Tool 2 :Methodologies of Hazard Assessment

/ Used for the Pilot Study

Contents

Methodology for Earthquake Hazard Assessment

The basic procedure of earthquake hazard assessment is shown in Figure-1. The precise of each item is stated below.

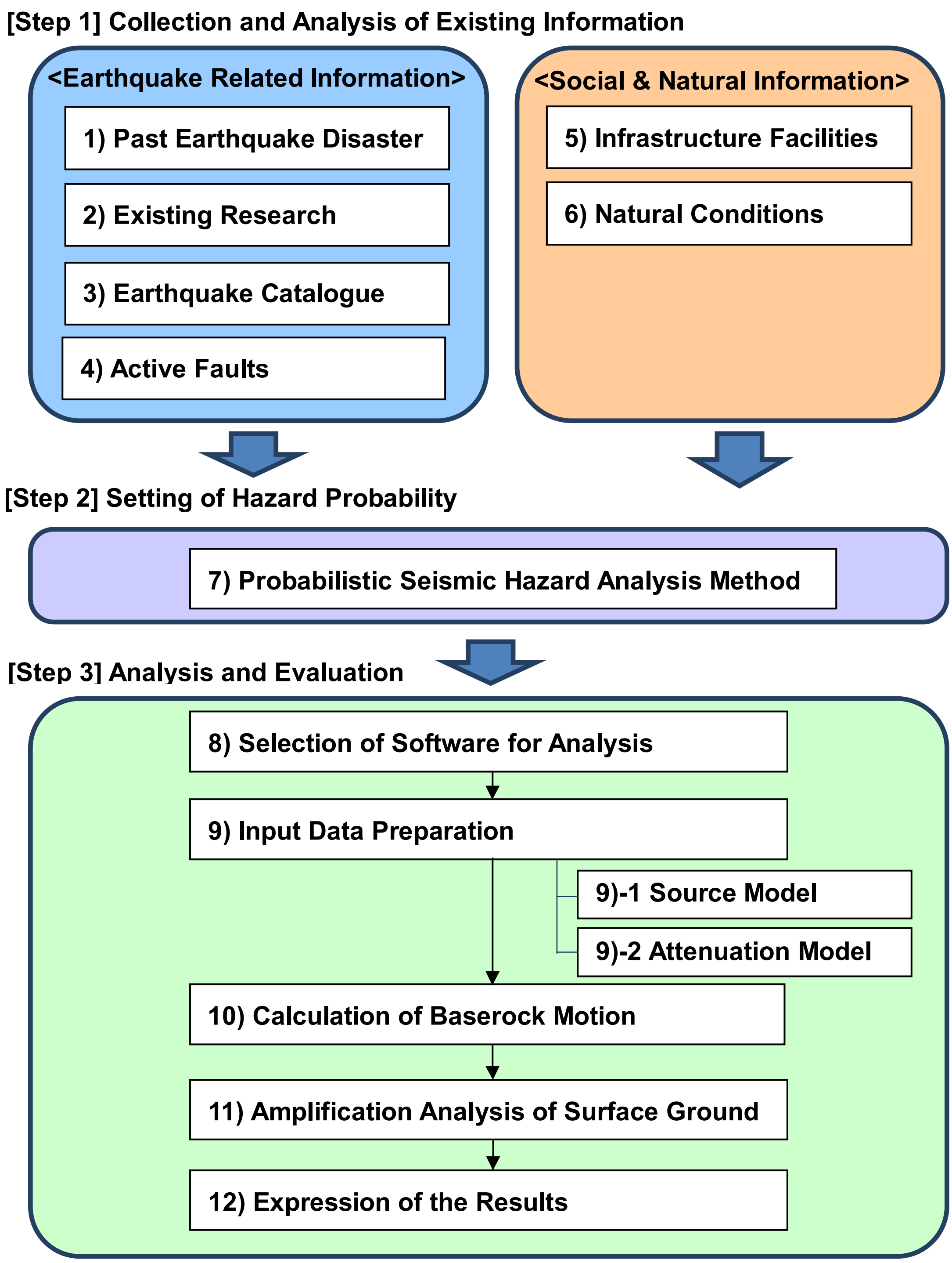

Figure-1 Basic Procedure of Earthquake Hazard Assessment

[Step 1] Collection and Analysis of Existing Information

The earthquake related information such as the seismic intensity distribution and the disaster records by past earthquakes are collected. The social and natural condition such as the industrial facilities that the industrial agglomerated area is relying on and the geological information of the site are also collected.

<Earthquake Related Information>

1) Past Earthquake Disaster Records

The seismic intensity distribution data and the disaster records by the past experienced earthquakes in the study area are collected from the following organizations. The frequency and the extent of earthquake disaster can be understood by the analysis of the year of occurrence, earthquake magnitude, seismic intensity distribution and damage distribution.

- National agency for disaster management
- Local government agency for disaster management
- University and Public research institute
- International research institute

  ex.) CRED (Centre for Research on the Epidemiology of Disaster): EM-DAT, International Disaster Database, http://www.emdat.be/database

2) Existing Research and Study

The existing research and study results of the earthquake hazards in the area are collected from the following organizations. The paleo seismic study, deterministic seismic hazard map for a scenario earthquake, probabilistic seismic hazard map and the ground amplification study of the earthquake motion are the main fields of collection.

- University and Public research institute
- International research institute and Project

  ex.) GSHAP (Global Seismic Hazard Assessment Program),
  http://www.seismo.ethz.ch/static/gshap/

3) Earthquake Catalogue

Earthquake catalogue is the list of past occurred earthquakes including the origin, depth, year/month/day/time of occurrence, seismic magnitude and so on. Plenty of catalogues with various contents and extents are produced and compiled by many researchers and research institutes in the world. As the earthquake catalogue is one of the bases of earthquake hazard analysis, the catalogue which cover longer period is preferable. The catalogue should include the earthquakes occurred within some hundred kilometers from the study area.

4) Active Faults

Active fault is the fault which may generate the earthquakes in the future. The data about the active fault such as the location, length and activity are the necessary for earthquake hazard assessment. The governmental institutes regarding the geology and the geological department of the university study the active faults and prepare the active fault maps in many countries.

<Social & Natural Information>

5) Infrastructure Facilities

The distribution of the infrastructure facilities that industrial agglomerated area is relying is studied. The following transportation facilities and the lifeline facilities are the main target.

- Transportation Facilities: Roads, Railroads, Ports, Airports
- Lifeline Facilities: Electricity, Water Supply, Sewage, Communication

The actual region to assess the earthquake hazard is decided based on the distribution of infrastructure facilities. As the infrastructure facilities spread widely outside of industrial agglomerated area, the region of hazard analysis does not remain in the industrial agglomerated area in general.

6) Natural Condition

The topography maps or DEM are collected as the basic information of the study area.
Also, the geological, geomorphological and land use maps are collected to assess the amplification of the earthquake motion by the subsurface grounds. These maps are usually prepared by the public geological institutes and universities.

[Step 2] Setting of Hazard Probability

The methodology of seismic hazard assessment is roughly divided into deterministic methodology and probabilistic methodology. By the deterministic methodology, earthquake ground motion is calculated if the specific earthquake source fault has been activated. The earthquake ground motion distribution by the future possible earthquake can be calculated precisely, but to estimate when the calculated earthquake ground motion will be realized is difficult because it is impossible to predict the future earthquake by current technology. By the probabilistic method, the expected earthquake ground motion within a certain period at the study point is calculated considering all the earthquake sources around the study point reflecting the possibility of each sources. Therefore, the earthquake motion distribution by probabilistic method is not the estimation of the earthquake motion distribution by future probable earthquake but the ensemble of independent expected earthquake motion at each point. The deterministic method is commonly used for disaster management purpose and the probabilistic methodology is usually used for zoning in the building seismic code or earthquake insurance system etc.
It is desirable to use the probabilistic method in the seismic hazard assessment for area BCP because the probability of the hazard is important. The hazard that has high possibility to occur in the lifetime of the industrial facilities is considered in area BCP, therefore to estimate the probability of the hazard is essential component in the analysis.

7) Methodology of Probabilistic Seismic Hazard Analysis

The combination of earthquake ground motion at a certain point and the probability to experience at least the ground motion in a certain period is calculated by the probabilistic seismic hazard analysis method. The flow of the analysis is shown in Figure-2. The general steps of the analysis are as follows.

1) Set up the model of seismic activity around the study point. Not only the earthquakes that the source faults are clearly known but the earthquakes that the earthquake sources are not known and definite estimation of the magnitude and the location of future event is difficult should be included.

2) Estimate the probability of the magnitude, probability of the distance from the study point and the probability of the occurrence of the modeled earthquakes.

3) Set up the probability model to estimate the earthquake ground motion if the magnitude of the earthquake and the distance from the study point are given. The empirical attenuation equation and the dispersion of the equation are usually used.

4) Calculate the probability that the earthquake ground motion at the study point by modeled earthquake become larger than a certain value in a certain period.

5) Steps 1) to 4) are carried out for each modeled earthquake and all the probabilities are aggregated. The probability to experience a certain earthquake ground motion at least once in a certain period at the study point is calculated as a result.

McGuire, R. K. (2004) [1)] is recommended as a textbook of probabilistic seismic hazard analysis.

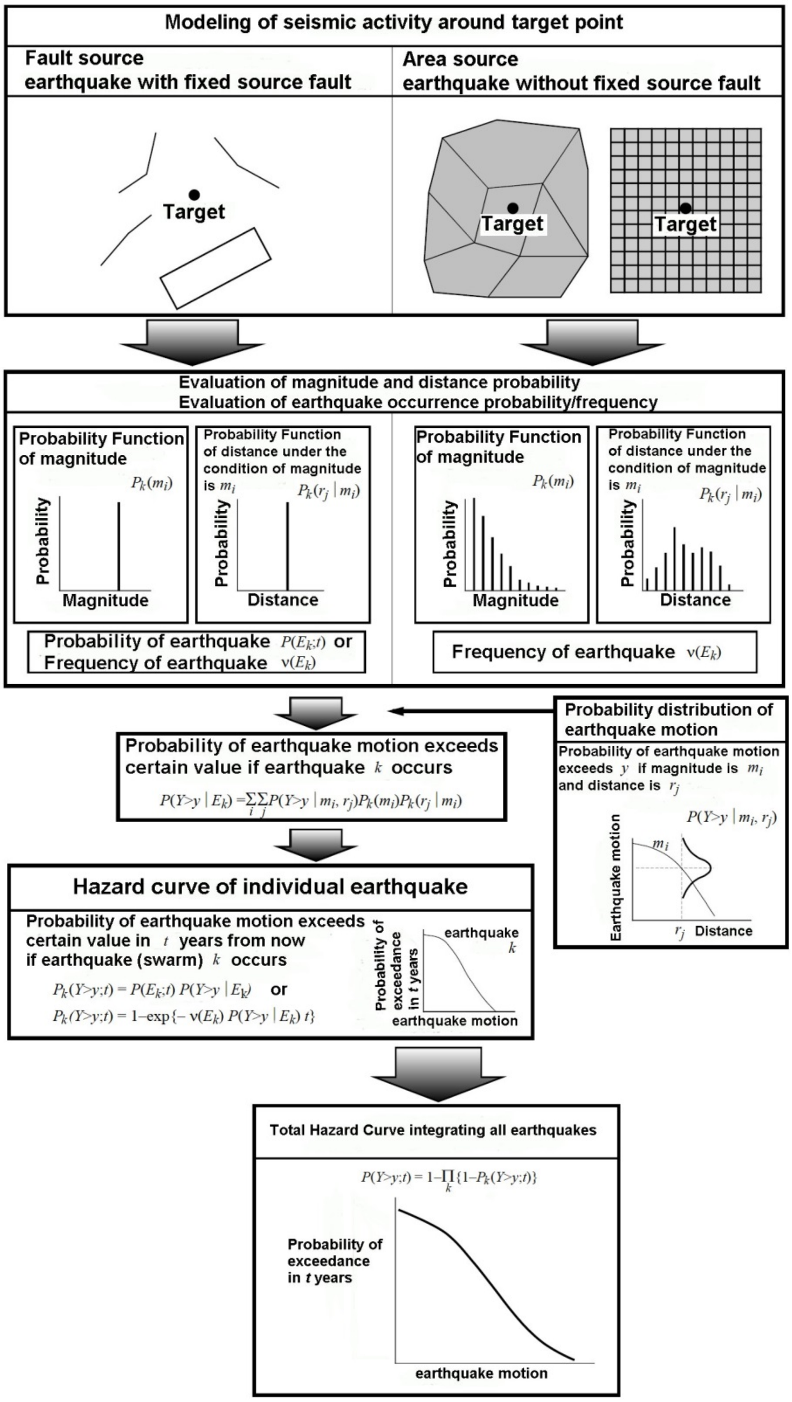

Figure-2 Flowchart of probabilistic seismic hazard analysis (NIED(2005)[2], original in Japanese)

As shown above, the earthquake ground motion according to the probability can be known from the hazard curve which is available by the probabilistic seismic hazard analysis. Therefore, it is not necessary to decide one probability to study before the calculation. Once hazard curve is created, the earthquake ground motion corresponding to the any probability is known.

[Step 3] Analysis and Evaluation

The probabilistic seismic hazard analysis is performed based on the collected and analyzed information, by setting an appropriate model.

8) Selection of Software for Analysis

As the probabilistic seismic hazard analysis involves complicated numerical calculation, many computing programs are developed and some of them are freely available. Among them, SEISRISK, FRISK, CRISIS, NSHMP and OpenSHA are famous but they are intended to be used by the researchers or the engineer with expert knowledge. Danciu et al. (2010)[3)] compiled the precise information about the probabilistic seismic hazard analysis programs. Table-1 is the general information of the major software for probabilistic seismic hazard analysis by Danciu et al. (2010).

Table-1 Major software for probabilistic seismic hazard analysis

Software Name	Version	Developer	Availability	Documentation	GUI	Program Language
CRISIS	6.0 (2007)	Ordaz, M., et al	Free upon Request	User Manual	Yes	Visual Basic
EQRM	3.2 (2009)	Robinson, D. et al.	Open Source	User Manual	No	Python
FRISK88M	1.8	R. McGuire	Proprietary	User Manual	No	Fortran
MoCaHAZ	2004	S. Wiemer	Free upon Request	Self-Explained	No	MATLAB
MRS	3.0	R. Laforge	Free upon Request	User Manual	No	C
NSHMP	2008	Frankel et al.	Free-Download	Self-Explained	No	Fortran, C
OHAZ	2.1	B. Zabikovic	Free upon Request	User Manual	Yes	Java
OpenSHA	2009	E. H. Field et al.	Open Source	Self-Explained	No	Java
SEISRISK IIIM	1996	Bender , B Perkins, D.M, R. LaForge	Free-Download	User Manual	No	Fortran
SeisHaz	2005	M. Stirling et al	Proprietary	Self-Explained	No	Fortran

EZ-FRISK is the expanded commercial version of FRISK and offered by Risk Engineering Inc. The analysis by EZ-FRISK is comparatively easy because the earthquake source model and attenuation formula are provided with computing program.

9) Input Data Preparation

9)-1 Source Model

The earthquake source model should include all the seismic activities within several 100km from the study point. The active faults in the area are modeled at first because earthquake basically occurs by the activity of the fault. However, not all the active faults are known or studied of the properties, the earthquakes that the earthquake sources are not known and definite estimation of the magnitude and the location of future event is difficult are modeled as the background seismic activities also. As the creation of the earthquake source model needs high grade capacity and expert knowledge, earthquake modeling is usually conducted in university or public research institute. Therefore, to conduct originally new probabilistic seismic hazard analysis, the earthquake source model should be given from academic organization.

9)-2Attenuation Formula

The so-called empirical attenuation formula is used to calculate the earthquake ground motion from the magnitude of the earthquake and the distance between epicenter and the study point. Many researchers proposed various attenuation formulas for several decades. They have different features based on the database and the algorithm that were used to create the formula, and they also have the limitation of applicability. It is desirable to use the attenuation formula that was intended to use the study site. The newer proposed attenuation formula is generally desirable to use because newer formula is derived based on the more precise recent earthquake observation records.

10) Calculation of Baserock Motion

The baserock motion is calculated based on the prepared input data set. The calculated earthquake ground motion by the probabilistic method is expressed as follows.

a) The probability that the study site experiences a certain earthquake ground motion.
  ex. The probability is 10% in 50 years to experience 100 gals or more.

b) The earthquake ground motion value for a certain probability.
  ex. 100 gals or more will be experienced on the probability of 10% in 50 years.

The probability is expressed as the combination of the period and the probability in the period. If the seismic activity is uniform not depending on the year, probability can be expressed by annual probability.

11) Amplification Analysis of Surface Ground

The earthquake ground motion is affected by not only the magnitude and the distance but by the ground condition around the study area. The seismic wave is amplified by the surface grounds and the extent of amplification is different depending on the structure of the surface ground. Some of the empirical attenuation formula includes the effect of surface ground amplification but another method is usually used to evaluate the wide area. At first, the earthquake motion at the bedrock is calculated by the empirical attenuation formula and the amplification of the surface ground is multiplied to get the surface ground motion.

There are several methodology to evaluate the amplification characteristics of surface grounds; for example, based on the surface soil, based on the average S wave velocity of surface soil layers and numerical response analysis using the ground structure model. The suitable method is selected considering the available data, necessary work and budget.

The methdology by FEMA(1995)[4] is well known as the simple and easy way to evaluate the amplification by subsurface ground. The ground classification and amplification factor are shown in Table-2 and Table-3. They are developed in U.S.A. and used in many countries recently. The soil profile, average S wave velocity of upper 30 meters and N value are used to define the site class. If the average S wave velocity is available by geophysical survey or N value is known by drilling survey, ground classification can be done by these data. If these data are not available, ground will be classified based on the geology map or geomorphology map.

Table-2 NEHRP Classification

Site Class	Profile	Average S-wave velocity of the upper 30 meters	N value
A	Hard rock	> 1500 m/sec	
B	Rock	1500 ≥ Vs > 760 m/sec	
C	Very dense soil and soft rock	760 ≥ Vs > 360 m/sec	N > 50
D	Stiff soil	360 ≥ Vs > 180 m/sec	50 ≥ N ≥ 15
E	Soil	180 m/sec ≥ Vs	15 > N

Table-3 NEHRP Amplification

Site Class B Spectral Acceleration	**Site Class**				
	A	**B**	**C**	**D**	**E**
Short-Period, S_{AS} (g)	**Short-Period Amplification Factor, F_A**				
≤ 0.25	0.8	1.0	1.2	1.6	2.5
0.50	0.8	1.0	1.2	1.4	1.7
0.75	0.8	1.0	1.1	1.2	1.2
1.0	0.8	1.0	1.0	1.1	0.9
≥ 1.25	0.8	1.0	1.0	1.0	0.9

12) Expression of the Results

The calculated value is a physical quantity, such as peak ground acceleration or velocity. The seismic intensity is another expression of the strength of the ground vibration by the earthquake and more popularly understandable. The seismic intensity is also used to estimate the damage based on the past earthquake disaster experiences. Though the relation between PGA or PGA with seismic intensity is not one by one, they are usually converted to seismic intensity by the empirical formula.

[References]

1) McGuire, R. K. (2004). Seismic Hazard and Risk Analysis, Earthquake Engineering Research Institute, Berkeley.

2) National Research Institute for Earth Science and Disaster Prevention (NIED), 2005, A Study on Probabilistic Seismic Hazard Maps of Japan, Technical Note of the National Research Institute for Earth Science and Disaster Prevention, No. 275.

3) Danciu, L., M. Pagani, D. Monelli and S. Wiemer (2010), GEM1 Hazard: Overview of PSHA Software, GEM Technical Report 2010-2.
4) Federal Emergency Management Agency, 1995. FEMA 222A and 223A - NEHRP Recommended Provisions for Seismic Regulations for New Buildings, 1994 Edition, Washington, D. C., Developed by the Building Seismic Safety Council (BSSC) for the Federal Emergency Management Agency (FEMA)

[Example of Seismic Hazard Analysis]　Cavite, Laguna and south of Metro Manila

8) Selection of Software for Analysis

EZ-FRISK Ver. 7.62 was used in this analysis.

9)-1Source Model

The source models provided with EZ-FRISK software are used in this analysis. The source model for the Philippines is shown in Figure-3. The surface projection of source models along the plate boundary is shown in rectangular shape and the inland faults are shown as folded lines. The seismic activities that the location and the magnitudes are not identified in advance are modeled as the comparatively broad area sources.

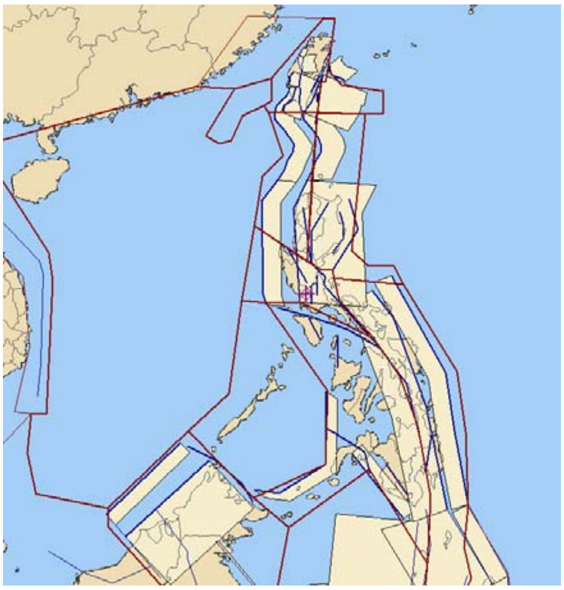

Figure-3　Source models for the Philippines

9)-2Attenuation Formula

The empirical attenuation formula for ASEAN region is not known. In this analysis, following formula based on the world wide earthquake observation records are adopted.

[for shallow crustal earthquake]

- ✓ Abrahamson and Silva (2008)[1)]
- ✓ Boore and Atkinson (2008)[2)]
- ✓ Campbell and Bozorgnia (2008)[3)]
- ✓ Chiou and Youngs (2008)[4)]

[for deep plate boundary earthquake]

- ✓ Atkinson and Boore (2003)[5)]
- ✓ Youngs et al. (1997)[6)]

10) Calculation of Baserock Motion

The acceleration distribution on the ground with Vs=760 m/sec is shown in Figure-4. The expected probability of occurrence is at least once in 200 years (200 years probability). The calculated acceleration is larger in north.

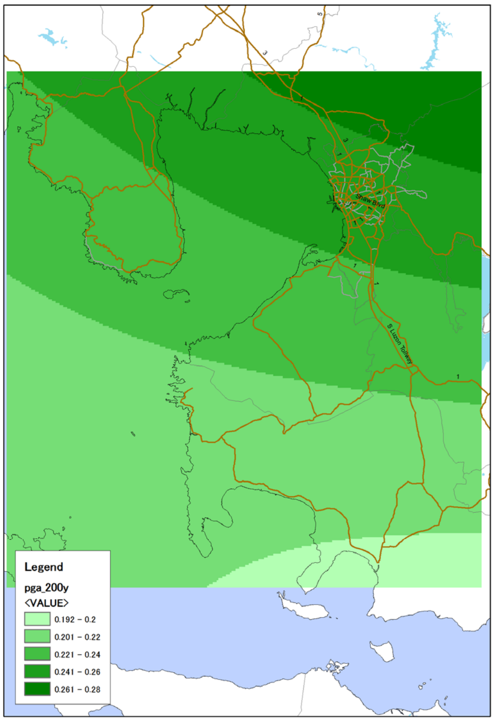

Figure-4　Baserock acceleration distribution (expected for 200 years, unit: g)

11) Amplification Analysis of Surface Ground

Following three data sets are used for the ground classification of the Philippines.

a) Proposed Vs30 value (average sheer wave velocity of the ground over 30m from surface) in Metro Manila, north of Cavite and Laguna by Grutas and Yamanaka (2012)[7].

b) Vs30 value calculated from the database of the ground model by JICA (2004)[8].

c) Geological maps with 1/50,000 scale by National Mapping and Resource Information Authority (NAMRIA)

The Vs30 values of a) and b) are used. Also, the geological time was read from c) and ground was classified as follows. If several classifications are possible, the geological classification with largest amplification value is adopted. The ground classification map is shown in Figure-5.

- ✓ Class B: Tertiary and before
- ✓ Class C: Pleistocene
- ✓ Class D: Holocene
- ✓ Class E: River deposit and marine deposit in Holocene

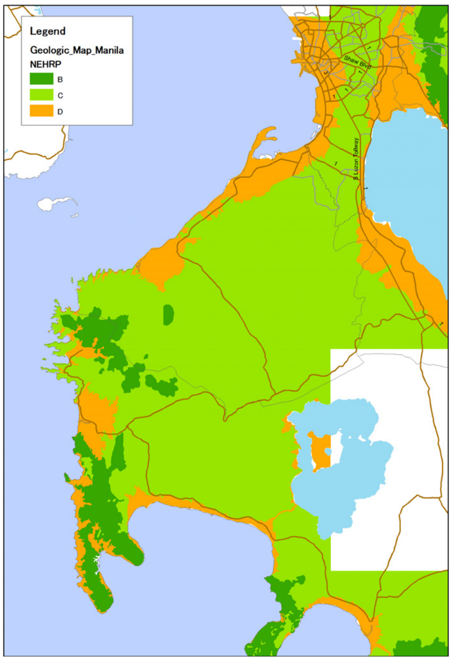

Figure-5　Ground classification

12) Expression of the Results

The acceleration at the ground surface is calculated multiplying the amplification factor to the acceleration value at the baserock. The acceleration value is converted to seismic intensity in MMI scale by empirical equation and shown in Figure-6. In this study, peak ground acceleration is converted to seismic intensity in MMI scale following empirical formula by Trifunac and Brady (1975)[9].

$\log PGA = 0.014 + 0.30*I$　　PGA: peak ground acceleration (gal),　I: seismic intensity (MMI)

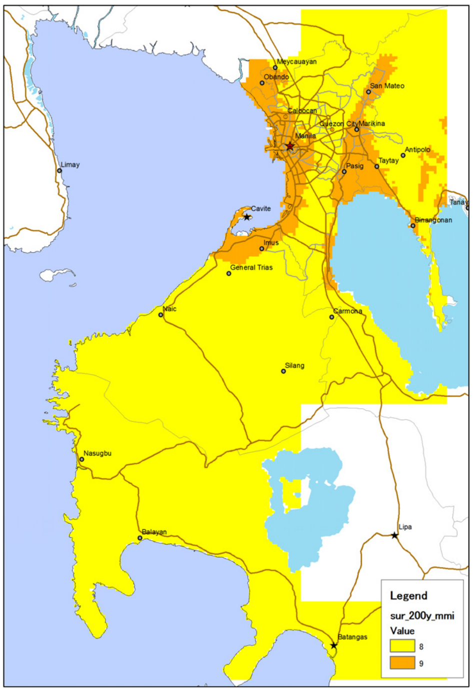

Figure-6　Seismic intensity distribution (expected for 200 years in MMI scale)

[References]

1) Abrahamson N. and W. Silva, 2008, Summary of the Abrahamson & Silva NGA Ground-Motion Relations, Earthquake Spectra, Vol. 24, Issue 1, pp. 67-97.
2) Boore D. M. and G. M. Atkinson, 2008, Ground-Motion Prediction Equations for the Average Horizontal Component of PGA, PGV, and 5%-Damped PSA at Spectral Periods between 0.01 s and 10.0 s, Earthquake Spectra, Vol. 24, Issue 1, pp. 99-138.
3) Campbell K. W. and Y. Bozorgnia, 2008, NGA Ground Motion Model for the Geometric Mean Horizontal Component of PGA, PGV, PGD and 5% Damped Linear Elastic Response Spectra for Periods Ranging from 0.01 to 10 s, Earthquake Spectra, Vol. 24, Issue 1, pp. 139-171.
4) Chiou B. S.-J. and R. R. Youngs, 2008, An NGA Model for the Average Horizontal Component of Peak Ground Motion and Response Spectra, Earthquake Spectra, Vol. 24, Issue 1, pp. 173-215.
5) Atkinson G. M. and D. M. Boore, 2003, Empirical Ground-Motion Relations for Subduction-Zone Earthquakes and Their Application to Cascadia and Other Regions, Bull. Seism. Soc. Amer., Vol. 93, No. 4, 1703-1729.
6) Youngs, R. R., S. -J. Chiou, W. J. Silva, and J. R. Humphrey, 1997, Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes, Seism. Res. Let., Vol. 68, No. 1, 58-73.
7) Grutas R. and H. Yamanaka, 2012, Mapping the Seismic Site Conditions in Metro Manila, Philippines based on Microtremor Measurements, Topographic Data and Geomorphology, Joint Conference Proceedings of 9th International Conference on Urban Earthquake Engineering/ 4th Asia Conference on Earthquake Engineering.
8) JICA, 2004, Earthquake Impact Reduction Study for Metropolitan Manila, Republic of the Philippines, Final Report, Vol.3.
9) Trifunac M. D. and A. G. Brady, 1975, On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Ground Motion, Bull. Seism. Soc. Amer., Vol. 65.

Methodology for Tsunami Hazard Assessment

The basic procedure of earthquake originated tsunami hazard assessment is shown in Figure-1. The precise of each item is stated below.

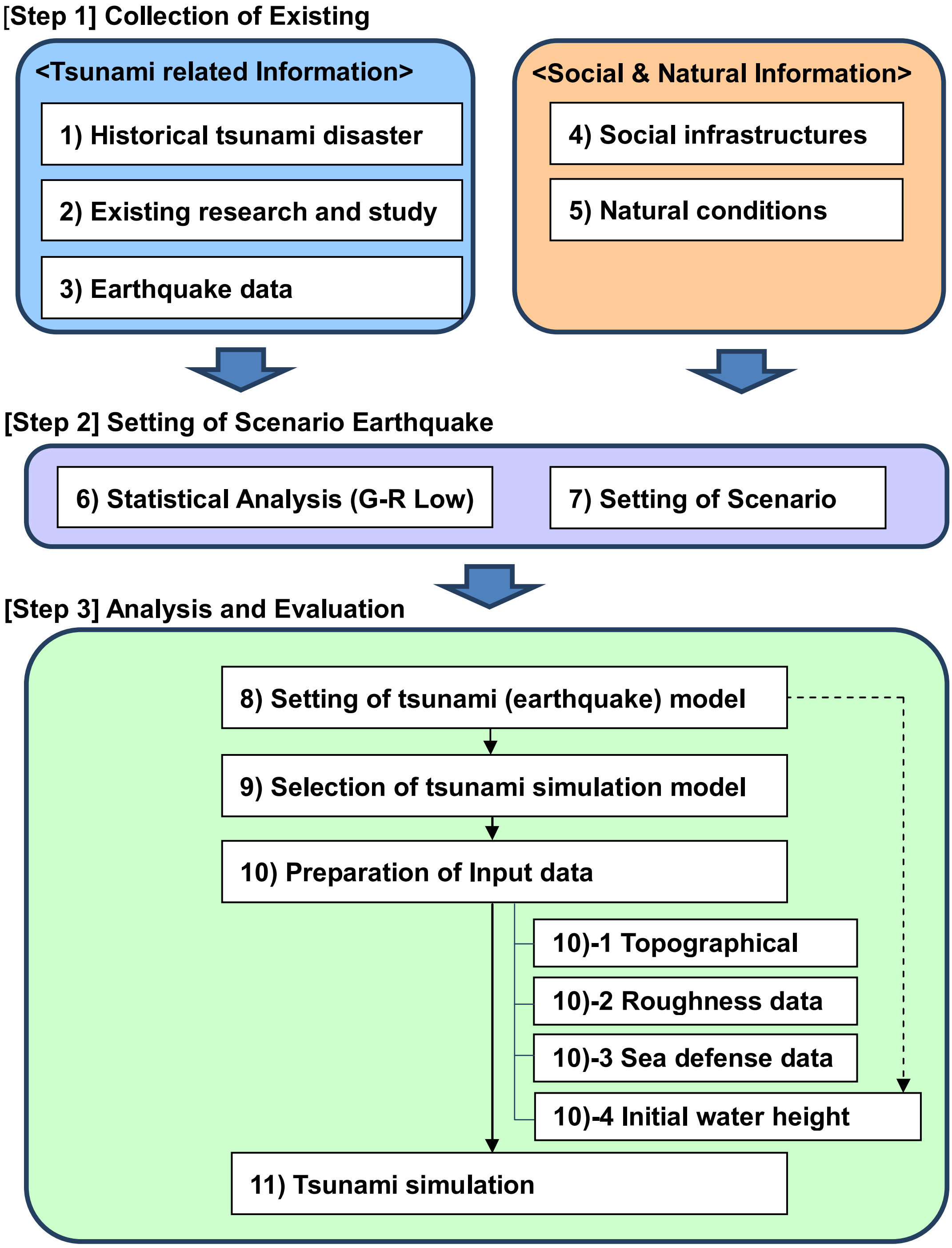

Figure-1 Basic Procedure of Tsunami Hazard Assessment

[Step 1] Collection of Existing Information

The tsunami related information such as the wave or run-up height distribution and the disaster records by past tsunamis are collected. The social and natural condition such as the industrial facilities that the industrial agglomerated area is relying on and the geological information of the site are also collected.

<Tsunami Related Information>

1) Records of historical tsunami disasters

Records of historical tsunami disasters surveyed by the following organizations are informative material to know and understand about tsunami disaster around the objective area.

- ✓ National agency for disaster prevention
- ✓ Municipal agency for disaster prevention
- ✓ Domestic university and research institute
- ✓ Global research institute

  ex.) CRED (Centre for Research on the Epidemiology of Disaster): EM-DAT, International Disaster Database, http://www.emdat.be/database
- ✓ Others

2) Literature of existing research and study

Tsunami hazard map and tsunami assessment report by the following organizations are informative material to know and understand about tsunami disaster around the objective area.

- ✓ National agency for disaster prevention
- ✓ Municipal agency for disaster prevention
- ✓ Domestic university and research institute
- ✓ Global research institute
- ✓ Others

3) Earthquake data (earthquake catalog)

Earthquakes data (catalog) by the following organizations are informative data to know the occurrence probability of earthquakes and develop earthquake model for tsunami simulation.

- ✓ National agency for disaster prevention
- ✓ Domestic university and research institute
- ✓ Global research institute
- ✓ Others

  ex.) NOAA: The Significant Earthquake Database

  http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1

<Social and Natural Information>

4) Social infrastructures

Information of industrial agglomerated areas and social infrastructure which would be potentially affected by tsunami is to be collected. Social infrastructures are categorized into transportation infrastructures and lifelines.

- ✓ Transportation infrastructures (for internal and external transportation): Highway, Railroad, Port, Airport
- ✓ Lifelines (essential for business continuity): Electric power supply, Water supply, Sewerage system, Gas, Communication, Oil

The actual region to assess the tsunami hazard is decided based on the distribution of infrastructure facilities. As the infrastructure facilities spread widely outside of industrial agglomerated area, the region of hazard analysis does not remain in the industrial agglomerated area in general.

5) Natural conditions

The impact of natural hazard is strongly associated with geomorphological features.
Geomorphological feature is understood by the following data.

- ✓ Altitude data of land area
- ✓ Water depth data of sea area

The following data is also helpful to understand geomorphological features. It is desirable to use the data with equal or less than 1km resolution to secure accuracy.

- ✓ Land use
- ✓ Geological information

<u>In case of insufficient information of natural conditions is available:</u>

The following public data is also available.

- ✧ Altitude data: GTOPO30 or SRTM. Note: The quality of GTOPO30 varies among the area.
- ✧ Water depth data: GEBCO08

[Step 2] Setting of Scenario Earthquake

A scale of tsunami disaster should be set for risk assessment based on the data collected in Step 1. The scale of tsunami is defined as the scale of earthquake which generates tsunami.

6) Statistical analysis of earthquake (Gutenberg-Richter Low)

The relationship of earthquake magnitude and return period is estimated by Gutenberg-Richter Low using earthquake data, usually called earthquake catalog, around the targeted earthquake zone.
It is well known that larger earthquake occurs less frequently. It was Gutenberg and Richter who formulate this relation by the following equation in 1941. It is the reason why this relation is called Gutenberg-Richter Low or G-R Low.

$$\log n(M) = a - b M$$

or

$$\log N(M) = A - b M$$

The relation between occurrence frequency, n(M) dM, and cumulative frequency with magnitude M and over, N(M), and 0.1 interval magnitude, dM = 0.1, is arranged in Table-1 for the earthquake data which occurred during 1965 to 1999 in and around Japan area. Figure-2 is the plot of the data with magnitude on x-axis and frequency on y- axis. The formula on the figure is a regression curve of M and N relation derived by the least square method.

M = 7.5 corresponds to N = 6.8 on the formula, for instance. It means that the occurrence frequency of the earthquake with magnitude 7.5 and over is 6.8 times on average in 35 years, during 1965 to 1999. And its annual probability is calculated as 6.8 / 35 = 0.19 / year. It is recognized that the earthquake with magnitude 7.5 and over is expected to occur 0.19 time on average in and around Japan area. On the other hand, inverse number of the annual probability, 1 /0.19 = 5.1 years in this case, is called recurrence time. Then it is expressed that the recurrence time of the earthquake with magnitude 7.5 and over is 5.1 years.

As described above, an annual probability or a recurrence time of the scenario earthquake of arbitrary magnitude can be estimated by using the G-R relation around the scenario earthquake area.

Table-1 Number of Shallow Earthquakes Occured in and around Japan (1965 - 1999) [9)]

M	$n(M)dM$	$N(M)$	M	$n(M)dM$	$N(M)$	M	$n(M)dM$	$N(M)$
8.2	0	0	7.1	5	18	6.0	52	224
8.1	1	1	7.0	5	23	5.9	56	280
8.0	0	1	6.9	4	27	5.8	79	359
7.9	1	2	6.8	2	29	5.7	91	450
7.8	2	4	6.7	9	38	5.6	94	544
7.7	1	5	6.6	14	52	5.5	134	678
7.6	0	5	6.5	14	66	5.4	138	816
7.5	3	8	6.4	18	84	5.3	199	1015
7.4	2	10	6.3	18	102	5.2	256	1271
7.3	0	10	6.2	30	132	5.1	343	1614
7.2	3	13	6.1	40	172	5.0	407	2021

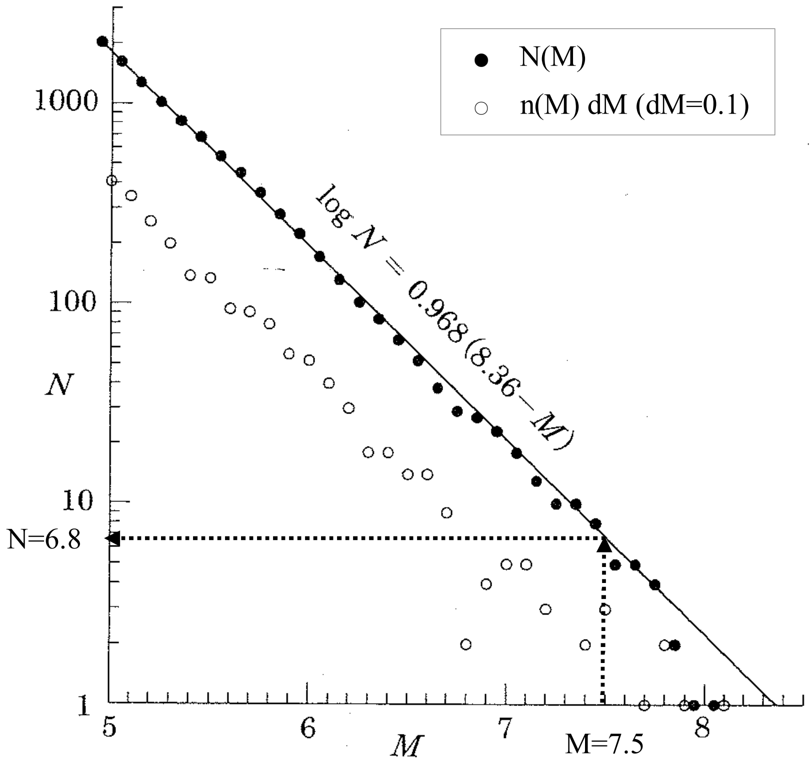

Figure-2 Data Plot of Table-5 [9)]

7) Setting of scenario earthquake

Scenario earthquake and its magnitude should be set for Area BCP. If larger magnitude is assumed, the components of Area BCP increase and the process to formulate it becomes complicated, however business in case of disaster will be more stable. On the other hand, if smaller magnitude is assumed, the Area BCP can be formulated easier but it is likely to suffer larger disaster than the estimated scenario and business continuity may become difficult. Therefore, it is desirable to decide the magnitude of the scenario earthquake by discussing within stakeholders including citizens about the local disaster management planning, governmental policy and feasibility of the plan.

One perspective for defining scenario:

One way for defining magnitude of scenario disaster is to assume several probability of occurrence like 1/100, 1/200 or 1/500 in one year and compare the results with other natural hazards and define the proper magnitude of the scenario.

[Step3] Analysis and Evaluation

The proper scenario earthquake for tsunami simulation which corresponds with the purpose of Area BCP is defined based on the information collected in clause 1), 2), 3), 6) and 7), and the tsunami simulation is conducted.

8) Setting of tsunami (earthquake) model

The following fault parameters of the scenario earthquake are necessary for the simulation.

- ✓ Depth (km)
- ✓ Strike angle (degree)
- ✓ Dip angle (degree)
- ✓ Rake angle (degree)
- ✓ Length of fault plane (km)
- ✓ Width of fault plane (km)
- ✓ Slip (m)
- ✓ Other information: coordinates of origin point (Longitude, Latitude)

9) Selection of tsunami simulation model

There are several theories to describe the behavior of tsunami such as liner long-wave theory, non-liner long-wave theory, liner dispersive wave theory and non-liner dispersive wave theory. Each of them is a theory based on the long-wave approximation which can be applied to the wave of long enough compared with the water depth. The wave length of tsunami is several 10 km to 100 km in general and it is long enough compared with 4km, which is the average depth of the ocean. That is the reason why the long-wave approximation is reasonable for tsunami.

Liner ling-wave theory can be applied to the deep water area, over around 50 m in depth, where the amplitude of the wave is small enough compared to the depth of water and the friction on the sea floor can be neglected. On the other hand, non-liner long-wave theory is usually applied to the shallow water area, say less than 50m in depth, where the amplitude of the wave is not small compared with the depth of water and the friction on the sea floor cannot be neglected. Also it is used in case of tsunami run-up to the land area.

The velocity of propagation of waves with shorter wave length is slower than those with longer wave length. Therefore, if tsunami is consisted with several lengths of waves, dispersion can be observed. The difference of velocity due to the wave length is called “dispersibility” and the theory considering this dispersibility is named the dispersive wave theory. The simulation based on the dispersive wave theory is not so common at this moment; however in case of distant tsunami which occurs over 1,000 km away from the study site, liner dispersive wave theory is often used. When the effect of dispersibility at shallow water area is the main concern, non-liner dispersive wave theory is applied.

Please see references 1) and 2) for more precise technical explanation of tsunami simulation theories.

Table-2 shows the several tsunami simulation models based on the long-wave theory and the dispersive wave theory introduced above.

Table-2 Tsunami Simulation Model

Program Name	Organization	Source	URL
Long Wave Theory			
TUNAMI	Tohoku University, Japan	Open	https://code.google.com/p/tunami/
STOC	The Port and Airport Research Institute, Japan	Open	http://www.pari.go.jp/cgi-bin/search-en/detail.cgi?id=2005060440205

COMCOT	Cornell University, USA	Open	http://ceeserver.cee.cornell.edu/pll-group/comcot.htm
GeoClaw	Washington University, USA	Open	http://depts.washington.edu/clawpack/geoclaw/
MOST	NOAA, USA	Closed	http://nctr.pmel.noaa.gov/model.html
ComMIT	NOAA, USA	Closed	http://nctr.pmel.noaa.gov/ComMIT/
Dispersive Wave Theory			
Disperse Potential Model	National Defense Academy, Japan	Open	http://www.nda.ac.jp/cc/kensetsu/index-e.html
FUNWAVE	University of Delaware, USA	Open	http://chinacat.coastal.udel.edu/programs/funwave/funwave.html
NEOWAVE	University of Hawaii, USA	Open	http://www.ore.hawaii.edu/OE/index.htm
COULWAVE	Cornell University, USA	Closed	http://ceeserver.cee.cornell.edu/pll-group/doc/COULWAVE_manual.pdf

10) Preparation of Input data

The general input data for tsunami simulation is as follows. These data are given to each grid which is explained in 10)-1 topographical data.

1. Topographical data
2. Roughness data
3. Sea defense data
4. Initial water height data (= deformation of sea-floor)

10)-1 Topographical data

Topographical model for the area which includes the source region of the scenario earthquake, the objective area and the route of tsunami propagation between them are required for simulation. Topographical model includes the topography of sea-floor, the topography of the land surface where tsunami might run up and the sea defense structures.

Orthogonal coordinate system is used for the modeled area of less than 1,000 km x 1,000 km and polar coordinate system is used for the wider area.

The simulation area is divided and covered by square grid and altitude and roughness data are given to each grid. Altitude describes topographic features and roughness is used for considering friction between water and sea-floor or land surface. The size of grid is properly defined considering the complexity of topography and the wave length of tsunami. The grid size is usually defined from larger to smaller according to the distance from coast, considering the condition that the topography becomes more complex and shorter wave component becomes dominant near the coast. This methodology is called "nesting". The grid size is defined as, for instance, 1350m -> 450m -> 150m -> 50m from tsunami source region to the coast. In this example, the grids with different size are connected with 1/3 step, which is most popular way, however 1/2 connection and 1/5 connection are also used for nesting.

Topographical data is available from the bathymetry charts and topographical maps. The digital data of these maps are also available in these days. If the digital data is not available, it is required to generate digital data by digitizing these maps. Table-3 shows the publicly available digital topographical data provided by international organizations. These data can be also used for the modeling.

Table-3 Publicly-available Bathymetry Data

Name	Explanation
GEBCO_08 Grid	**-** General Bathymetric Chart of the Ocean - Organization: British Oceanographic Data Centre (BODC) - Topographic data of 30 sec grid covering sea-floor and land surface - URL: http://www.gebco.net/data_and_products/gridded_bathymetry_data/
SRTM30_PLUS	- Organization: Scripps Institution of Oceanography, University of California San Diego - Topographic data of 30 sec grid covering sea-floor and land surface - URL: http://topex.ucsd.edu/

Following maps show the examples of topographical model preparation by GEBCO_08 data (Figure-3) from source region to coastal area and from coastal area to the coastline and inland area by more detailed bathymetry chart (Figure-4).

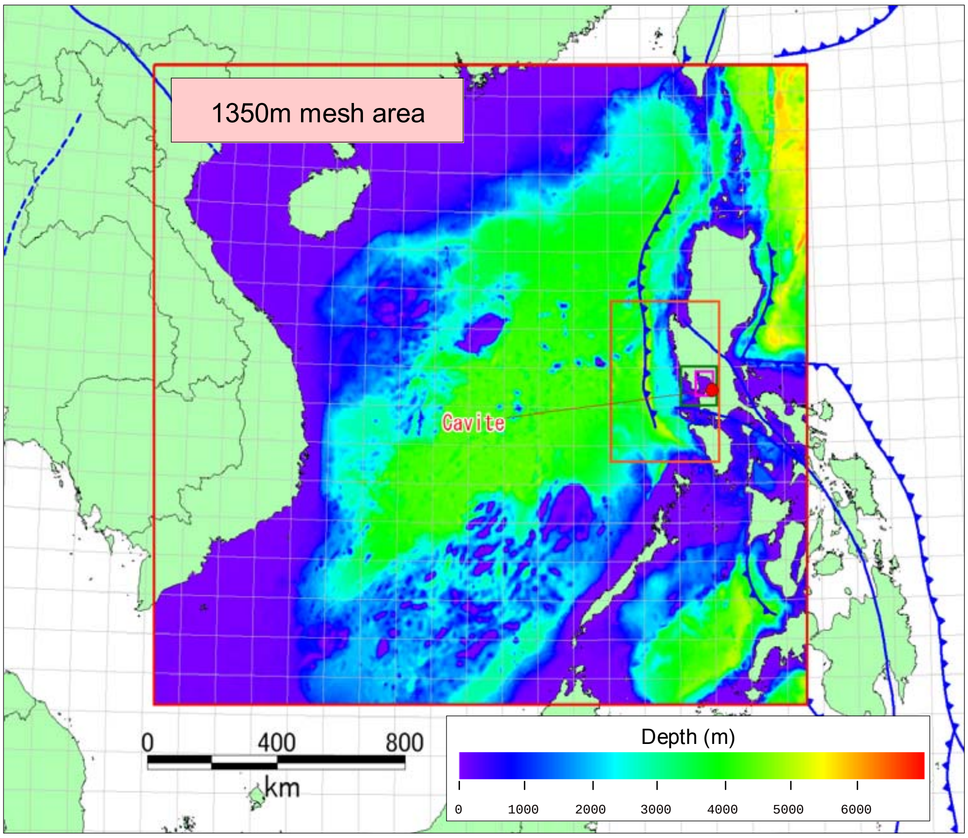

Figure-3 Wide Area Topography Model by GEBCO Data (South China Sea Area)

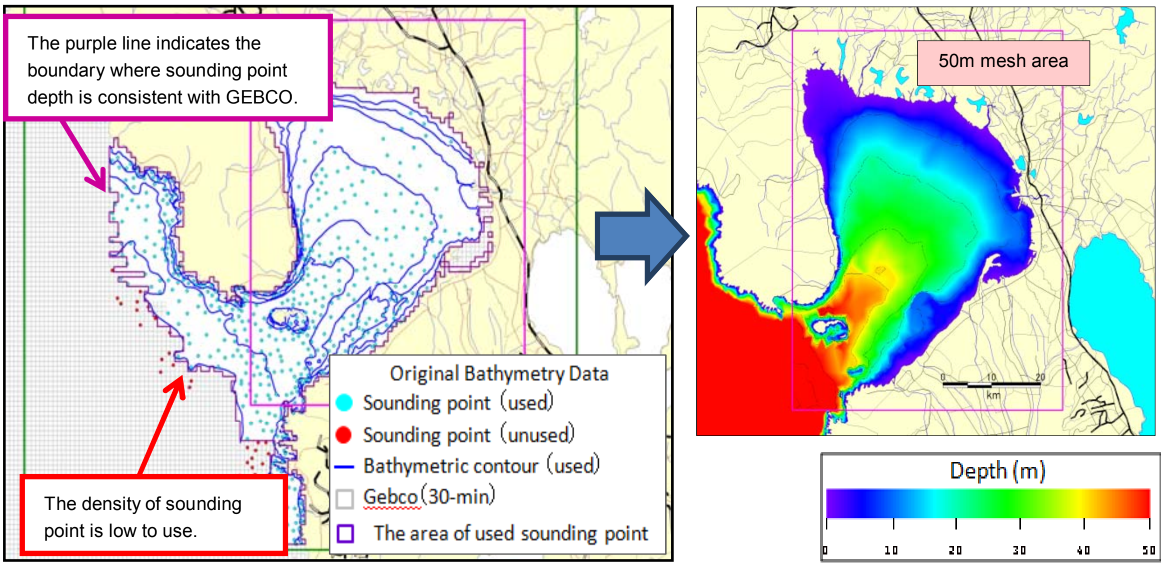

Figure-4　Topography Model of Coast Area by Bathymetry Data (Manila Bay Area)

10)-2 Roughness data

The effect of friction for tsunami wave propagation is expressed by Manning's roughness coefficient (n). "n=0.025" is usually adopted as roughness coefficient for marine area. Table-4[3)] and Table-5 [4)] shows Manning's roughness coefficients for different types of ground surfaces.

Table-4　Comparison of Manning's roughness coefficients [3)]

Fukuoka et al. (1994)		Aida (1977)		Goto and Shuto (1983)		Kotani et al. (1998)	
category	estimated roughness coefficient	category	equivalent roughness coefficient	category	estimated coefficient	category	setup roughness coefficient
80%	0.1			high density	0.01		
50～80%	0.096	dense zone	0.07			high density residential zone	0.080
20～50%	0.084	rather high density zone	0.05	mid density	0.05	mid density residential zone	0.060
0～20%	0.056			low density	0.03	low density residential zone	0.040
road	0.043	other land zone	0.02			forest zone (inc. garden, tide protection forest)	0.030
						field zone (inc. waste land)	0.020
		Shoreline (inc. tide protection forest)	0.04			sea and river zone (w/o tide protection forest)	0.025

Table-5 Manning values for land cover classes [4)]

Land cover class	Mannings n	Manning M in $m^{1/3}\ s^{-1}$	Source
Barren land/mud, sand, beach, roads	0.0310	32	b
Grassland	0.0360	28	b
Young Plantation	0.0370	27	b
Scrubland	0.0380	26	b
Cashew Plantation	0.0430	23	b
Other plantation	0.0430	23	b
Coconut plantation	0.0458	22	a
Semi open landscape	0.0550	18	b
Oil plantation	0.0573	17	a
Middle density urban area	0.0600	17	c,d
Melaleuca forest	0.0550	18	b
Rubber plantation	0.0609	16	a
Casuarina forest	0.0731	14	a
Inner beach forest	0.0744	13	a
High density urban area	0.0800	12.5	c,d
Other forest/rainforest	0.0850	12	c,e
Outer beach forest	0.0870	12	a
Mangrove forest	0.0951	11	a
Buildings non-resistant	0.0900	11	c,f
Buildings resistant	0.4000	2.5	c,f
Mangrove area 2005 (post-tsunami)			
Mangrove → water	0.0110	90	a,b,g
Mangrove → mud	0.0310	32	a,b,g
Mangrove → damaged understory	0.0310	32	a,b,g
Mangrove → sand	0.0310	32	a,b,g
Mangrove → inclined, roots remaining	0.0360	28	a,b,g
Mangrove → no damage	0.0951	11	a,b,g
Mangrove → indirect damage	0.0951	11	a,b,g

Values are derived from [a] measurement of tree stand parameters in the field followed by calculation of Manning's n according to Eq. (1); [b] measurement of stand parameters for different land cover classes in the field and subsequent estimation of Manning's n; [c] literature; [d] Kotani (1998) in Latief and Hadi (2007); [e] Arcement and Schneider (1989); [f] Gayer et al. (2010), Leschka et al. (2009); [g] + change detection/Ikonos

10)-3 Sea defense data

Embankment and other sea defense structures are modeled as height data of grid boundary.

10)-4 Initial water height data (= deformation of sea-floor)

Change of water height caused by fault movement should be prepared as an initial condition for tsunami simulation. Change of water height is assumed to be same as vertical component of sea-floor deformation.

The sea-floor deformation is calculated as a displacement cause by a slip on the fault in the semi-finite elastic body using fault parameters shown in Table-6. The theory of the calculation is described in the following references like Mansinha and Smilie (1971) [5)] or Okada (1992) [6)] and others. The website of Cornell University[7)] and National Research Institute for Earth Science and Disaster Prevention (NIED) [8)] are also informative.

Figure -5 shows a calculated deformation of sea-floor by the program named DC3D0 / DC3D [8] developed by Okada.

Table-6 Fault Parameters

Fault Parameter	Sample Value (corresponding to Figure-5)
Depth (km)	18
Strike angle (degree)	177
Dip angle (degree)	24
Rake angle (degree)	90
Length (km)	313
Width (km)	70
Slip (m)	9.6

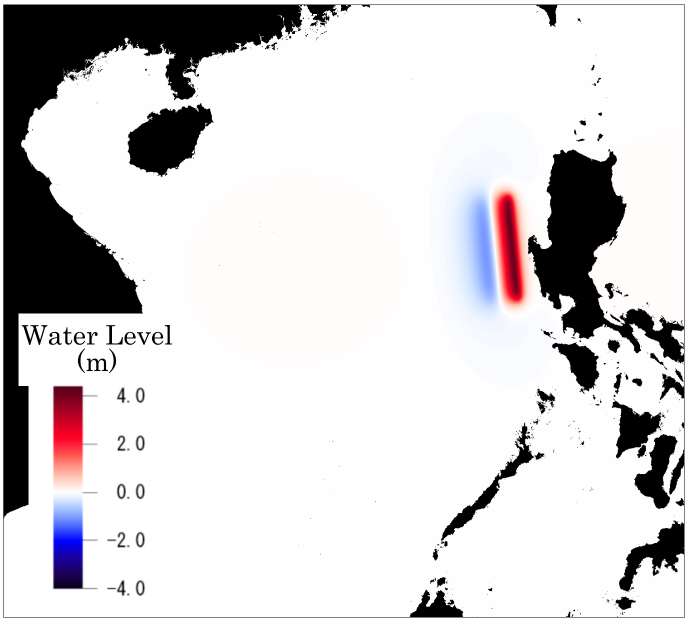

Figure-5 Example of Calculated Vertical Deformation

11) Tsunami simulation

Tsunami simulation can be conducted using the input data prepared in the clause 10). The general output of the tsunami simulation is as follows. Output items are obtained for each grid.

1. Maximum water height or maximum inundation height (for all grids)
2. Maximum velocity (for all grids)
3. Elapsed time of maximum water height (for all grids)
4. Elapsed time of given water height (x cm, for instance) (for all grids)
5. Time history of water height (selected grids)
6. Time history of water velocity (selected grids)

Figure-6 shows a sample of tsunami simulation result by the program "TUNAMI" developed by Tohoku University in Japan. The left side of Figure-6 shows maximum water height distribution map and the right side shows time history of water height at the selected grids.

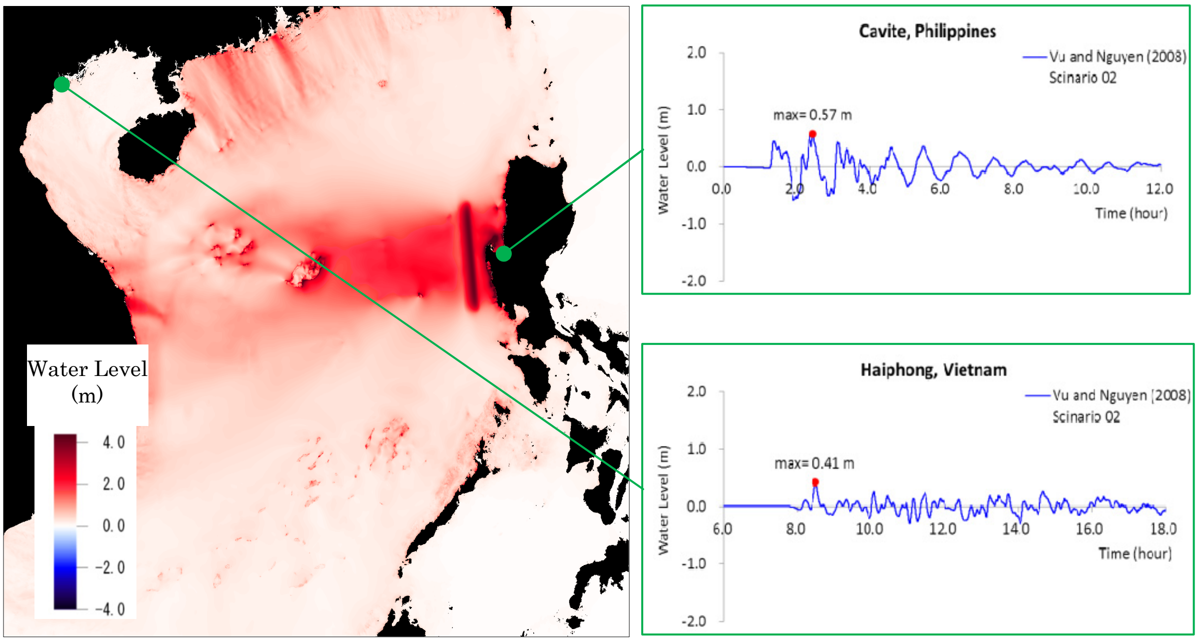

Figure-6　Example of Tsunami Simulation Result

[References]

1) IUGG/IOC Time Project: Numerical Method of Tsunami Simulation with the Leap-frog Scheme, IOC Manuals and Guides No.35, UNESCO 1997
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2) Imamura, Yalciner and Ozyurt (2006): TSUNAMI MODELLING MANUAL (TUNAMI model)
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4) Kaiser, Scheele1, Kortenhaus, Løvholt, Romer, Leschka (2011): The influence of land cover

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5) Mansinha, Smilie (1971): The Displacement Fields of Inclined Faults, Bulletin of the Seismological Society of America, Vol. 61, No. 5, pp. 1433-1440
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6) Okada (1992): Internal deformation due to shear and tensile faults in a half-space, Bull. Seism. Soc. Am., 82, 1018-1040.
7) COMCOT, Cornell University
http://ceeserver.cee.cornell.edu/pll-group/comcot_fault.htm
8) Program to calculate deformation due to a fault model DC3D0 / DC3D
http://www.bosai.go.jp/study/application/dc3d/DC3Dhtml_E.html
9) Seismology, 3rd edition (Japanese)(2001): Utsu, Kyoritsu Shuppan Co., Ltd.

[Example of Tsunami Hazard Analysis] Cavite, Laguna and south of Metro Manila

[Step 1] Collection of Existing Information

The following information and data are collected for setting scenario earthquake and conducting tsunami simulation.

1) Literatures related to scenario earthquakes
   - EMILE A. OKAL et al. (2011) [1)]: Tsunami Simulations for Regional Sources in the South China and Adjoining Seas
   - Vu Thanh Ca1 et al. (2008)[2)]: Tsunami risk along Vietnamese coast
   - Nguyen Hong Phuong et al. (2013)[3)]: Simulation of a Worst Case Tsunami Scenario from the Manila Trench to Vietnam
2) Literatures related to earthquake environment
   - Earthquake Impact Reduction Study for Metropolitan Manila, Republic of the Philippines Final Report (2004)[4)]: JICA, MMDA, PHIVOLCS
3) Data related to bathymetric feature
   - Wide area: GEBCO_08 Grid
   - Vicinity of objective area: Topographical map by NAMRIA (National Mapping and Resource Information Authority)

[Step 2] Setting of Scenario Earthquake

6) Statistical analysis of earthquake (Gutenberg-Richter Low)

The earthquake data along the Manila Trench is picked up from the data[4)] as shown in Figure-1 and the return period of the earthquake is estimated by statistical analysis based on the Gutenberg-Richter Law. The estimated result is shown in Figure-2. Followings are the results obtained by the analysis.

- ✓ Formula-1: G-R Law parameters are derived from the data during 1980 to 2002 as ‘b = 1.0’ and ‘a = 5.2’.
- ✓ Formula-2: In case of drawing envelope assuming ‘b = 1.0’, ‘a = 6.0’ is estimated.
- ✓ Formula-3 (for reference): In case of drawing envelope for all data, ‘b = 0.9’ and ‘a = 5.2’ are estimated.

Magnitude of the earthquake along the Manila Trench with 100 years return period is estimated to be 7.2 to 8.0 from Formula-1 and Formula-2.

On the other hand, the return period of the earthquakes with magnitude 8.0 is estimated to be 100 to 630 years and 1,000 to 6,300 years for magnitude 9.0.

7) Setting of scenario earthquake

The west side of Luzon Island where Cavite is located faces the South China Sea where fewer earthquakes occur than the Pacific Ocean. In addition, Cavite is located inside the Manila Bay. Therefore, there is almost no record of large tsunami disaster around the area. In this study, the possible tsunami that may cause impact to the study area, though the possibility is very low, is simulated considering that the result will be used in the future.

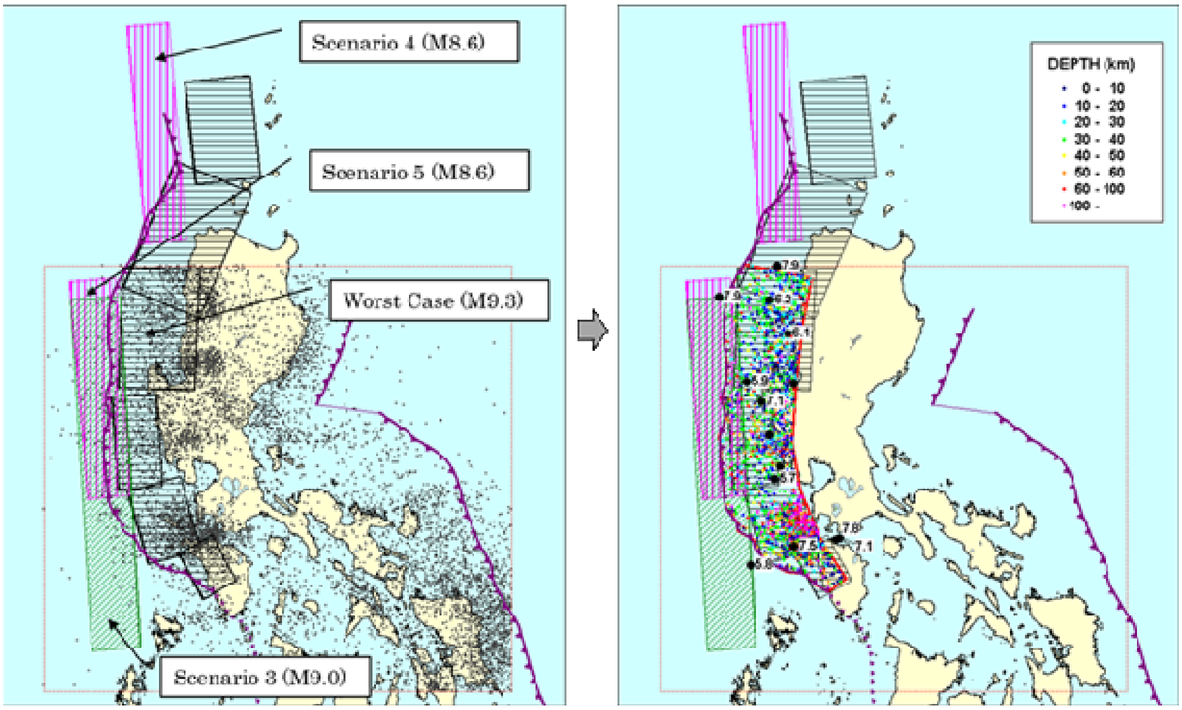

Figure-1 Epicenter Data along Manila Trench used for Statistical Analysis

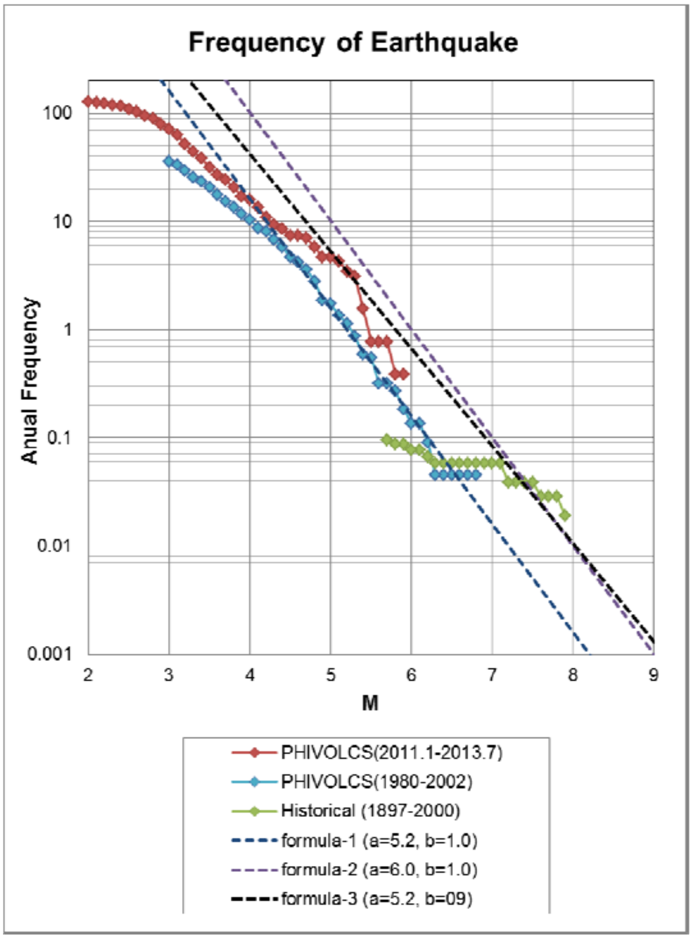

Figure-2 Return Period of the Earthquakes along Manila Trench (Gutenberg–Richter law)

[Step3] Analysis and Evaluation

8) Setting of tsunami (earthquake) model

Scenario earthquakes which may affect to the objective area are selected from the existing researches [1)2)3)]. Table-1 shows fault parameters of scenario earthquakes. The locations of the scenario earthquakes are shown in Figure-3 to Figure-5.

Table-1 Source Model

Scenario No.	Mw	Depth (km)	Strike (degree)	Dip (degree)	Rake (degree)	Length (km)	Width (km)	Slip (m)
1 [2)]	8.0	12	177	24	90	151	47	5.3
2 [2)]	8.5	18	177	24	90	313	70	906
3 [2)]	9.0	27	177	24	90	646	101	17.5
4 [1)]	8.6	10	355	35	57	400	90	6.0
5 [1)]	8.6	10	355	24	72	400	90	6.0
6	8.0	10	355	24	72	151	47	5.3
Worst Case [3)]	9.3	0	35.4	10	90	190	120	25.0
		0	22	20	90	250	160	40.0
		0	2	28	90	220	160	40.0
		0	356	20	90	170	90	28.0
		0	344	22	90	140	110	12.0
		0	331	26	90	95	80	5.0

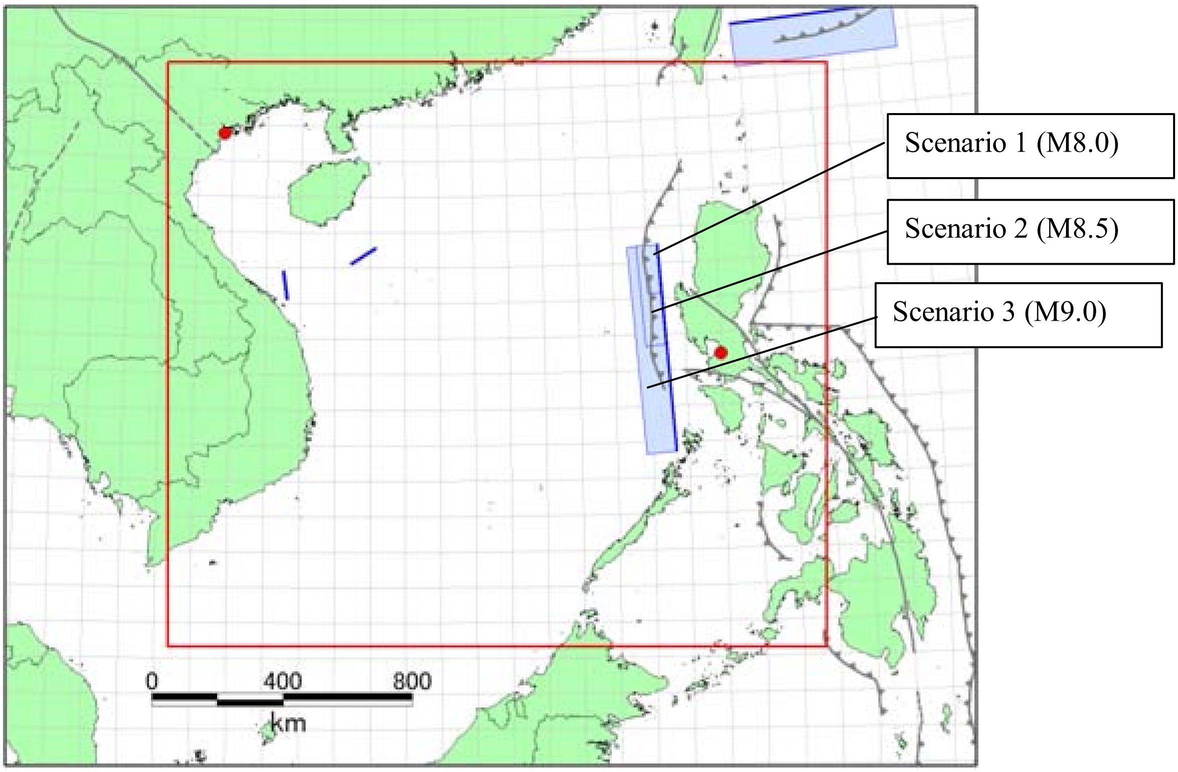

Figure-3 Tsunami Source Model (Scenario 1 - 3)

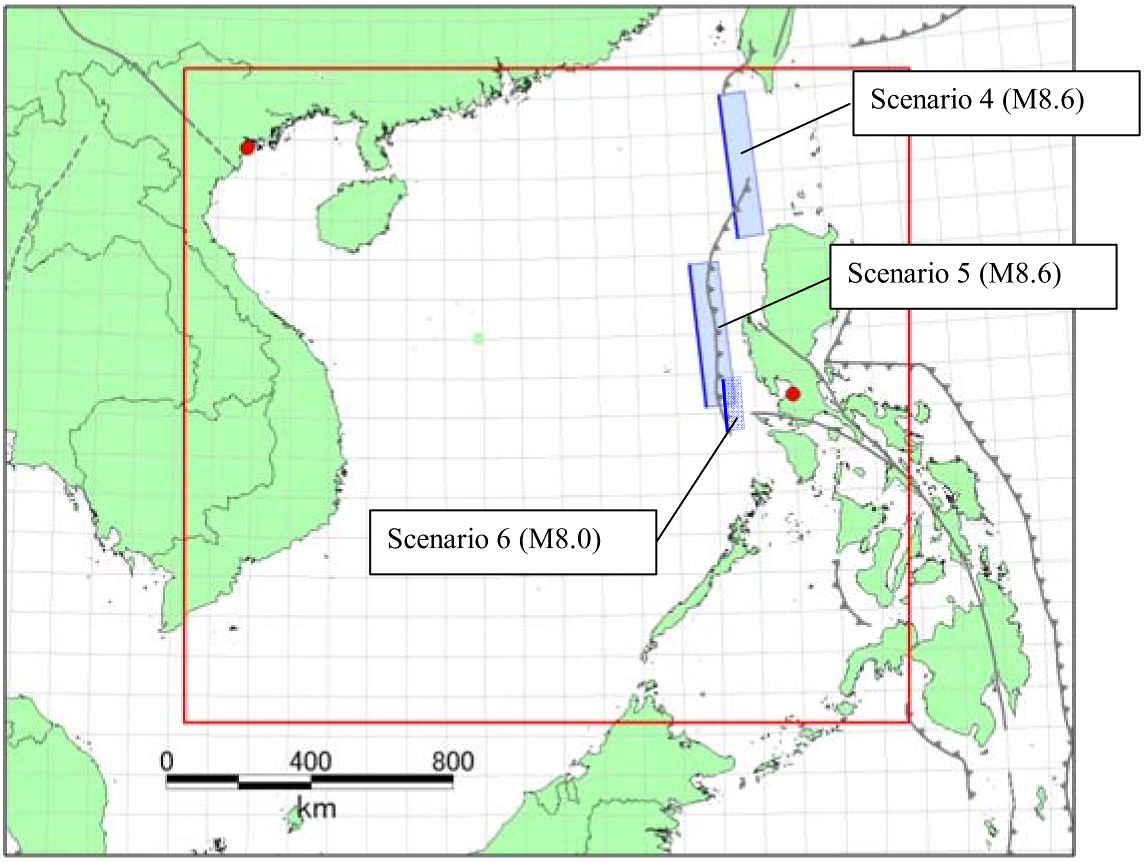

Figure-4 Tsunami Source Model (Scenario 4 - 6)

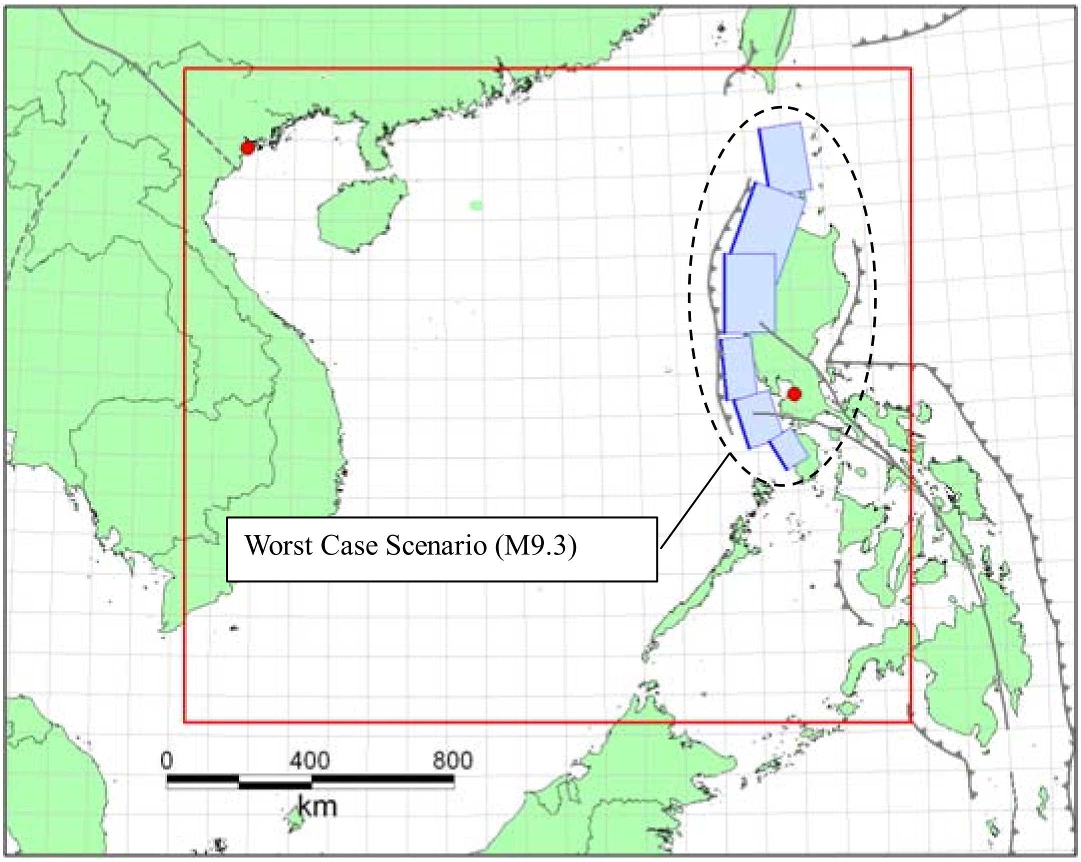

Figure-5 Tsunami Source Model (Worst Case Scenario)

9) Selection of tsunami simulation model

Tsunami simulation program "TUNAMI" which is developed by Tohoku University based on the non-linear long wave theory is used for the analysis. Analysis period is set to be 24 hours after earthquake occurrence.

10) Preparation of Input data

UTM coordinate system is used. Square grids are adopted for topographical model. The size of grids are defined as 1350m, 450m, 150m and 50m, from tsunami source region to the coast based on the nesting method.

10)-1 Topographical data

The depth of the grids in the ocean area with the size of 1350m, 450m and 150m and the inland 50m grids are generated based on "GEBCO_08 Grid" data prepared by BODC (British Oceanographic Data Centre).

The point water depths in the topography map prepared by NAMRIA (National Mapping and Resource Information Authority) are digitized and used for creating the depth data of the 50m grids in the Manila Bay.

Figure-6 shows the wide area topographical model prepared from "GEBCO_08 Grid". Figure-7 shows the topographical model around the Manila Bay prepared from topographical map.

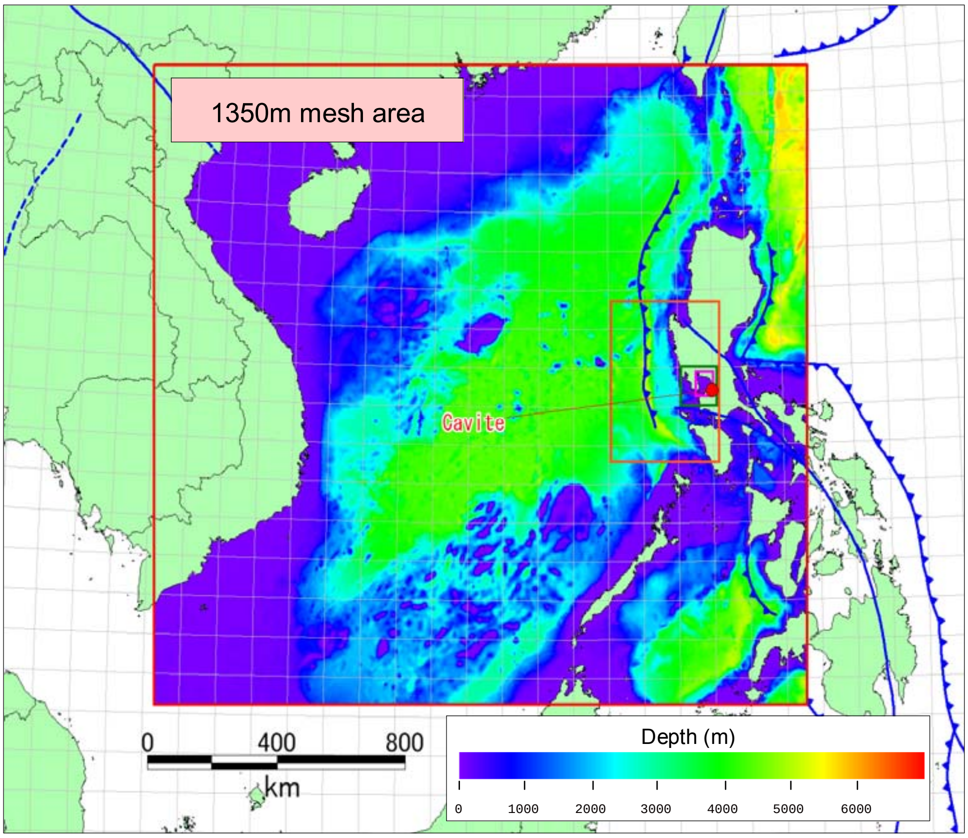

Figure-6 Wide Area Topography Model by GEBCO Data (South China Sea Area)

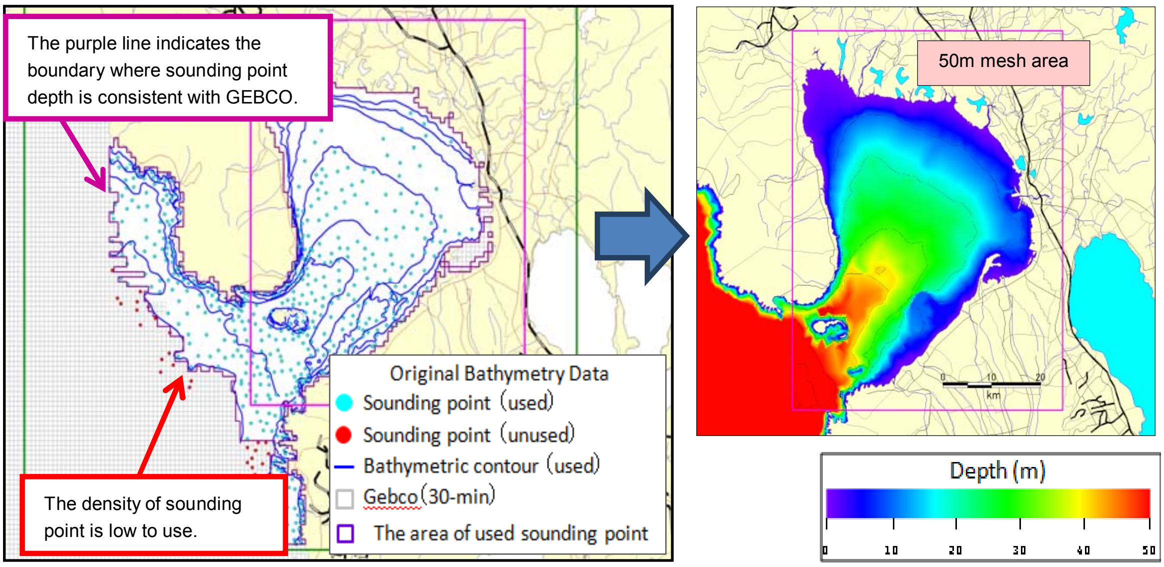

Figure-7 Topography Model of Coast Area by Bathymetry Data (Manila Bay area)

10)-2 Roughness data

Roughness coefficient “0.025” is used for ocean and land area.

10)-3 Sea defense data

Embankment and other sea defense structures are not considered in this study.

10)-4 Initial water height data (= deformation of sea-floor)

Deformation of sea-floor is calculated by Okada's program “DC3D0 / DC3D” with using fault parameters of scenario earthquakes and the vertical component of the deformation of sea-floor is given to corresponding grid as initial water height.

Calculated deformation of sea-floor is shown in Figure-8.

11) Tsunami simulation

Figure-9 shows the results of the simulation for Worst Case Scenario. Table-2 shows the maximum tsunami height at Cavite and the expected return period calculated from magnitude of each scenario earthquake.

Cavite is located inside of the Manila Bay, therefore tsunami height is not so high compared to the open ocean. It is estimated that the tsunami heights by the earthquakes with magnitude around 8.5 which occur along the Manila Trench are less than 1 m by the simulation (Scenario 2, 4, 5, 6). If earthquake of magnitude 9.0 occurs, the tsunami height may become larger than 2 m (Scenario 3 and Worst Case Scenario); however the probability of such a huge earthquake may be once in several thousand years.

Table-2 Maximum Tsunami Height at Cavite for Each Scenario

Scenario No.	Mw	Return Period (year)	Max. Tsunami Height (m)
1	8.0	100～630	0.12
2	8.5	300～2000	0.57
3	9.0	1000～6300	2.66
4	8.6	400～2500	0.24
5	8.6	400～2500	0.66
6	8.0	100～630	0.34
Worst Case	9.3	2000～13000	2.98

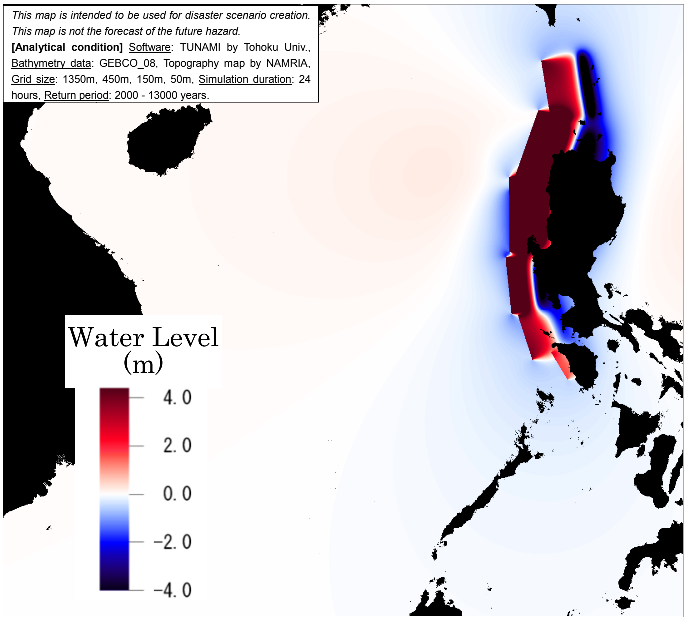

Figure-8 Vertical deformation (Worst Case Scenario)

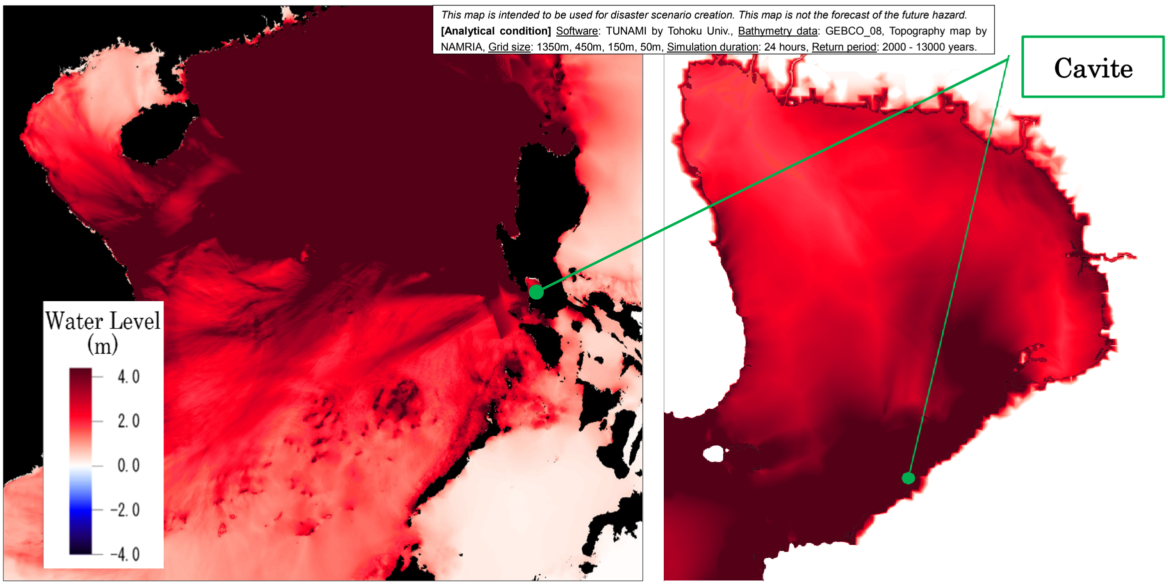

Figure-9 Maximum Water Height (Worst Case Scenario)

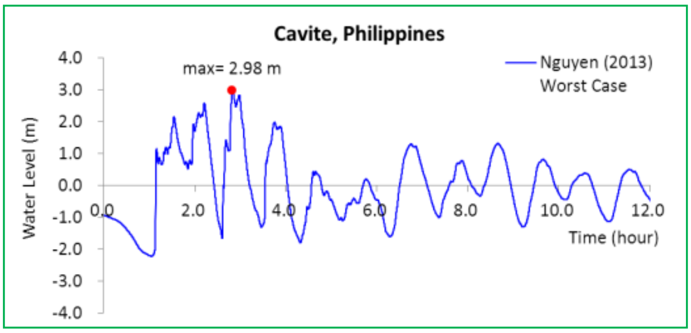

Figure-10 Wave form of Tsunami Height at Cavite (Worst Case Scenario)

[References]

1) EMILE A. OKAL, COSTAS E. SYNOLAKIS, and NIKOS KALLIGERIS (2011): Tsunami Simulations for Regional Sources in the South China and Adjoining Seas, Pure and Applied Geophysics 168 (2011), 1153–1173

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Methodology for Flood Hazard Assessment

The basic procedure of Flood Hazard Assessment is shown in Figure-1. The detailed procedure is prescribed below.

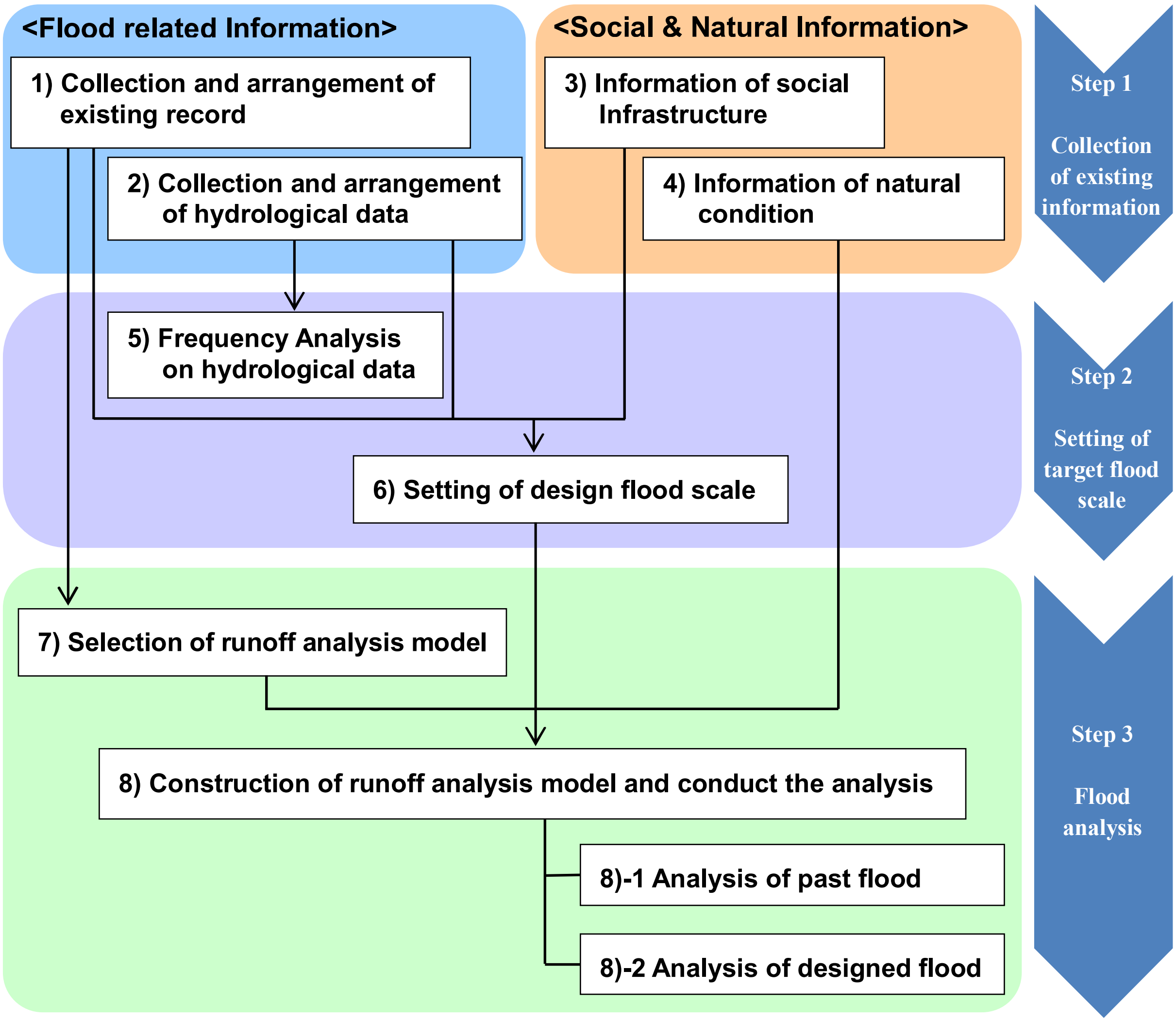


Figure-1　Basic procedure of flood hazard assessment

[Step1] Collection of existing information

Collect the society and nature related information such as the existing flood information including past flood record and hydrological data and information relating to society and nature including urban infrastructure and environmental condition.

<Information relating to flood>

1) Collection and arrangement of existing flood record

Collect the flood related information in target area for evaluation of flood risk. Collecting the data such as rainfall during flood, water level, river discharge makes it possible to grasp the characteristic of flood. The inundation area, duration time, water depth and the cause of flood implicated in the damage report or photograph are also helpful to understand the phenomena of inundation. If flood hazard map is available in the target area, utilize the information (inundation area, duration time and depth) shown in the map.

If there is little information about past flood,

Try to gather additional information by conducting field survey or interview survey (check the inundation area, the trace of water level and flood continued time) to local resident. Inundation area can be confirmed in the Google Earth in some cases.

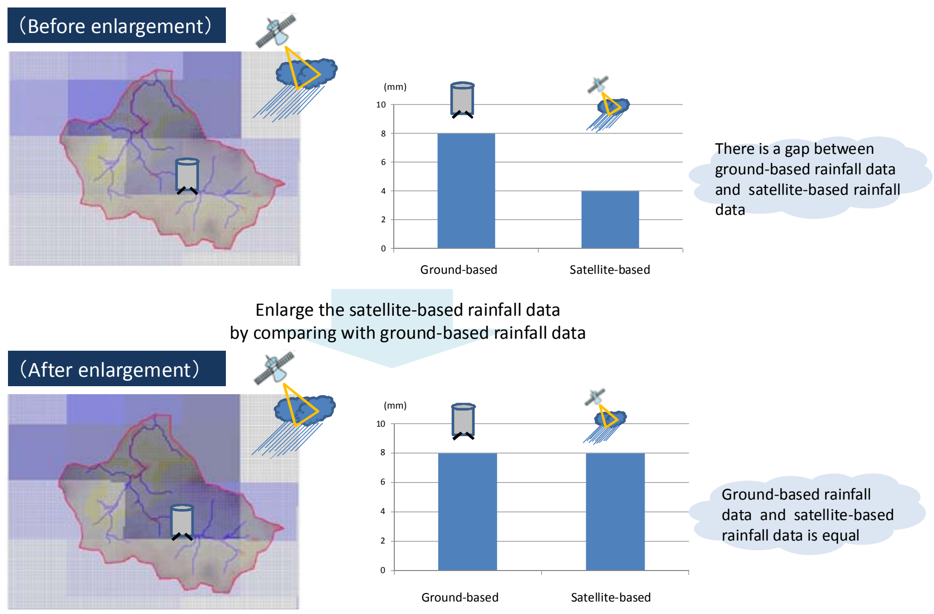
2) Collection and arrangement of hydrological data

Collect existing hydrological data in target area. Data on rainfall (hourly data or daily data), river water level, river discharge and tidal level should be collected. If there are river facilities such as dam or gate, it is advisable to collect the operation report of these facilities during flood. Before arranging these data, confirm if wrong or missing data is included.

Based on the collected hydrological data, analyze the flood continued time, probability of flood occurrence and situation when the largest recorded flood occurred. Cross-cutting profile data also would be helpful in the step of model construction.

If there is little hydrological data,

If the availability of ground-based rainfall data is limited, utilize the satellite-based rainfall data. From various kind of satellite-based rainfall data, 3B42RT, GSMaP、Qmorph、Cmorph can be utilized into flood runoff model IFAS directly. (The detail about IFAS is shown in the following.) Because the reliability of data accuracy would change depend on the observation condition, the data need to be modified (enlarged) by comparing the ground-based rainfall data.



<Information on social infrastructure and natural condition>

3) Collection and arrangement of information on social infrastructure

Collect the information of industrial estates and social infrastructure which would be affected by flood. Social infrastructure can be divided into two category; transportation infrastructure to be concerned with importation into/from industrial estates and lifeline infrastructure which are necessary to maintain the business.

- Transportation infrastructure: road, railway, harbor, airport, etc.
- Lifeline infrastructure: electricity, water and sewerage system, gas, communication, oil, etc.

The actual region to assess the flood hazard is decided based on the distribution of infrastructure facilities. As the infrastructure facilities spread widely outside of industrial agglomerated area, the region of hazard analysis does not remain in the industrial agglomerated area in general.

If there is little information on social infrastructure,

Try to collect the information on special important infrastructure (industrial estates, main arterial road, etc.) for formulating Area BCP in the target area. Creating the GIS data by extracting the important infrastructure information from commonly shared topographic map is possible measures to complement the required information.

4) Collection and arrangement of information on natural condition

Collect the topographic map and arrange the data relating to natural condition such as altitude, land use pattern and geology. From the aspect of data accuracy, it is advisable to use detailed map than 1/5,000 scale.

If there is little information on natural condition,

Elevation…ASTER GDEM (Advanced Space borne Thermal Emission and Reflection Radiometer Global Digital Elevation Model) can be used for global altitude data. Note that ASTER GDEM is satellite-based data; therefore if the data area includes buildings, the data shows the height of building, not on the ground.

Land use pattern…GLCC (Global Land Cover Characteristics) provided by USGS is available.

[Step2] Setting of target flood scale

Based on the data collected in Step1, the target flood scale for formulating the Area BCP is set. Basic flood scale is largest recorded flood, 50-year return period, 100-year return period and 200-year return period

5) Frequency analysis on hydrological data

Calculate probable hydrological value by using hydrological data collected in 2). As for statistic processing procedure, apply probability density function such as Exponential Distribution, then evaluate the probability density function, and finally decide the appropriate probability density function. Note that the result of probability density function highly depends on the total number of sample; therefore the accuracy of probability density function would decrease with small samples. (To have reliable result of probability density function, samples for 50 years are at least needed.)

have reliable result of probability density function, samples for 50 years are at least needed.)

<u>Typically used probability density function and evaluation method in Japan</u>

Probability density function	Exponential Distribution, Gumbel Distribution, Square-root Exponential Type Maximum Distribution, Extreme Value Distribution, Peason Type III Distribution (Real Space), Peason Type III Distribution (Logarithmic Space), Iwai Method, Ishihara・Takase Method, Log-normal Distribution (Quantile Method), Log-normal Distribution 3 (Slade II), Log-normal Distribution 2 (Slade I, L-moment method), Log-normal Distribution 2 (Slade I, Product moment method), Log-normal Distribution 4 (Slade IV, Product moment method)
Plotting position	In commonly used plotting position, Cunnane plot (α=0.4) is applicable for all probability density distribution, so Cunnane plot is used in many cases.
Evaluation method	The Probability density function with standard Least-Squares Criterion is 0.04 and fewer, correlation coefficient is high, and expected error by Jack knife is small. SLSC: The indexical deference of probable hydrological value between "data estimated by using Probability density function" and "plotting positioned data". When the deference is small, the goodness of fit is high. Jack knife method: The method to calculate the expected accuracy. Select Probability density function with small value.

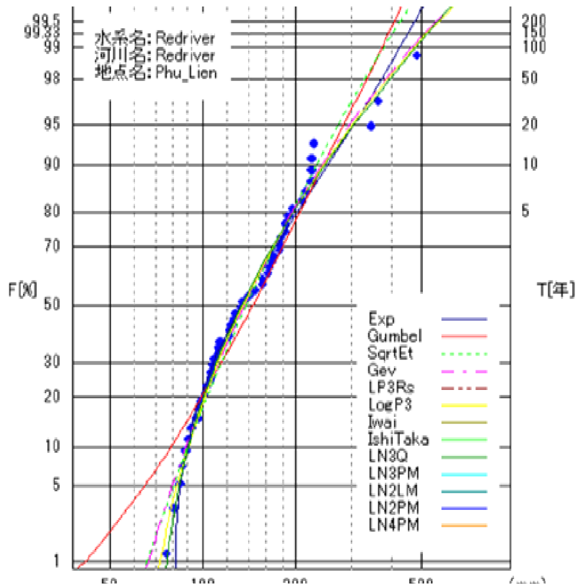


Figure-2 Example of Frequency analysis

6) Setting of design flood scale

Set the design flood scale for formulating the Area BCP. If the designed flood scale is huge, there should be much more content to formulate Area BCP. In this case, it requires considerable work to formulate Area BCP, but safeness of the plan become high. On the other hand, if the designed flood scale is small, the target scope of the Area BCP become limited, and makes it easier to formulate Area BCP. In this case, there is a possibility Area BCP doesn't work effectively. Hence, design flood scale should be set in accordance with regional city plan, administrative strategy, feasibility of plan with the discussion among the relevant people including local resident.

<u>A way of thinking to set design flood scale</u>

If to set the design flood scale is difficult, as initial scale, set some scale like largest recorded flood, 50, 100, 200-year return period flood. After that, set the design flood scale in conjunction with the result of flood risk evaluation.

On the basis of past flood information summarized in 1), select the appropriate model to simulate the flood in the target area and conduct flood analysis.

7) Selection of runoff analysis model

Select appropriate model to analyze the characteristics of flood in target area. Commonly used flood analysis models are shown in Table-1. Depend on the characteristics of the flood, select single model or combine some models.

The appropriate analysis model should be selected from the view point of runoff characteristics, required resolution, and financial capacity to afford the software. At the very beginning, it is desirable to actively promote the formulating the Area BCP by using the charge-free software like IFAS.

8) Construction of flood analysis model and conduct the analysis

8)-1 Analysis of past flood

Conduct flood analysis with the model selected in 7) and past rainfall data. After that, confirm the simulation accuracy by comparing the result of simulation with actual discharge record. (If river water level and other relevant hydrological data are available, compare these records also.) If simulation precision is not satisfactory, try to improve the accuracy by modifying the parameter. Modifiable parameter varies by each model. Generally, parameters relating to roughness coefficient, infiltration rate, soil hydraulic property, thickness of soil and bedrock hydraulic property are modified by utilizing the information on natural condition.

To secure the model accuracy, modify the model so as to simulate past several floods as precise as possible.

8)-2 Analysis of designed scale flood

Conduct the runoff analysis on designed flood prepared in 6).

Table-1 Major Flood analysis models

Item	Representative hydraulic analysis model							
	IFAS (Integrated Flood Analysis System)	RRI (Rainfall Runoff Inundation Model)	iRIC (International River Interface Cooperative)	MIKE-Series	HEC-RAS (The Hydrologic Engineering Centers River Analysis System)	Info Works	FLOW 2D	River 2D
Model	Distributed runoff model.	Distributed runoff model (including inundation analysis model).	Hydraulic analysis model. (for river)	Runoff analysis model, Hydraulic analysis model (for river), Inundation analysis model, Ground water analysis model and so on	Hydraulic analysis model.	Runoff, hydraulic (for river channel), and inundation analysis model. And sewage, water quality and pollution load etc. can be analyzed.	Runoff analysis model Hydraulic analysis model (for river channel) Inundation analysis model	Hydraulic analysis model (for river channel)
Purpose	Calculate runoff (discharge) at arbitrary calculation grids	Calculate runoff (discharge) at arbitrary calculation grids considering inundation and groundwater at the same time	Simulate water behavior (flow velocity, direction, discharge etc.) with not only 1-dimeinonal also 2-, 3-dimensional model. User can conduct inundation analysis with 2-dimentiona model. Calculate riverbed valuation with sediment model.	Runoff analysis, Inundation analysis, groundwater analysis, Water quality analysis, Calculation water balance. It carries plural various calculation modules.	1-dimensional hydraulic analysis Quasi 2-dimensional river hydraulic analysis, (Estimating each flow velocity of high and low flow channel individually) User can select unsteady model or uniform/non-unifor m model, depending on needs.	River hydraulic analysis, flood inundation analysis with river channel and flood plain model and sewage system model, runoff analysis, water quality (incl. pollution load) analysis. User can analyze various hydraulic phenomenon calculation modules integrally.	Two-dimensional flood inundation analysis, One-dimensional river channel hydraulic analysis (unsteady flow model).	Two-dimensional river channel hydraulic analysis (unsteady flow model)
Main Input	Elevation data (SRTM, ASTER etc.) Rainfall data (Satellite rainfall data)	Elevation data (SRTM, ASTER etc.) Rainfall data Boundary condition data (up-stream: release water from dams etc. , downstream: tidal level etc.)	Elevation data (SRTM, ASTER etc.) Boundary condition data (up-stream: release water from dam etc. downstream: tidal level etc.)	Cross section data of river channel. Elevation data (SRTM, ASTER etc.) Boundary condition (up-stream: release water from dam etc. , downstream: tidal level etc.) Structures (weir, gate, pump etc.)	Cross section data of river channel. Boundary condition (up-stream: release water from dam and so on, downstream: tidal level and so on)	Cross section data of river channel. Elevation data (SRTM, ASTER etc.) Rainfall data Boundary condition (up-stream: release water from dam etc. , downstream: tidal level etc.) Structures (weir, gate, pump etc.)	Cross section data of river channel. Elevation data (SRTM, ASTER etc.) Rainfall data Boundary condition (up-stream: release water from dam etc. , downstream: tidal level etc.)	Cross section data of river channel. Boundary condition (up-stream: release water from dam etc. , downstream : tidal level etc.)
Main Output	Hydrograph at arbitrary points (In river channel, From each river basin , From protected plane)	Hydrograph, inundation area/depth in flood plain. River discharge, water level at river calculation grids.	Water level and discharge, flow velocity in river Inundation depth and flow velocity and flax of each grid in flood plain (in case of considering flood plain analysis)	Runoff at arbitrary point (in rivers/ channels, river basin etc.) Water level and discharge, flow velocity in river/channel. Inundation area/depth, flow velocity and flux flow in flood plain.	Water level, discharge and flow velocity etc. in river/channel.	Water level, discharge, flow velocity etc.in river/channel. Inundation area/depth, flow velocity and flux flow in flood plain. Water level, discharge and pollution load in pipe line.	Water level, discharge and flow velocity etc. in river channel. Inundation area/depth and flow velocity and flux flow in flood plain.	Water level, discharge and flow velocity etc. in river channel.
Distri buter	ICHARM http://www.icharm.pwri.go.jp/index_j.html	Same as on the left	iRIC Project http://i-ric.org/ja/	DHI Water & Environment http://www.dhigroup.com/	USACE http://www.hec.usace.army.mil/software/hec-ras/	Innovyze Ltd http://www.innovyze.com/	FLO-2D Software, INC http://www.flo-2d.com/flo2d-basic	University of Alberta in Canada http://www.river2d.ualberta.ca/
Price	Free	Under considering	Free	Over 15,000 Euro (depending on combination of analysis modules)	Free	About 4 - 18 million JPY. (depending on combination of analysis modules)	Free version (basic version) Payment version (advanced version).	Free
Remarks	IFAS was developed in order to analyze rainfall runoff in a developing country where there is no hydrological observation. IFAS has affinity with satellite products.	This model is able to conduct runoff analysis considering retarding function in protected plain caused by inundation. In addition, behavior of ground water can be calculated.	This software was developed by MD_SWMS (USGS) and RIC-Nays. Afterwards, it has improved and integrated by Dr. Shimizu (Hokkaido Univ.) and Dr. Jon Nelson (USGS).	MIKE is equipped with user-friendly interface, MIKE-ZERO This software has high affinity with ArcGIS (ESRI, US).		Mainly, water service, sewage system, and water environment etc. shall be examined. Also data management tool is equipped. Especially sewage system is well-analyzed. Most modules are integrated with GIS.	It has operation interface. The one-dimensional river channel calculation can input a rectangular section, an arbitrary section, but section distance can be controlled by limitation each a calculation grid size. So, calculation precision of the river channel water level is a problem.	This model was developed in order to investigate water environment such as fish biotope. By using a finite element method, river flow condition shall be calculated.

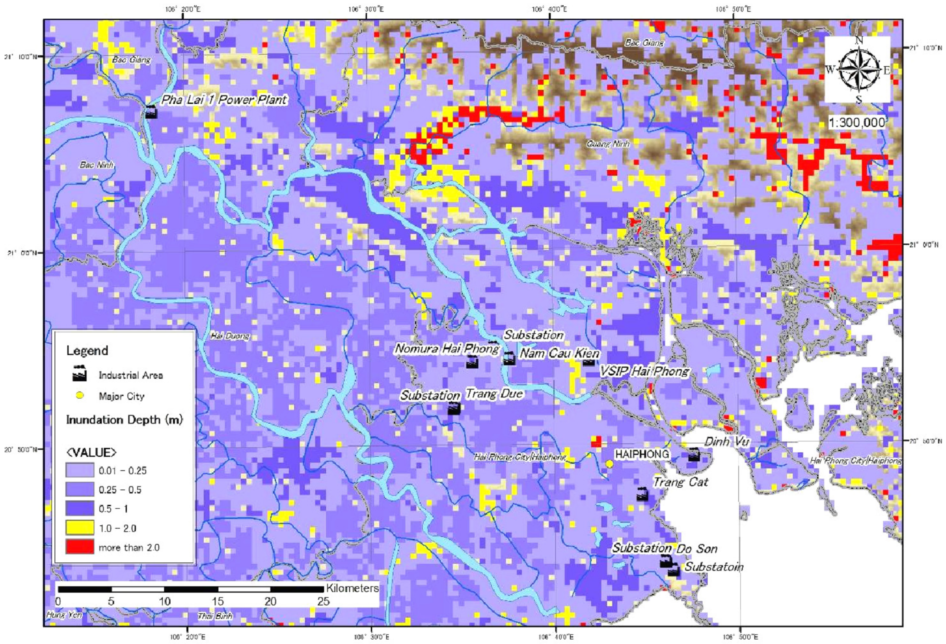


Figure-3 Output of flood analysis

[Example of Flood Hazard Analysis]　Bakasi/Karawan in Indonesia
- Runoff analysis with IFAS and inundation analysis with iRIC -

The following example shows the procedure for flood analysis by using IFAS and iRIC. As the merit of using IFAS, even if the availability of ground-based rainfall data is limited, IFAS can conduct runoff analysis with satellite-based rainfall data. Although IFAS can't analyze inundation phenomena, the user can conduct inundation simulation by using iRIC with the output of IFAS.

[1] Get the analysis software

Get and install IFAS and iRIC through the Internet

- IFAS : http://www.icharm.pwri.go.jp/research/ifas/
  （Developed and provided by ICHARM of Public Works Research Institute）
- iRIC : http://i-ric.org/en/
  （Developed and provided by Foundation of Hokkaido River Disaster Prevention Research Center, U.S. Geological Survey and Hokkaido University）

[2] Set up runoff analysis condition

Set up runoff analysis condition for IFAS.

1) Calculation period
- Set calculation period for runoff analysis
- Calculation period should include initial rise, peak and decay of flood.
- In the case of Indonesia,
  → 8 – 14 November, 2007 (7 days)
  Period the largest rainfall recorded at Cisomang gauging station.

2) Discharge calculation point
- Set the point of discharge calculation
- This point become input condition of inundation analysis of iRIC
- If actual discharge data are recorded, set the point for the purpose of comparing the actual discharge with calculated discharge
- In the case of Indonesia,
  → Set at the downstream side of Jatiluhur dam in Citarum river

3) Topographic data
- Set the data on altitude, land use pattern and geology
- In the case of Indonesia,
  → The following data are employed
  [Altitude]：GTOPO30
  [Land use pattern]：GLCC
  [Geology]：CGWM

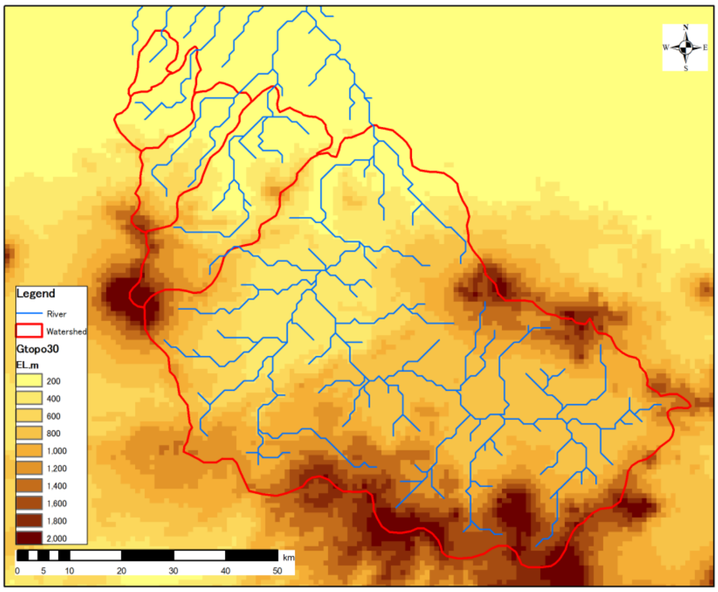


Figure-1 Elevation data

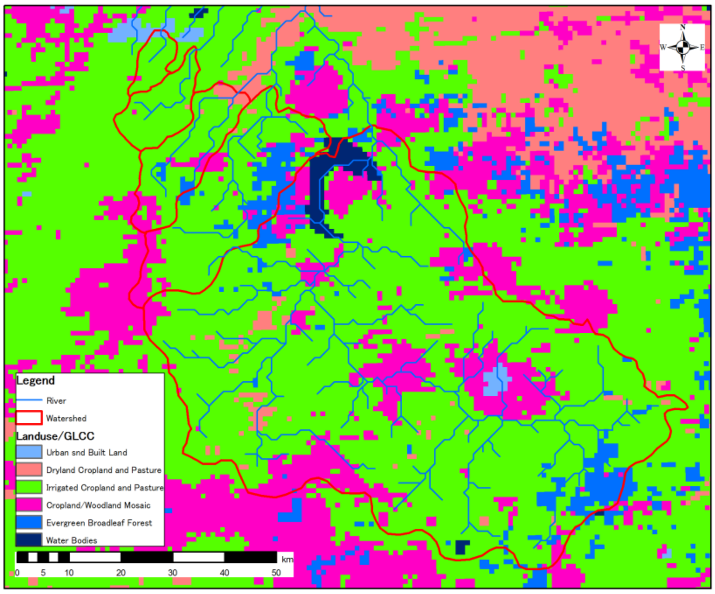


Figure-2 Land use pattern data

4) Rainfall data

- Input the actual rainfall data for past flood analysis. For designed flood analysis, input the estimated design magnitude.
- If the availability of ground-based rainfall data is limited, utilize satellite-based rainfall data instead.
- In the case of Indonesia,
  - → Since the ground-based data is limited, utilized satellite-based rainfall data, 3B42RT(V5). Satellite-based rainfall data are enlarged to the scale of ground-based rainfall data.

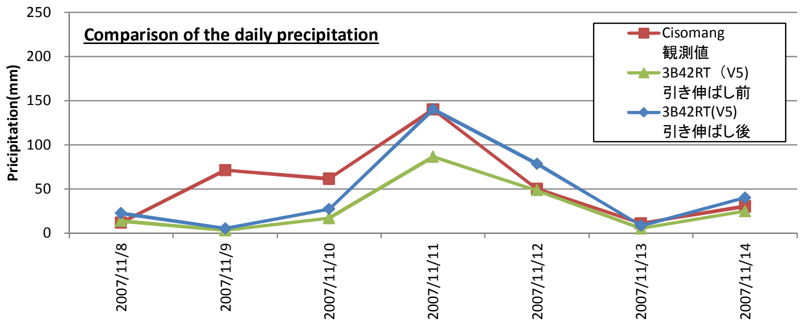


Figure-3　Enlargement of rainfall data

5) Other parameters

- Modify the parameter by comparing actual discharge with calculated discharge
- In the case of Indonesia,

  → Employed the default parameter setting because the parameter identification is impossible due to the lack of discharge data.

[3] Runoff analysis

Conduct the runoff analysis with constructed IFAS model.

In the case of Indonesia, the following 4 cases were performed.

- Case 1 : 2007 year flood as target flood
- Case 2 : 50-year return period flood as target flood
- Case 3 : 100-year return period flood as target flood
- Case 4 : 200-year return period flood as target flood

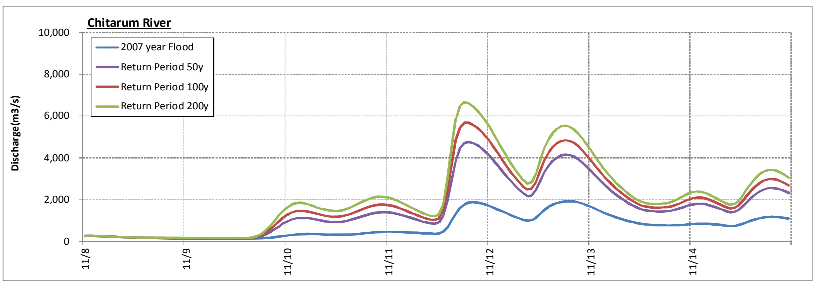


Figure-4　Output of runoff analysis

[4] Set up condition of inundation analysis (iRIC model)

Set up the followings as calculation condition

1) Set up the software/ calculation method

- Conduct the simulation of inundation by using Two-dimensional plane flow analysis model with the input data, which is the output data of IFAS. A kind of software “Nays2dFlood” is used in Two-dimensional plane flow analysis model.

2) Target area of inundation analysis

- Set the areas in which important social infrastructure like industrial estates and main arterial road are included.

- In the case of Indonesia,
  - → Set the areas in which industrial estates are located along the Cikampek Highway, and city area is located in the downstream side

3) Grid size

- If there are many grids, it takes many times to calculate. Therefor take into account the calculation capacity.
- In the case of Indonesia,
  - → Set grid size as 200m*200m

4) Elevation data

- Set up elevation data by using available data
- In the case of Indonesia,
  - → ASTER(Advanced Space-borne Thermal Emission and Reflection Radiometer) was utilized. Since the special resolution of ASTER DEM is 30m and there was a possibility that elevation data on the highway is incorrect, the complementary data were collected by spot elevation measuring with handy GPS.

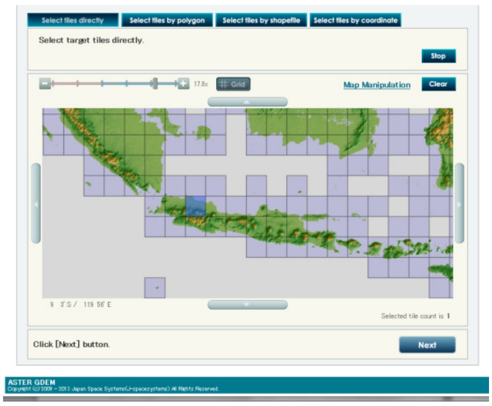


Figure-5 ASTRE GDEM data (http://gdem.ersdac.jspacesystems.or.jp/)

5) Boundary condition

- As upper boundary condition, give the hydrograph data calculated in runoff analysis.
- In the case of Indonesia,
  - → Five hydrographs calculated with runoff model are given as upper boundary conditions.

6) Roughness Coefficient

- Give Roughness Coefficient in each mesh depending on the land use pattern
- In the case of Indonesia,
  - → Global map managed by ISCGM (International Steering Committee for Global Mapping) was employed for determination of land use conditions to which the values of roughness coefficient are corresponding.

7) Drainage Effect

- Consider the drainage effect based on the actual drainage condition

- In the case of Indonesia,
  → Assumed the drainage capacity of $2m^3/s/\ km^2$ and deducted the amount of water from each grid

[5] Inundation analysis

Evaluate the inundation situation (inundated area, duration time and depth) by comparing the analysis output with location point of industrial estates and social infrastructure.

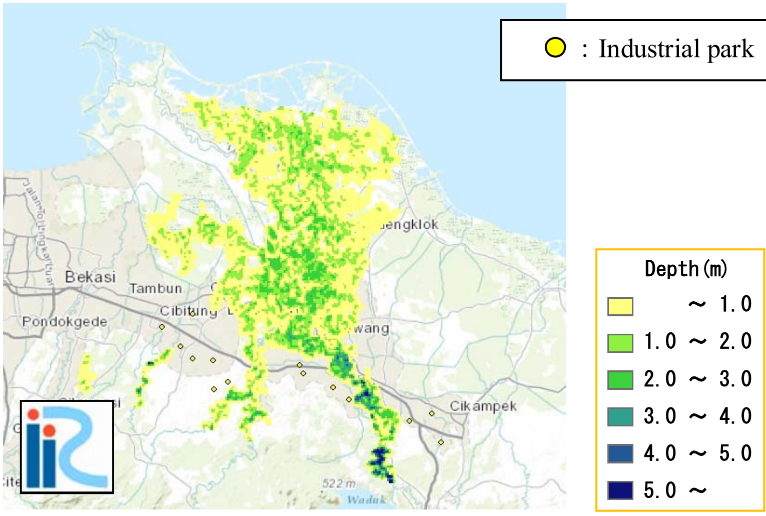


Figure-6 Output on inundation analysis by iRIC

Methodology for Hazard Assessment of Storm Surge

Figure-1 shows the basic procedure of the methodology for the hazard assessment of storm surges. The details of each step are indicated below.

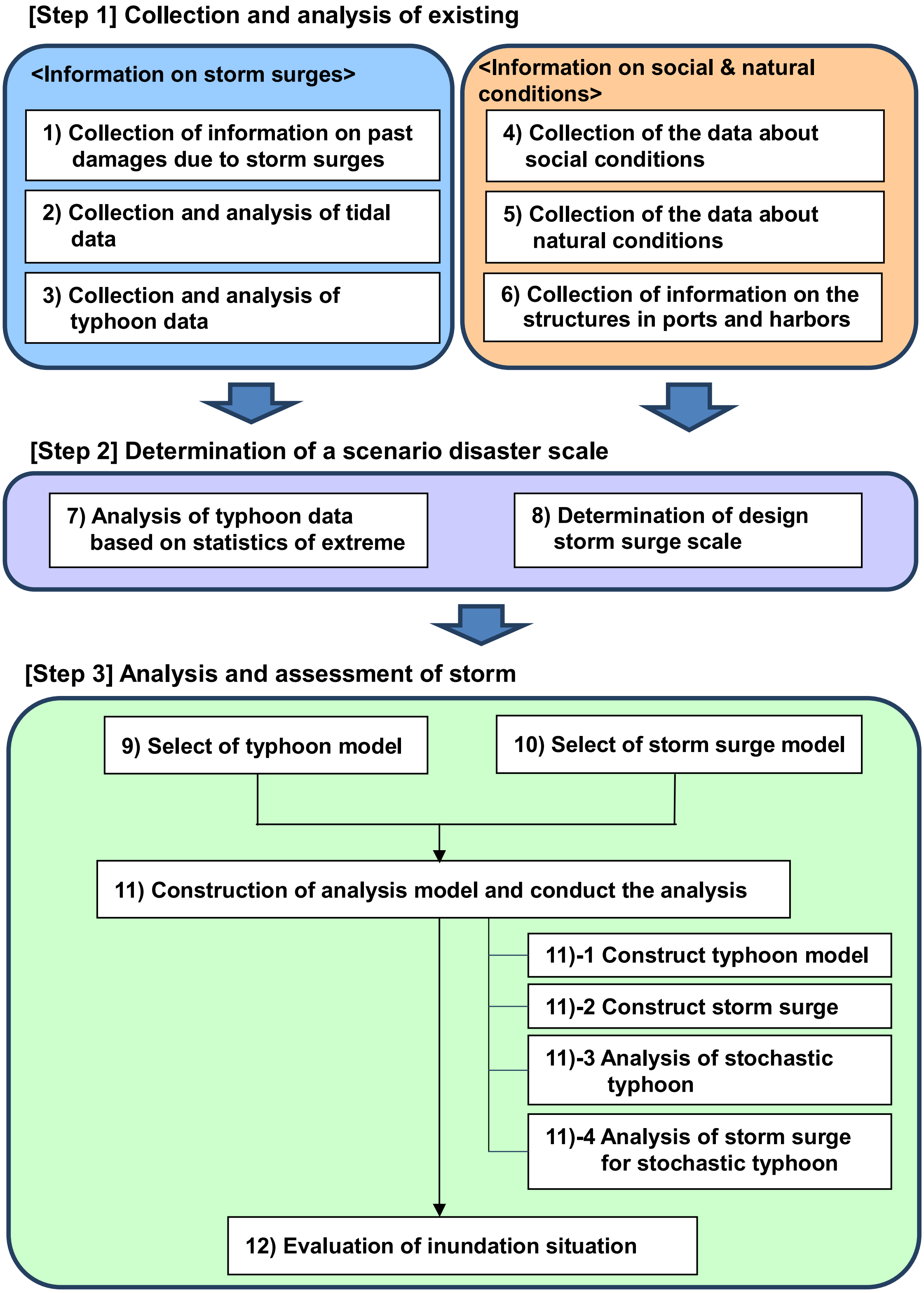


Figure-1 Basic procedure for hazard assessment of storm surge

[Step 1] Collection and analysis of existing data

The typhoon and storm surge related information such as the damage records by past storm surges, observation data of tide level and wind and best track data of typhoon are collected. As for observation data, the confirmation that observatories and observation methods are effective and the avoidance of overestimation, underestimation, errors and missing data are necessary. The social and natural condition such as the industrial facilities that the industrial agglomerated area is relying on and the geological information of the site are also collected.

< Information on storm surges >

1) Collection of information on past damages due to storm surges

Records of past storm surges in the study area where a hazard assessment will be conducted are collected. The following information is necessary:

- ✓ Time and tide data when large storm surges occurred
- ✓ Damage records and pictures
- ✓ Inundation area and its depth

Characteristics of storm surges in the study area are comprehended by organizing and analyzing these data.

> ***In case of insufficient information on storm surge is available:***
>
> Field study and hearing surveys (i.e. confirming inundation situation) to residents are conducted to comprehend the characteristics of storm surges in the study area.

2) Collection and analysis of observed tidal data

Continuous tidal data in the study area are collected. These data are used to estimate the astronomical tide in the study area. The risk of storm surges is assessed by adding sea level variations caused by typhoons to the astronomical tide level. Comprehending the highest astronomical tide level such as mean high water springs is required to evaluate in the safe side. Observation data of more than one year is desirable for the implementation of a harmonic analysis to estimate astronomical tide level.

> ***In case of lack of observed tidal data:***
>
> NAO.99b, opened to the public by the National Astronomical Observatory of Japan (NAOJ), is available for the astronomical sea level prediction model. However, it is desirable to use observed data because the 0.5 degree spatial resolution of the global scale model (NAO.99b) is rough.

3) Collection and analysis of typhoon data

Following data are collected regarding past typhoons in the study area.

- ✓ Atmospheric pressure
- ✓ Wind direction and speed
- ✓ Center position and time
- ✓ Radius of maximum wind

The characteristics of typhoons in the studyt area are comprehended by organizing and analyzing the data.

In case of lack of typhoon data:

Typhoon best track data is available from meteorological organizations around the world. Atmospheric pressure, location, time and radius of maximum wind can be complemented by weather charts.

<Information on social and natural conditions>

4) Collection of data about social conditions

Information on industrial agglomerations and social infrastructure in the study area which would be affected by storm surges are collected and arranged. Social infrastructures can be divided into two category; transportation infrastructures and lifelines.

- ✓ Traffic infrastructures (Internal and external transportation of industrial agglomerations):
  - Roads, railways, ports, harbors and airports
- ✓ Lifelines (Necessary for business continuity):
  - Electricity, water and sewerage, gas, communication and oil

The actual region to assess the hazard by storm surge is decided based on the distribution of infrastructure facilities. As the infrastructure facilities spread widely outside of industrial agglomerated area, the region of hazard analysis does not remain in the industrial agglomerated area in general.

If there is little information on social infrastructure,

Try to collect the information on special important infrastructure (industrial estates, main arterial road, etc.) for formulating Area BCP in the target area. Creating the GIS data by extracting the important infrastructure information from commonly shared topographic map is possible measures to complement the required information.

5) Collection of data about natural conditions

Following data are collected to understand the topographic features of the study area.

- ✓ Elevation data
- ✓ Bathymetry

The data below are also useful for more detailed investigation.

- ✓ Land use map
- ✓ Data related to geological information

It is desirable to use data with equal or less than 1km resolution to secure accuracy.

In case of insufficient information of natural conditions is available:

The following public data is also available.
Elevation: GTOPO30 (Global 30-Arc-Second digital elevation model data) and SRTM (Shuttle Radar Topography Mission) can be used for global altitude data. Note that the quality (resolution) of GTOPO30 varies among the area.
Bathymetry: GEBCO08 (Global 30-second grid, General Bathymetric Chart of the Oceans) data is available.

6) Collection of information on the structures in ports and harbors

Information on the artificial structures such as breakwaters and seawalls are not included in the elevation data. These structures are important factors in assessing the storm surges. The following data are collected.

- ✓ Existence of the structures
- ✓ Location of the structures
- ✓ Function and performance of the structures

> ***If there is little information on structures in ports and harbors,***
>
> These structures can be confirmed by field survey or aerial photographs with high resolution. The efficacy of the structures is analyzed in conjunction with the disaster records collected in 1).

[Step 2] Determination of a scenario disaster scale

Based on the data collected in Step1, the target scale of storm surge for formulating the Area BCP is set. Note that the scale of storm surge is defined as the scale of typhoon which generates storm surge.

7) Analysis of typhoon data based on statistics of extreme

The typhoon scale in the study area is studied based on the collected data in 3). The return period is calculated using the analysis on statistics of extreme.

[Procedure of the statistical analysis]

1. Apply multiple probability distribution functions
2. Perform the goodness of fit evaluation
3. Adopt the optimum probability distribution function

The result of the extreme statistical analysis depends on the number of samples. The reliability of the return period of typhoons becomes lower if the number of samples is insufficient. It is desirable to collect the annual maximum value at least for 50 years to perform a reliable analysis.

> ***Typical statistical processing technique,***
>
> Gouda method: Apply several probability distribution functions*). Adopt the one whose residual error becomes a minimum against the mean value of the residual error of the coefficient of correlation.
>
> *) Exponential distribution, Gumbel distribution, Extreme type-II distribution, Weibull distribution, etc.

8) Determination of a design storm surge scale

Set the design storm surge scale for formulating the Area BCP. If the designed scale is huge, there should be much more content to formulate Area BCP. In this case, it requires considerable work to formulate Area BCP, but safeness of the plan become high. On the other hand, if the designed storm surge scale is small, the target scope of the Area BCP become limited, and makes it easier to formulate Area BCP. In this case, there is a possibility Area BCP doesn’t work effectively. Hence, design hazard scale should be set in accordance with regional city plan, administrative strategy, feasibility of plan with the discussion among the relevant people including local resident.

A way of thinking to set design storm surge scale

If to set the design storm surge scale is difficult, as initial scale, set some scale like 50, 100, 200-year return period hazard. After that, set the design storm surge scale in conjunction with the result of disaster risk evaluation.

[Step 3] Analysis and assessment of storm surges

On the basis of past storm surge information summarized in 1), select the appropriate model to simulate the storm surge in the study area and conduct analysis.

9) Select of typhoon model

Select the appropriate model to create the fields of surface wind and air pressure caused by typhoons. To simulate the storm surge by the stochastic typhoon, the typhoon model to reproduce the fields of surface wind and atmospheric pressure which are the external forces in the storm surge simulation. The two-dimensional typhoon model based on the Myers' formula is used usually.

10) Select of storm surge model

Select the appropriate storm surge model to calculate sea level variations using surface wind and pressure estimated by the typhoon model. The appropriate analysis model should be selected among several general storm surge models from the view point of the characteristics of the study area, the degree of required accuracy and the available computer resources.

Example of storm surge model

	POM (Princeton Ocean Model)	MOM・GOLD (Modular Ocean Model Generalized Ocean Layered Model)	FVCOM (Finite Volume Coastal Ocean Model)
Model	Hydrostatic	Hydrostatic	Hydrostatic/Nonhydrostatic
Purpose	Analyze the marine current and the changes in the surface caused by meteorological fields based on the marine climate conditions such as insolation, wind and air pressure.	Analyze the marine current and the changes in the surface caused by meteorological fields based on the marine climate conditions such as insolation, wind and air pressure. GOLD accommodates oil defluxion and flowage.	Analyze the marine current and the changes in the surface they caused based on the marine climate conditions such as tide, river water flow and ground water flow.
Original creator	Princeton University	GFDL (Global Fluid Dynamics Laboratory) of NOAA (National Oceanographic and Atmospheric Administration)	University of Massachusetts
Distributor	http://www.ccpo.odu.edu/~tezer/POMDB/adduser.htm	https://fms.gfdl.noaa.gov/gf/account/?action=UserAdd	http://fvcom.smast.umassd.edu/FVCOM/Source/code.htm

11) Construction of analysis model and conduct the analysis

11)-1 Construct typhoon model

A past typical typhoon is selected among several typhoon data collected in 3). The field of surface wind and air pressure are calculated using the typhoon model selected in 9). The reproducibility of the typhoon is confirmed by comparing the analyzed and the observed wind and air pressure. If the reproducibility is not enough, the parameters of the model are modified to upgrade reproducibility.

11)-2 Construct storm surge model

The tide level for the selected typhoon is calculated using the storm surge model selected in 10) and the surface wind and air pressure distribution calculated in 11)-1. The reproducibility of tide level is confirmed by comparing the analyzed and the observed tide level collected in 1) and 2). If the reproducibility is not enough, the parameters of the model are modified to upgrade reproducibility. It is desirable to perform the affirmation of reproducibility for several cases to secure the reliability.

11)-3 Analysis of stochastic typhoon

The conditions of designed typhoon are decided based on the analysis in 7). The hazard by storm surges is not only determined by the scale of typhoon but also by its course and velocity. Therefore, it is desirable to study several courses for the target typhoon. Based on the typical course of past hazardous typhoon collected in 1) and 3), the conditions of designed typhoon is studied and adjusted.

11)-4 Analysis of storm surge for stochastic typhoon

The tide level for the designed typhoon is studied based on the wind and atmospheric pressure calculated in 11)-3. The magnitude and range of hazard varies depending on the specified scale, radius, course and speed of typhoon. The course of typhoon is selected finally referring to the inundation area and depths caused by storm surges and the effect to the important facilities.

12) Evaluation of the inundation situation

The inundation area and depths are calculated from the results of the storm surge analysis in 11). Examples of the method to evaluate the inundation are shown below. The method is selected considering the required accuracy, available computational resource and etc.

- Level Flooding Method···Simplified technique, capable of assessing the safe side
- Dynamic technique···Capable of assessing the detailed distribution of inundation area and duration

[Example of Storm Surge Hazard Analysis]　Hai Phong in Vietnam

- Storm surge analysis using a two dimensional typhoon model and POM-

The procedures mentioned below are the steps in performing an analysis of storm surges using publicly available data and models.

[1] Get the analysis software and necessary data

1) Get the ocean model

Download POM (Princeton Ocean Model) from the site below

◆http://www.ccpo.odu.edu/POMWEB/

2) Get the terrain model

Download GEBCO08 data from the site below.

◆http://www.gebco.net/data_and_products/gridded_bathymetry_data/

3) Get the typhoon data

Download best track data from Japan Meteorological Agency.

◆http://www.jma.go.jp/jma/indexe.html

4) Get the tidal data

Download NAO.99b from the site below.

◆http://www.miz.nao.ac.jp/staffs/nao99/

[2] Setting a calculation condition

1) The domain of the storm surge model

Taking into account the computation time and the stability of the calculation, nesting calculation has to be performed. Terrain data of a specified area is prepared.

In the case of Hai Phong, the calculation domain was performed as shown in Figure-1.

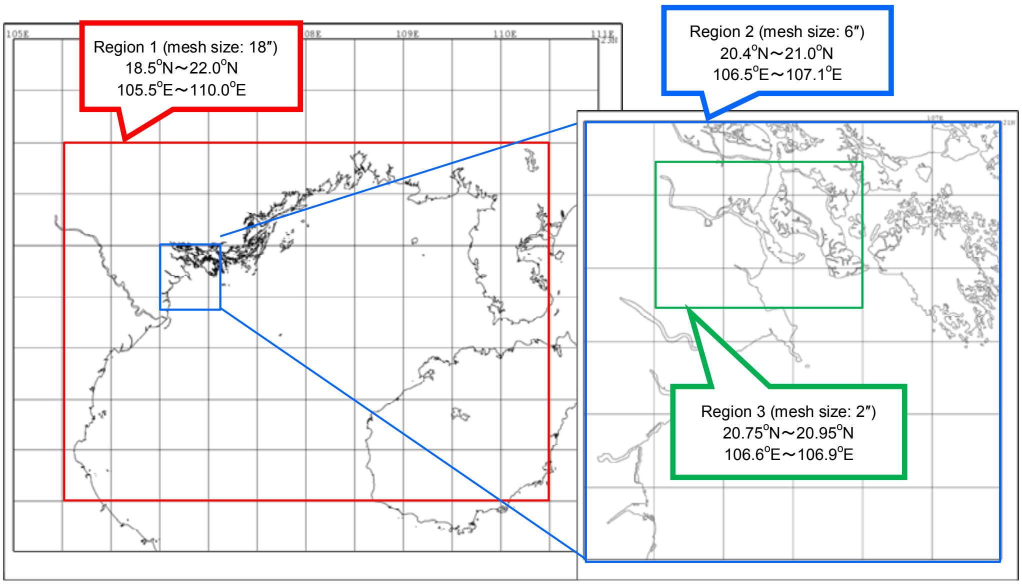


Figure-1　The domain of the storm surge model at Haiphong, Vietnam

2) Selection of the past typhoon for verification

The typhoon Son Tinh (coded T1223), which caused significant damage to north of Vietnam in 2012, was selected for verification.

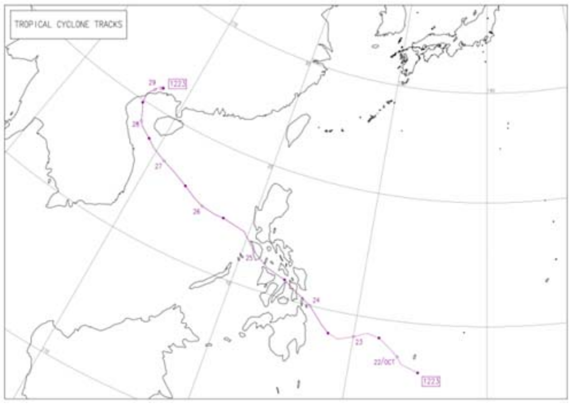
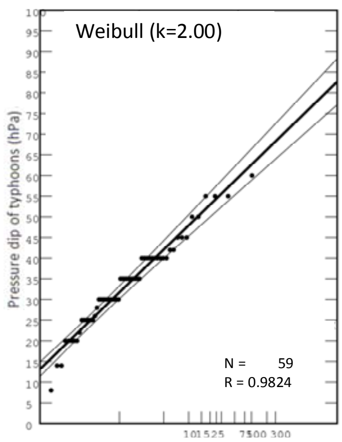


Figure-2 Track of typhoon Son Tinh (T1223)

3) Analysis of typhoon based on statistics of extreme for the return period of the typhoon

Return periods of the typhoon to the study area are analyzed based on the collected typhoon data. In the case of Hai Phong, 50, 100 and 200-years return periods are studied by Gouda method.



Return Periods (Year)	Pressure dip of typhoons (hPa)	Standard Deviation (hPa)
1	-	-
2	31.720	1.547
5	42.078	2.140
10	47.922	2.576
15	50.925	2.815
20	52.917	2.977
25	54.397	3.099
30	55.568	3.197
50	58.688	3.460
75	61.020	3.660
100	62.608	3.797
200	66.240	4.113
300	68.253	4.290

Figure-3 Analysis of typhoon based on statistics of extreme in Vietnam

(Return Period and probability of exceedance for pressure dip of typhoons)

4) Generating wind and air pressure fields using a two dimensional typhoon model (the Myers' formula)

Generate wind and air pressure fields from the central atmospheric pressure and radius of maximum wind speed based on the Myers' formula below.

$$P(r) = P_0 + \Delta P exp\left(\frac{r_0}{r}\right)$$

P_0 : Minimum pressure at the typhoon center (hPa)

$\triangle P$: The difference between environmental atmospheric pressure and pressure at the maximum wind area (hPa)

r_0 : The radius of maximum wind (km)

r : The distances from typhoon center (km)

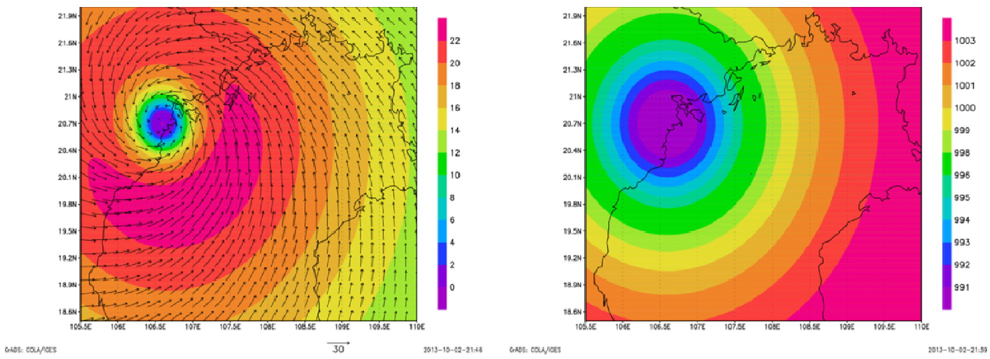


Figure-4　Distribution of wind (left) and air pressure (right) generated using two dimensional typhoon model

5) Setting a typhoon course

Considering geomorphological condition and typhoon characteristics, the typical course or the course which is assumed to cause the greatest damage to the study area are set by performing multiple investigations.

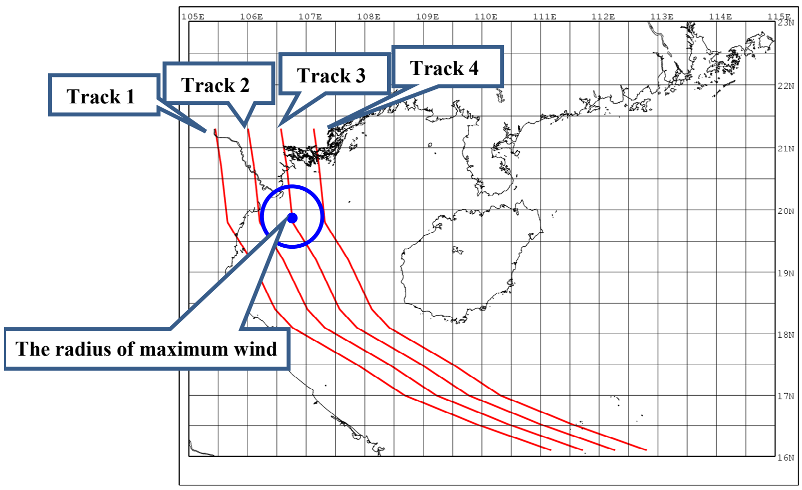


Figure-5　Example of the setting of a typhoon course in the case of Hai Phong

[3] Analysis using a storm surge model

1) Calculation of storm surge of the past typhoon for verification

The reproducibility is confirmed by comparing the analyzed and the observed wind speed, air pressure and tide level; and the parameters for computation are adjusted.

In case of Hai Phong, predicted wind speed by the typhoon model was underestimated at first in comparison with the actual observed data. The correction factor is introduced.

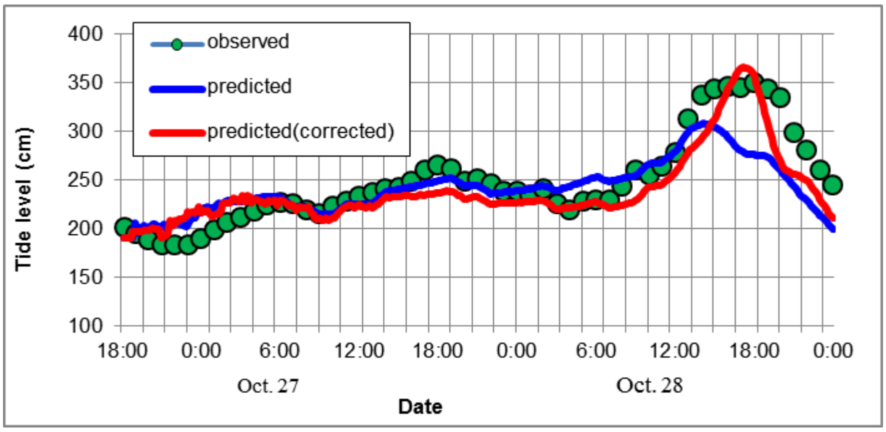


Figure-6 Reproducibility of sea level in the case of Vietnam

2) Storm surge estimation for stochastic typhoons

Storm surge estimation is performed using stochastic typhoons after adjusting the model. In case of Hai Phong, 50, 100 and 200-years return period cases were studied with multiple courses.

[4] Inundation calculation

Inundation area and depths are analyzed from the results of the storm surge analysis using stochastic typhoons. The distribution map of the maximum inundation depth is prepared using the Level Flooding Method.

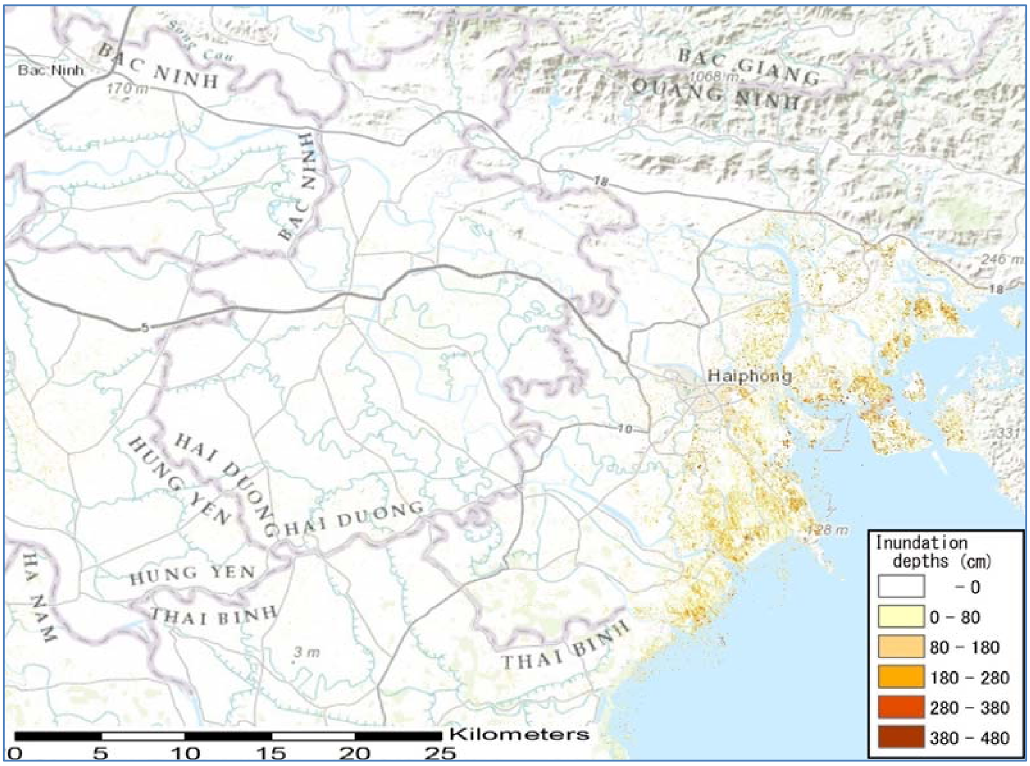


Figure-7 Inundation map (Inundation depths)