direction*
f : *Coriolis force coefficient*

Variables in Governing Equations.

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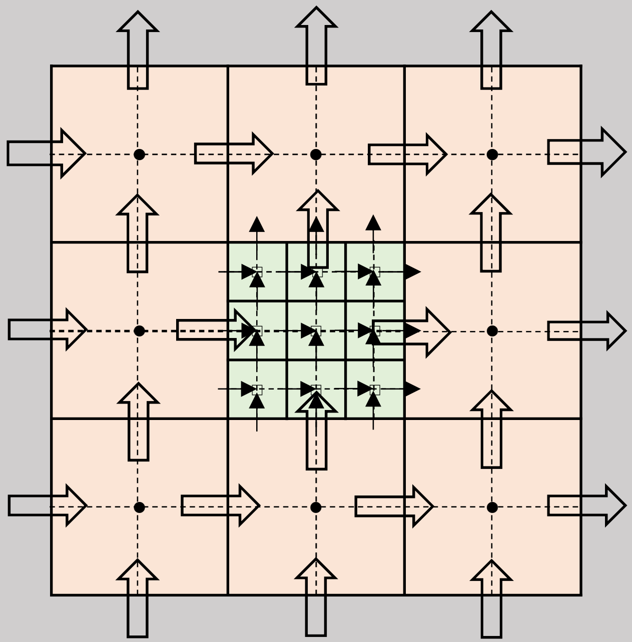
Tsunami Simulation Numerical Code

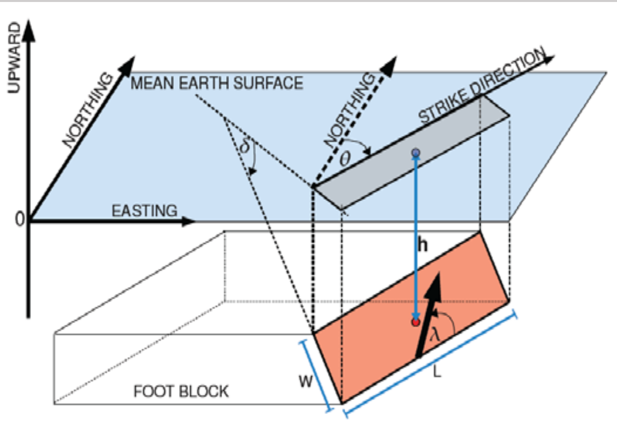
- **COMCOT v1.7**
  - **Multi-Grid Setup**
    - Wave length varied during the shoaling of waves, It is imperative that adopts computational domains which has **different size and resolution**.
    - Volume flux at entrance of smaller grid system is determined by interpolating the neighboring Volume flux form large grid system linearly.
    - Time step is determined automatically depending on the maximum water depth in each region.
  - **Moving boundary Scheme**
    - During calculating, **Shore line** could be determined by comparing total water level (H) between neighboring grid point.
    - If Water elevation at the front mesh is bigger than current mesh height, then shore line is moving between two grids.



Detailed view of Multi-Grid Setup

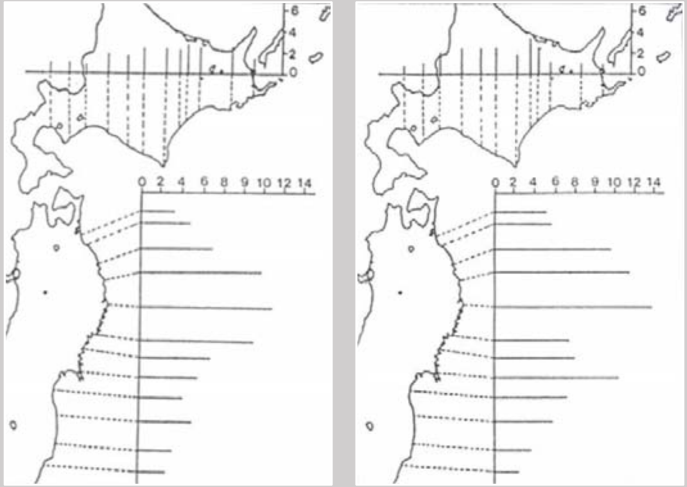
Tsunami Simulation Numerical Code

- **COMCOT v1.7**
  - **Tsunami generating**
    - For arbitrary earthquake that could make tsunami, seafloor deformation is calculated by using **Okada model(1985)**.
    - Okada model assumes homogenous isotropic elastic rectangular fault plane which has uniform displacement.
    - To determine geological traits of earthquake whose magnitude and occurrence location was known, Tatehata correlation(JMA, 1997) was used.



δ : *Dip angle of Fault plane*
λ : *Rake angle*
θ : *Strike angle*
h : *Focal depth*
L : *Length of Fault plane*
W : *Width of Fault plane*

Okada Fault modeling and geometry



(a) (b)

$$\log L = 0.5M - 1.88$$
$$\log U = 0.5M - 1.40$$
$$W \approx L/2$$

Tatehata correlation and Validation

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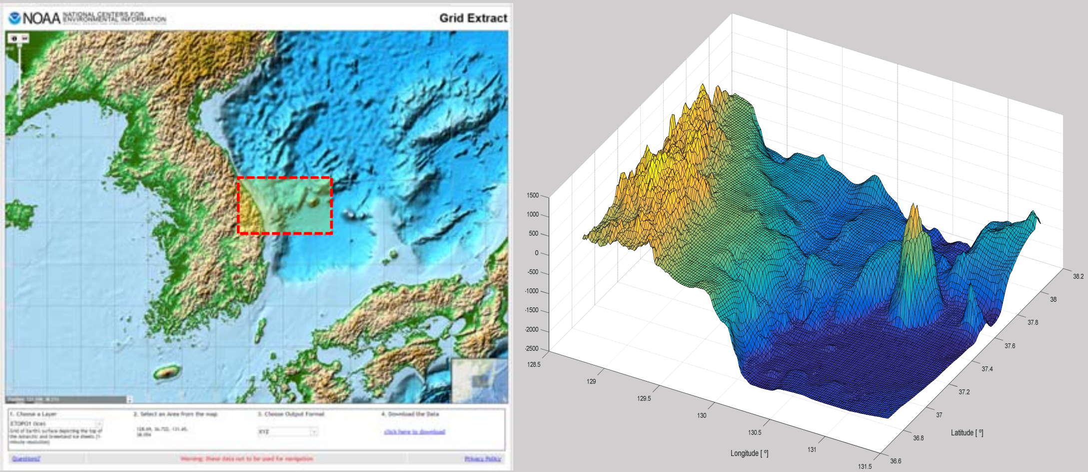
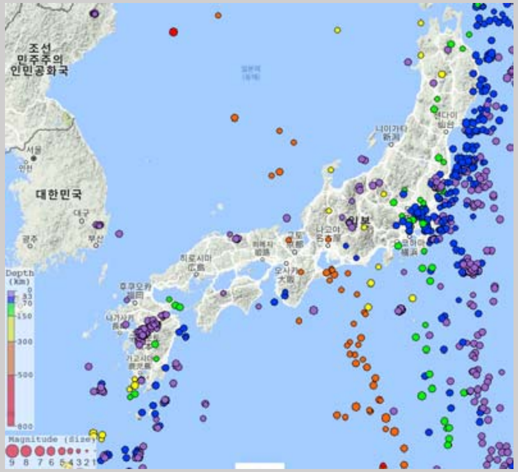
Generating Input Data

- **Geological Data Acquisition**
  - **Topology data** near Korea peninsula
    - Topology data could be obtained in NGDC (National Geophysical Data Center) of **NOAA**.
    - Global scale topology data could be provide for the analysis area in 1, 2, 5 degree increments.
  - **Faults geological data**
    - Faults geological data could be obtained in IRIS(Incorporated Research Institutions for Seismology).
    - Geological data of Faults which could generate tsunami could be obtained.
      - **Location of Faults (Longitude, Latitude)**
      - **Dip, Rake, Strike angle of Faults**
      - **Focal depth of epicenter**



Extracting topology data in xyz format



Earthquake data acquisition.

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Generating Input Data

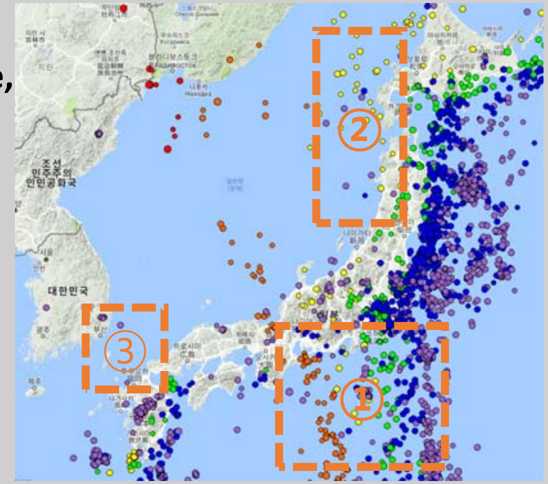
▪ Selection of Analysis Faults & Area

➢ Analysis Faults

- Based on previous studies, **Nankai trench, Northwest Japan Faults zone, and Korean strait** were selected as analysis faults.
- For conservative assumption, earthquakes generated tsunami simultaneously. Analysis case of earthquake combination is composed in order of magnitude of the earthquakes.

➢ Analysis Area

- Tsunami traits near Kori Nuclear power plant was main target of analysis, so 8 measuring points were located.
- Tsunami height was measured at measuring points.
- **Volume flux and water elevation** was measured at each point of analysis layer.



Selection of Analysis Faults

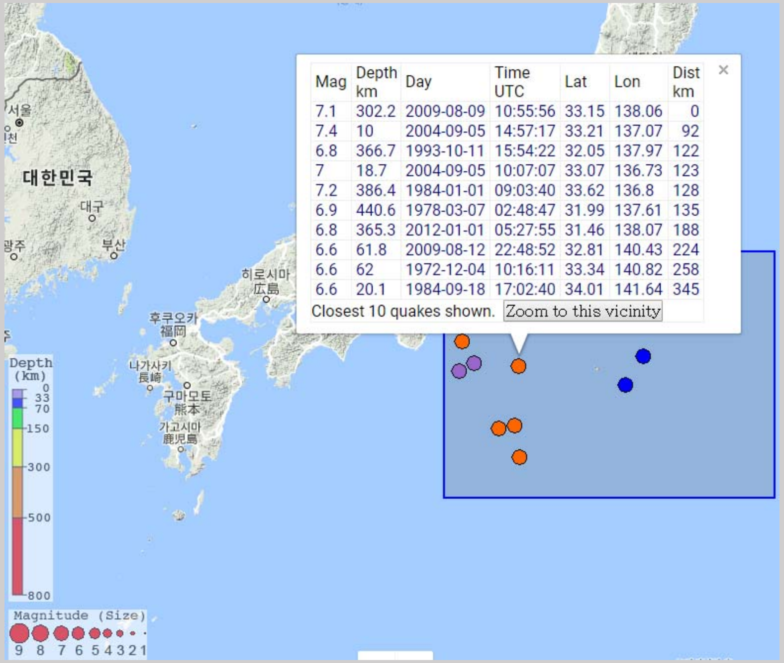
Measuring Points near Kori NPP

Selection of Analysis Faults

Measuring Point	P1	P2	P3	P4
Latitude [º]	35.3205	35.3159	35.3176	35.3141
Longitude [º]	129.2862	129.2867	129.2941	129.2946
Measuring Point	P5	P6	P7	P8
Latitude [º]	35.3210	35.3167	35.3275	35.3207
Longitude [º]	129.3028	129.3023	129.3109	129.3109

Generating Input Data

- **Faults Geological Data**
  - **Historical Faults**
    - **Nankai Trench, Northwest Japan faults zone and Korean strait** were candidates for a earthquake generating tsunami which could affect the safety of NPP in Korean peninsula. **Five earthquakes** were selected at Nankai trench and Northwest in the order of magnitude.
    - **Three historical faults** were selected at Korean strait.



Nankai Trench faults sampling

Nankai Trench faults information

Magnitude	Date	Location [°]	Focal Depth [km]	Strike angle [°]	Dip angle [°]	Rake angle [°]
7.4	2004.09.05	[33.21, 137.07]	10.0	79	46	72
7.2	1984.01.01	[33.62, 136.80]	386.4	31	23	137
7.1	2009.08.09	[33.15, 138.06]	302.2	86	17	168
7.0	2004.09.05	[33.07, 136.73]	18.7	277	38	100
6.9	1978.03.07	[31.99, 137.61]	440.6	18	19	133

Magnitude	Rupture Length [km]	Rupture Width [km]	Dislocation [cm]	IRIS ID
7.4	66.0693	33.0347	199.5262	1777461
7.2	52.4807	26.2404	158.4893	2963666
7.1	46.7735	23.3868	141.2538	2872654
7.0	41.6869	20.8435	125.8925	1775657
6.9	37.1535	18.5768	112.2018	188023

Generating Input Data

▪ Faults Geological Data

➢ Historical Faults

Northwest Japan faults information

Magnitude	Date	Location [°]	Focal Depth [km]	Strike angle [°]	Dip angle [°]	Rake angle [°]	Rupture Length [km]	Rupture Width [km]	Dislocation [cm]	IRIS ID
7.7	1993.07.12	[42.71, 139.28]	16.5	179	55	90	93.3254	46.6627	281.8383	319620
6.5	1993.08.07	[42.04. 139.86]	25.7	183	52	94	23.4423	11.7211	70.7946	318623
6.5	1996.12.22	[43.18, 138.92]	238.9	131	27	-38	23.4423	11.7211	70.7946	557925
6.2	1992.08.24	[41.94, 140.74]	128.9	178	87	58	16.5959	8.2979	50.1187	278758
5.6	1997.11.23	[39.92, 138.87]	15.0	15	52	86	8.3176	4.1588	25.1189	619881

Korean strait faults information

Magnitude	Date	Location [°]	Focal Depth [km]	Strike angle [°]	Dip angle [°]	Rake angle [°]	Rupture Length [km]	Rupture Width [km]	Dislocation [cm]	IRIS ID
5.1	2004.05.29	[36.61,130.06]	15.8	186	38	106	4.6774	2.3387	14.1254	1918893
5.0	1981.04.15	[35.78,130.10]	17.6	220	69	165	4.1687	2.0843	12.5893	2904568
4.7	2016.07.05	[35.54,129.90]	10.0	202	89	-179	2.9512	1.4756	8.9125	5187056

Generating Input Data

- **Faults Geological Data**
  - **Virtual Faults**
    - For conservative assumption, the Hypothetical extreme faults that didn't occur. It was assumed that large scale earthquakes occurred in the **Northwest Japan faults zone** and **Korean Strait**.
    - It was assumed that a magnitude **9.0 earthquake** occurred at the Northwest Japan Faults zone and **three earthquakes with a magnitude of 7.5** are assumed to occur simultaneously at the Korea Strait.

Northwest Japan faults information

Geological Data	
Magnitude	9.0
Location[°]	[41.10, 138.52]
Focal Depth [km]	23.27
Strike Angle [°]	312.4
Dip Angle [°]	30
Rake Angle [°]	30
Rupture Length [km]	416.8694
Rupture Width [km]	208.4347
Dislocation [cm]	1258.900

Korean straits faults information

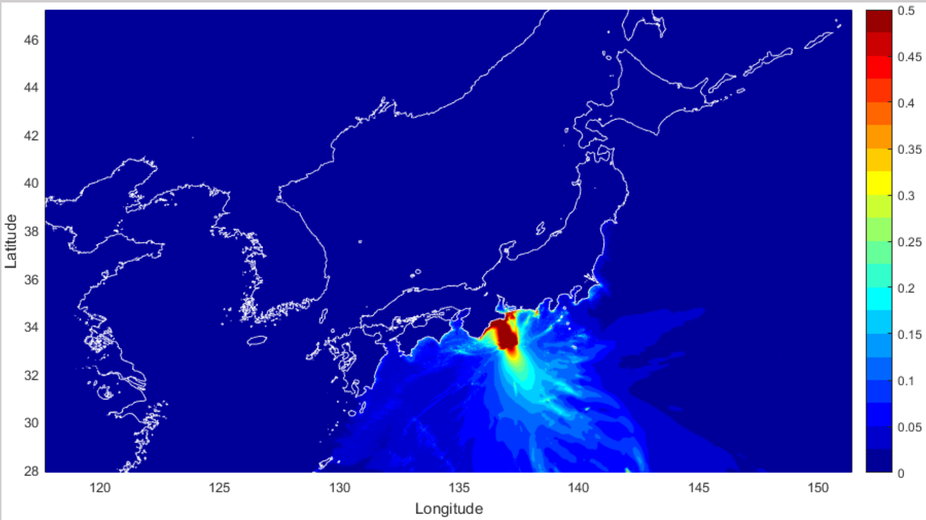
Magnitude	Location [°]	Focal Depth [km]	Strike angle [°]	Dip angle [°]	Rake angle [°]
7.5	[35.07,129.83]	7.2	300	35	106
7.5	[34.90,130.19]	12.0	315	65	23
7.5	[35.06,130.89]	302.2	307	68	46

Rupture Length [km]	Rupture Width [km]	Dislocation [cm]
74.1310	37.0655	223.8721
74.1310	37.0655	223.8721
74.1310	37.0655	223.8721

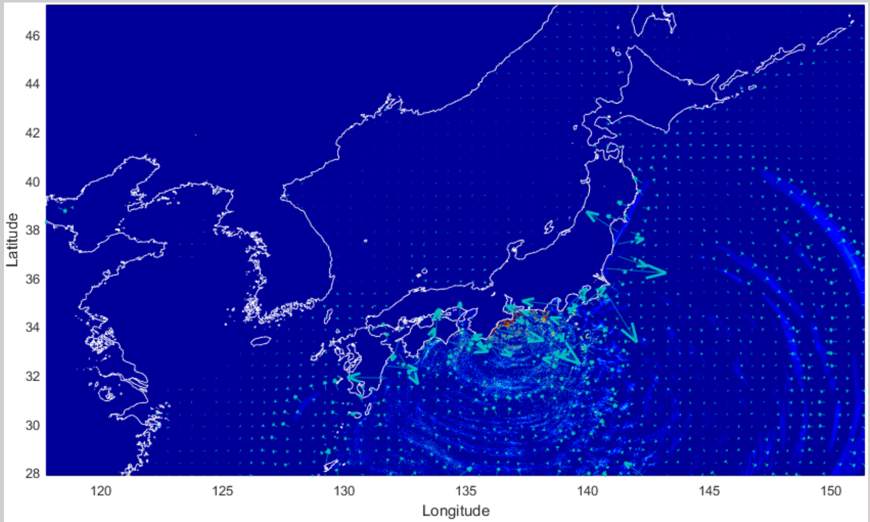
ESLAB

Result of Simulation

- **Result of Historical Earthquake Simulation.**
  - Earthquake in Nankai Trench
    - As a result of the most conservative assumptions, the effect of tsunami wave reaching the Kori Nuclear Power Plant was analyzed to be limited.
    - The tsunami has reached a peak of about 2m from Honshu, Japan, near the epicenter. To reach the vicinity of the Kori Nuclear Power Plant, it is necessary to bypass the southern part of Fukuoka in Japan.
    - These results are similar to previous study.(Lee, 2015)



Maximum Height of each point in Analysis layer after 18000s of earthquake occurrence.

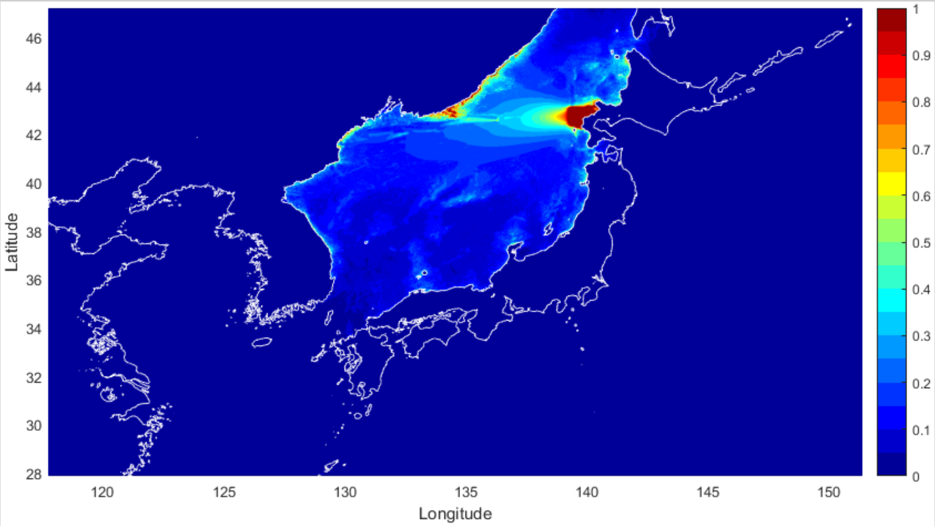


Velocity Vector at t = 7000s After earthquake.

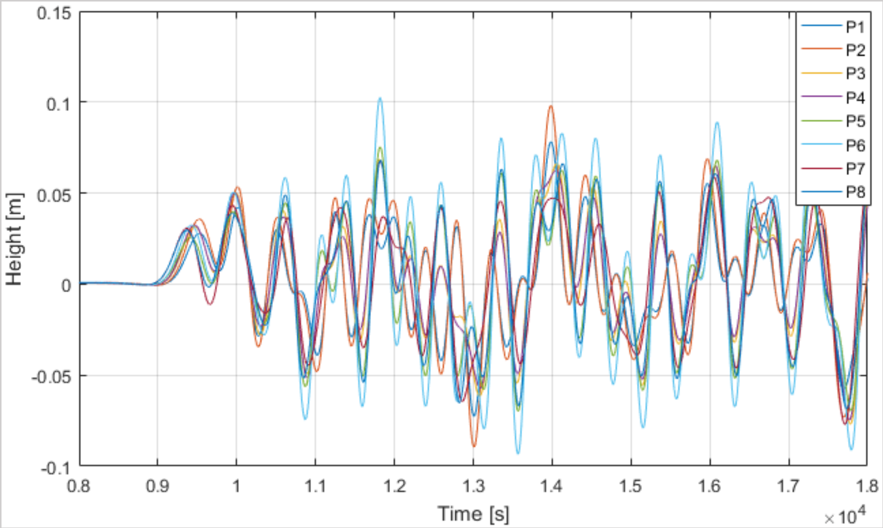
ESLAB

Result of Simulation

- **Result of Historical Earthquake Simulation.**
  - Earthquake in Northwest Faults zone.
    - it is **more influential** than the case of the Nankai trench because it reaches the Korean peninsula without detouring.
    - Since the **strike angle** is not directed toward the Korean Peninsula because it is based on historical earthquake data, its influence is less than expected.
    - The maximum / minimum level at the point of measurement is 0.1m, which means that it does not have a significant effect on the nuclear power plant.



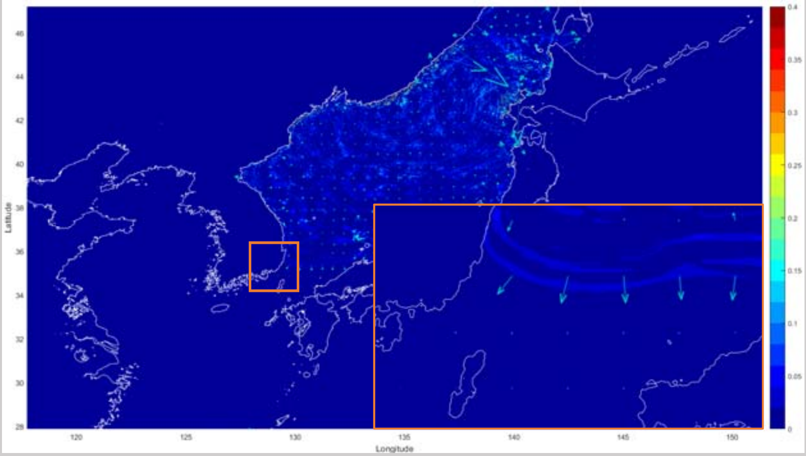
Maximum Height of each point in Analysis layer after 18000s of earthquake occurrence.



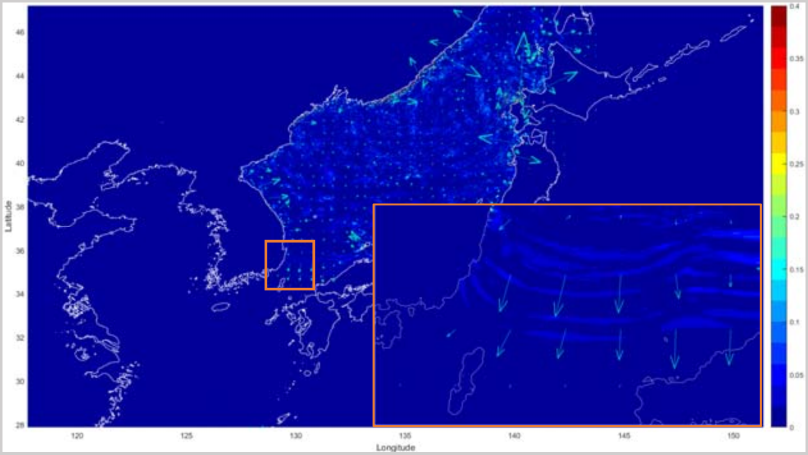
Water elevation at Measuring Point Of 5 Northwest Japan earthquakes case.

Result of Simulation

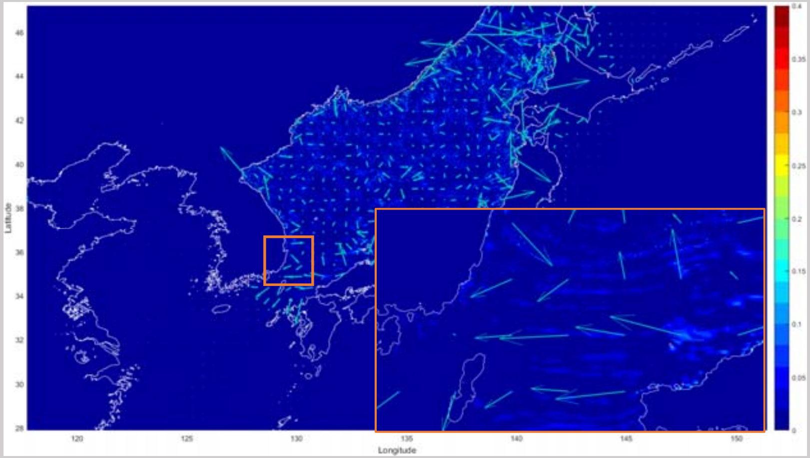
- **Result of Historical Earthquake Simulation.**
  - Earthquake in Northwest Faults zone.



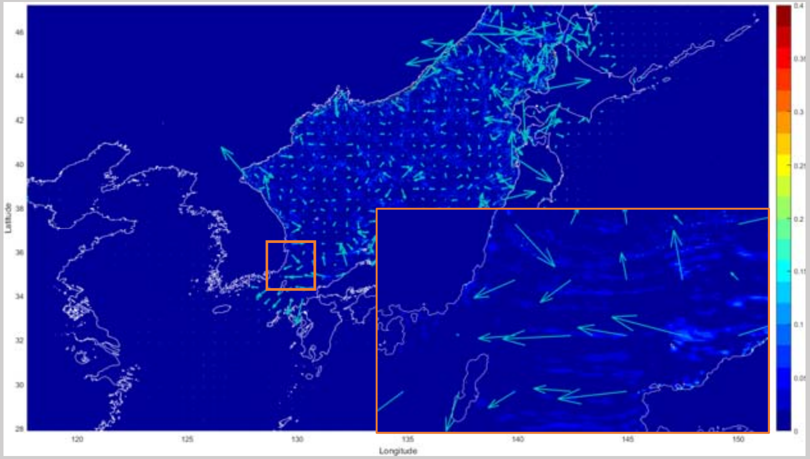
Velocity Vector at t = 8000



Velocity Vector at t = 9500



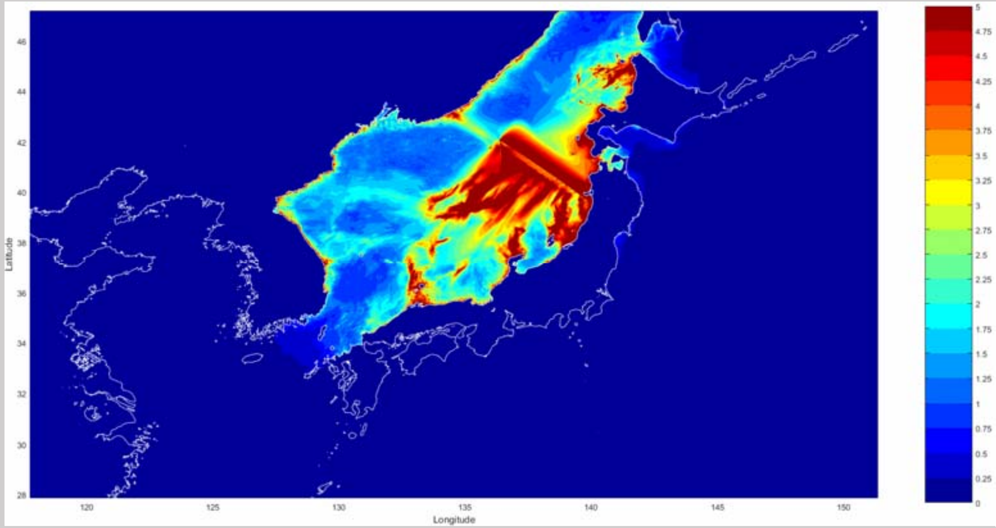
Velocity Vector at t = 12000



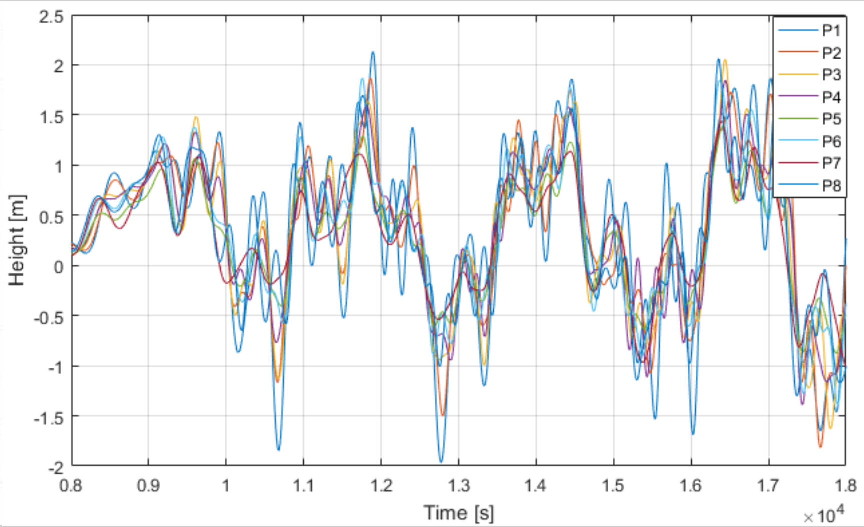
Velocity Vector at t = 14000

Result of Simulation

- **Result of Virtual Earthquake Simulation.**
  - Earthquake in Northwest Faults zone.
    - The strike angle of the historical earthquake was modified to direct the fault to the Kori Nuclear Power Plant and the geological size of the fault was set assuming an earthquake magnitude of 9.0.
    - In case of occurrence location of faults and other geological characteristics, The value which one historical earthquake had was used.
    - It is analyzed that the peak wave height is about 2.5m, and the first arriving wave reaches 8000 seconds after the earthquake. The lowest water level was 2m lower than the normal water level.



Maximum Height of each point in Analysis layer after 18000s of earthquake occurrence.



Water elevation at Measuring Point Of Extreme Northwest Japan earthquakes case.

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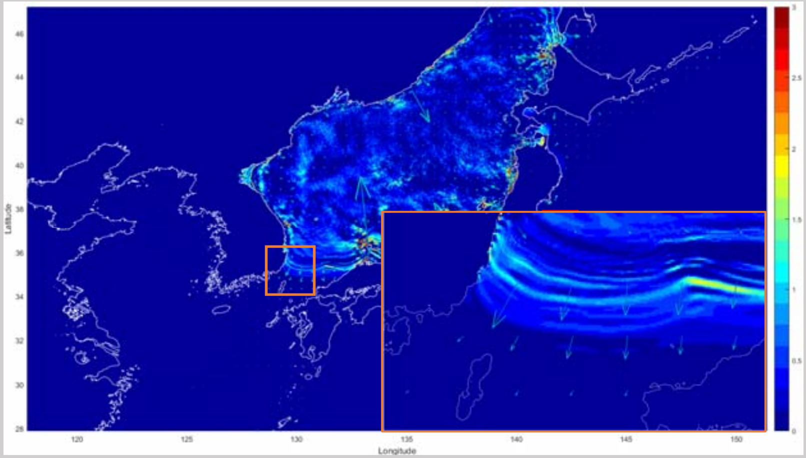
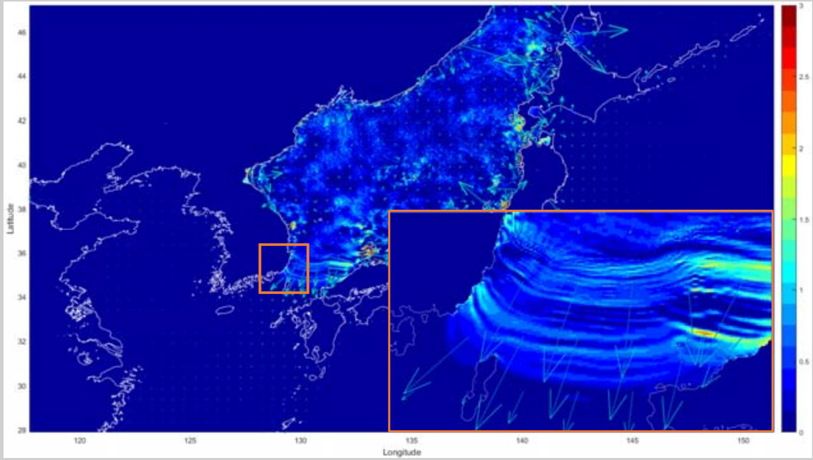
Result of Simulation

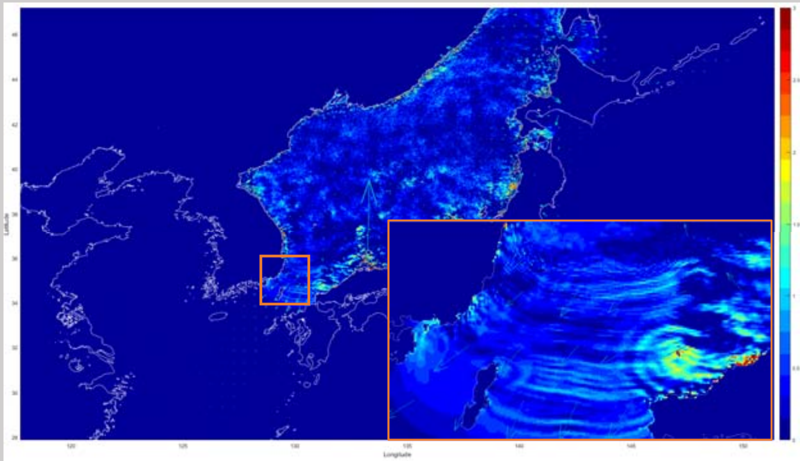
- **Result of Virtual Earthquake Simulation.**
  - Earthquake in Northwest Faults zone.



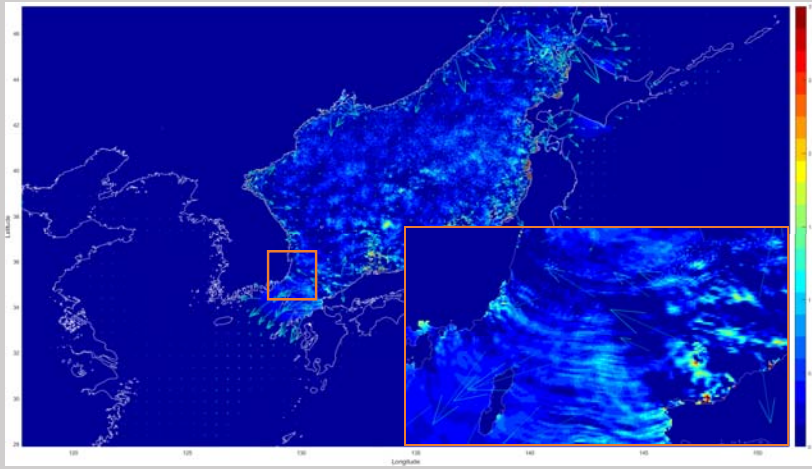
Velocity Vector at t = 8000



Velocity Vector at t = 9500



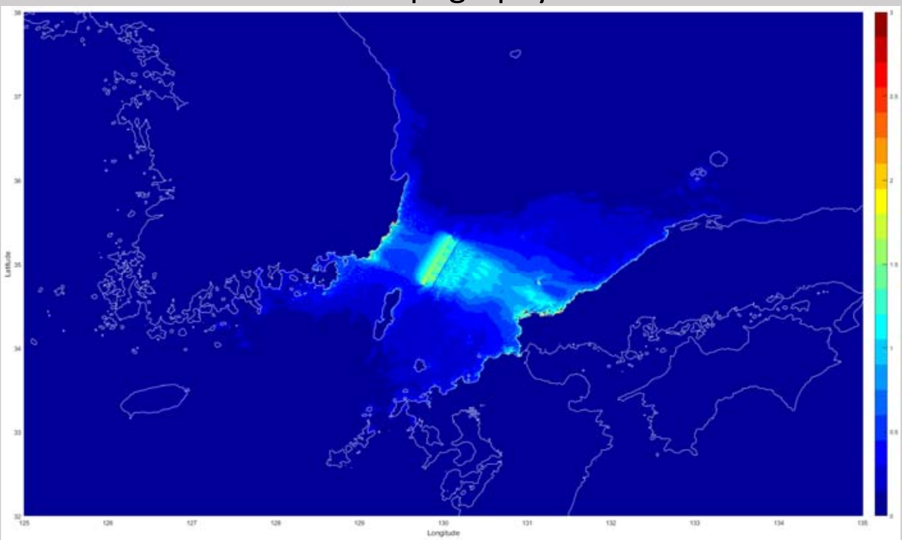
Velocity Vector at t = 12000



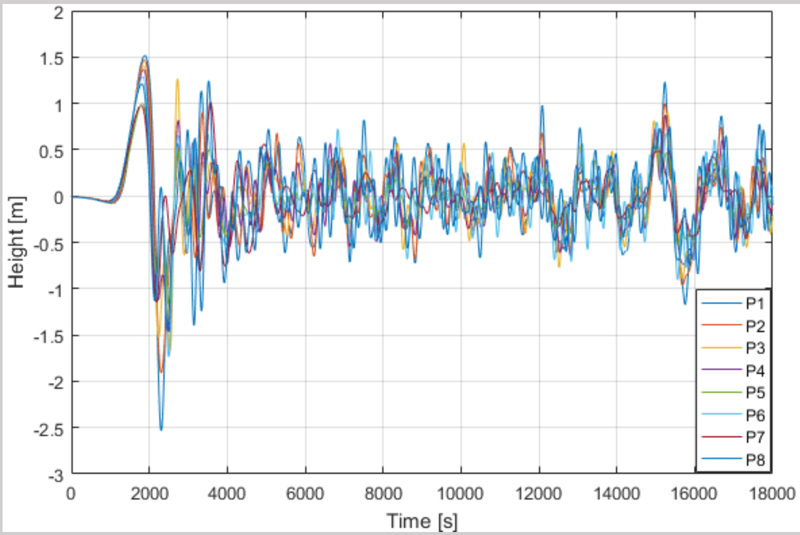
Velocity Vector at t = 14000

Result of Simulation

- **Result of Virtual Earthquake Simulation.**
  - Earthquake in Korea strait.
    - In the case of the Korean Straits, there are no large faults to cause a tsunami, but it is assumed that three earthquakes with a scale of 7.5 occur simultaneously for conservative calculation.
    - The geological characteristics of faults such as occurrence location, dip angle, slip angle excluding fault length, width and dislocation were substituted with characteristics of historical faults.
    - In this case, it was analyzed that the peak was about 1.5m and the lowest point was about -2.5m. It was confirmed that the Japanese side was more affected by the tsunami that occurred in Korea Strait due to the sea floor topography.



Maximum Height of each point in Analysis layer after 18000s of earthquake occurrence.

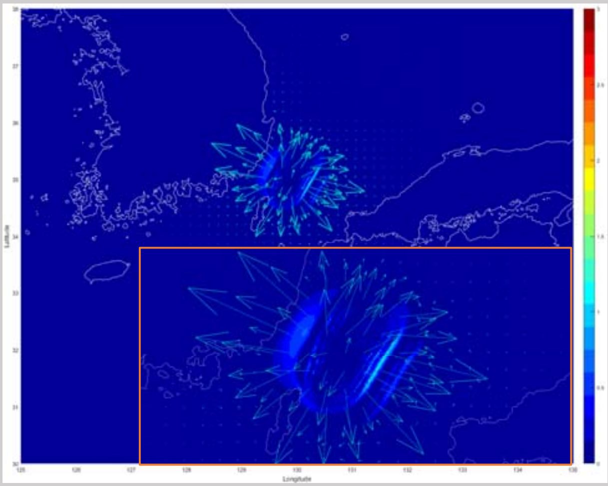


Water elevation at Measuring Point Of Extreme Korea strait case.

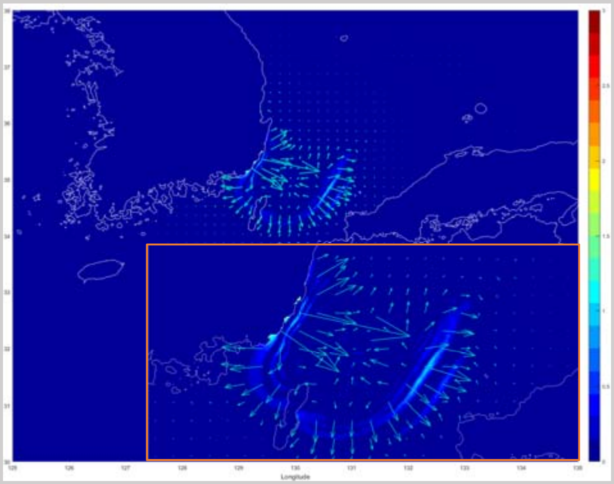
ESLAB

Result of Simulation

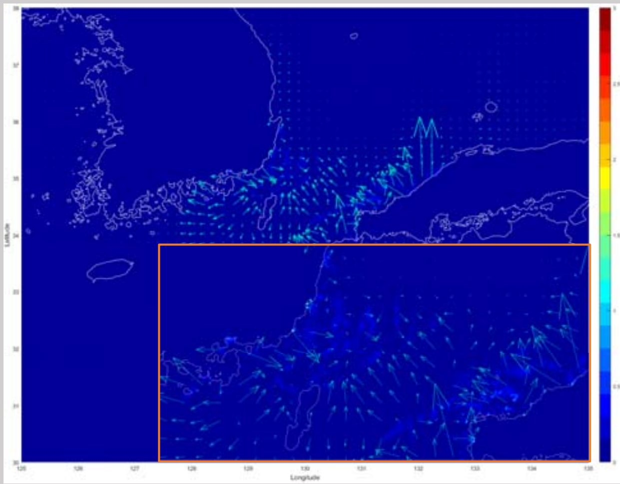
- **Result of Virtual Earthquake Simulation.**
  - Earthquake in Korea strait.
    - After the earthquake, the largest velocity vector was formed in the strike angle direction.
    - A tsunami occurred in the fault reaches the Korea peninsula in about 2000 seconds. But it does not reach the coast of Japan.
    - After the peak wave is generated, the wave oscillation is affected by the reflected waves on the shoreline, and this effect is long in this code, which is not considered the breaking wave phenomenon.
    - In case of a tsunami occurring in the near sea, Another analysis code is needed for the analysis of the wave after the first arrival wave because the influence of the reflection wave is more severe.



Velocity Vector at t = 1000



Velocity Vector at t = 2000



Velocity Vector at t = 6000

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Conclusion

- **Result of Earthquake Simulation.**

  - COMCOT, which enables global scale earthquake tsunami analysis, was selected as the analysis code. Bottom friction during the propagation of tsunami and Coriolis forces due to earth rotation were considered.
  - Underwater topography information was acquired at NOAA and the location and geological characteristics of historical earthquakes was acquired at IRIS.
  - Based on the acquired information, the COMCOT input data was prepared and the water elevation change with time near the Kori Nuclear Power Station in Korea was analyzed.
  - The analyzed earthquakes are historical earthquakes in the Nankai and Northeast Japan fault zones. In both cases, the Kori Nuclear Power Plant was not significantly affected.
  - An analysis was conducted on the occurrence of an earthquake with extreme assumptions of strike angle and magnitude at the Northwest Japan Fault and the Korea Strait.
  - As a result, it was found that the peak wave height and the minimum wave height near the Kori Nuclear Power Plant are about 2m, which does not seriously affect the safety of the nuclear power plant.

Thank you.

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Appendix 1. Numerical Scheme

- **COMCOT v1.7**
  - Numerical Method
    - Explicit leap-flog finite different scheme was used to solve.

$$\frac{\eta_{i,j}^{n+1/2}-\eta_{i,j}^{n-1/2}}{\Delta t}+\left\{\frac{1}{R\cos\varphi}\right\}_{i,j}\left\{\frac{P^n_{i+1/2,j}-P^n_{i-1/2,j}}{\Delta\psi}+\frac{(\cos\varphi_{i,j+\frac{1}{2}})Q^n_{i,j+1/2}-(\cos\varphi_{i,j-\frac{1}{2}})Q^n_{i,j-1/2}}{\Delta\varphi}\right\}=-\frac{h_{i,j}^{n+1/2}-h_{i,j}^{n-1/2}}{\Delta t}$$

    - The nonlinear convection terms are discretized with an upwind scheme.

$$\frac{\partial}{\partial x}\left\{\frac{P^2}{H}\right\}=\frac{1}{\Delta x}\left\{\boxed{\lambda_{11}}\frac{(P^n_{1+\frac{3}{2},j})^2}{H^n_{1+\frac{3}{2},j}}+\boxed{\lambda_{12}}\frac{(P^n_{1+\frac{1}{2},j})^2}{H^n_{1+\frac{3}{2},j}}+\boxed{\lambda_{13}}\frac{(P^n_{1-\frac{1}{2},j})^2}{H^n_{1+\frac{3}{2},j}}\right\}$$

$$\frac{\partial}{\partial y}\left\{\frac{PQ}{H}\right\}=\frac{1}{\Delta y}\left\{\boxed{\lambda_{21}}\frac{(PQ)^n_{i+\frac{1}{2},j+1}}{H^n_{i+\frac{1}{2},j+1}}+\boxed{\lambda_{22}}\frac{(PQ)^n_{i+\frac{1}{2},j}}{H^n_{i+\frac{1}{2},j}}+\boxed{\lambda_{23}}\frac{(PQ)^n_{i+\frac{1}{2},j-1}}{H^n_{i+\frac{1}{2},j-1}}\right\}$$

$$\frac{\partial}{\partial x}\left\{\frac{PQ}{H}\right\}=\frac{1}{\Delta x}\left\{\boxed{\lambda_{31}}\frac{(PQ)^n_{i,+1j+1/2}}{H^n_{i+\frac{1}{2},j+1}}+\boxed{\lambda_{32}}\frac{(PQ)^n_{i,j+1/2}}{H^n_{i+\frac{1}{2},j}}+\boxed{\lambda_{33}}\frac{(PQ)^n_{i-1,j+1/2}}{H^n_{i+\frac{1}{2},j-1}}\right\}$$

$$\frac{\partial}{\partial y}\left\{\frac{Q^2}{H}\right\}=\frac{1}{\Delta y}\left\{\boxed{\lambda_{41}}\frac{(Q^n_{1+\frac{3}{2},j})^2}{H^n_{1+\frac{3}{2},j}}+\boxed{\lambda_{42}}\frac{(Q^n_{1+\frac{1}{2},j})^2}{H^n_{1+\frac{3}{2},j}}+\boxed{\lambda_{43}}\frac{(Q^n_{1-\frac{1}{2},j})^2}{H^n_{1+\frac{3}{2},j}}\right\}$$

Variables in discretized nonlinear convection term

Variable(V)	$V \geq 0$	$V < 0$
$\boldsymbol{P^n_{i+1/2,j}}$	$\lambda_{11}=0$, $\lambda_{11}=1$, $\lambda_{13}=-1$	$\lambda_{11}=1$, $\lambda_{12}=-1$, $\lambda_{13}=0$
$\boldsymbol{Q^n_{i+1/2,j}}$	$\lambda_{21}=0$, $\lambda_{22}=1$, $\lambda_{23}=-1$	$\lambda_{21}=1$, $\lambda_{22}=-1$, $\lambda_{23}=0$
$\boldsymbol{P^n_{i,j+1/2}}$	$\lambda_{31}=0$, $\lambda_{32}=1$, $\lambda_{33}=-1$	$\lambda_{31}=1$, $\lambda_{32}=-1$, $\lambda_{33}=0$
$\boldsymbol{Q^n_{i,j+1/2}}$	$\lambda_{41}=0$, $\lambda_{42}=1$, $\lambda_{43}=-1$	$\lambda_{41}=1$, $\lambda_{42}=-1$, $\lambda_{43}=0$