Training for seismic and tsunami warning operators on strengthening standard operating procedures for seismic data and tsunami warning in the South China Sea region [Online], 9-10th December 2021

Tsunami risk assessment method and its application

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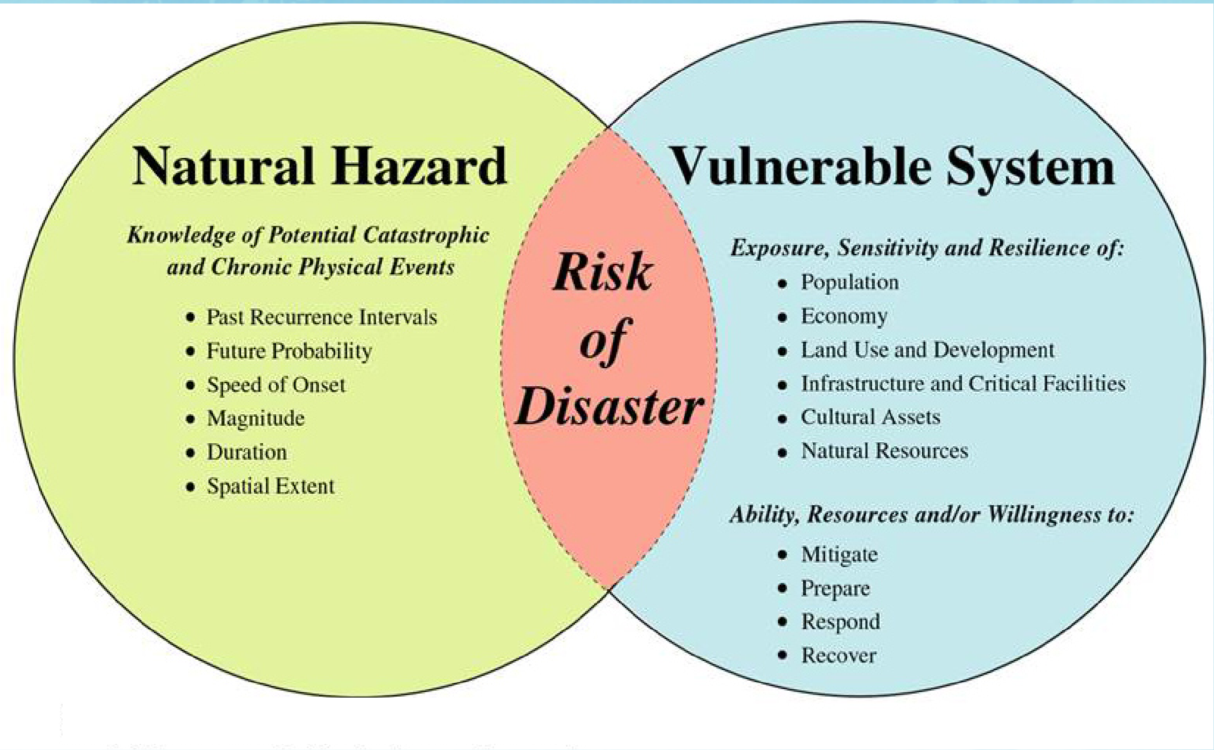
Contents

Related concept

Tsunami Risk

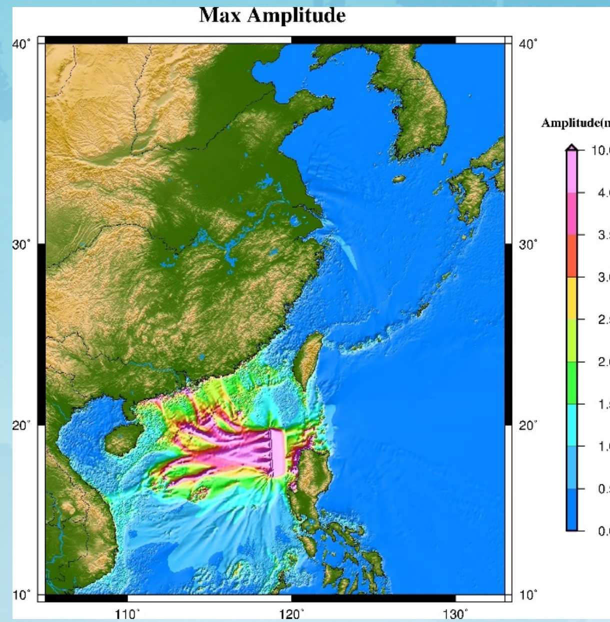
- Disaster risk signifies the possibility of adverse effects in the future. It derives from the interaction of social and environmental processes, from the combination of physical hazards and the vulnerabilities of exposed elements.

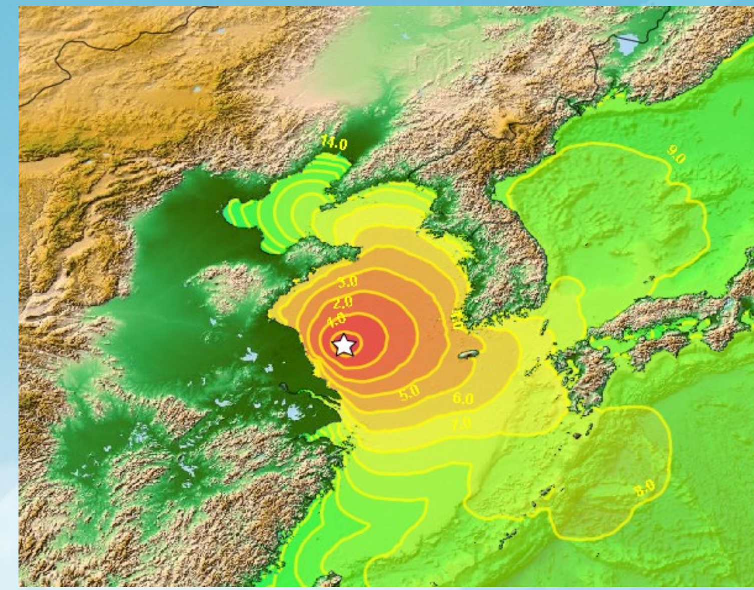


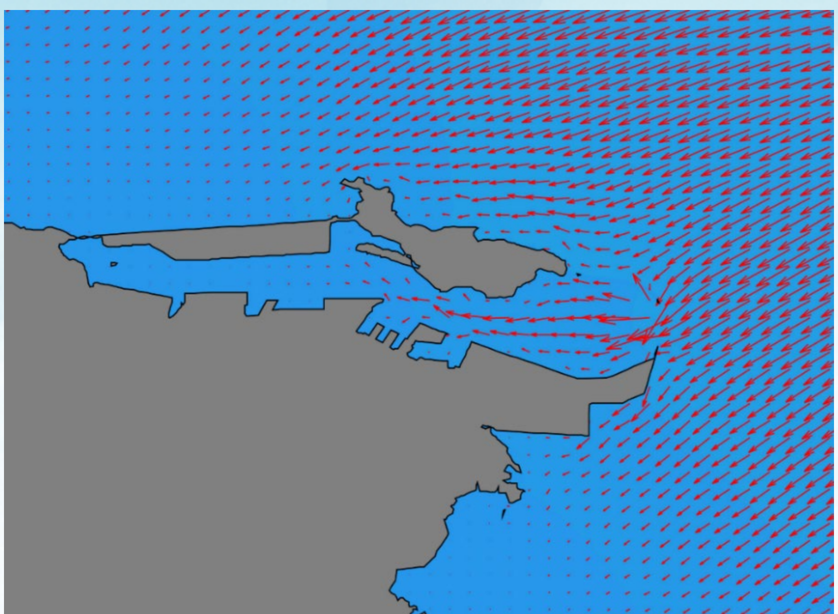
Related concept

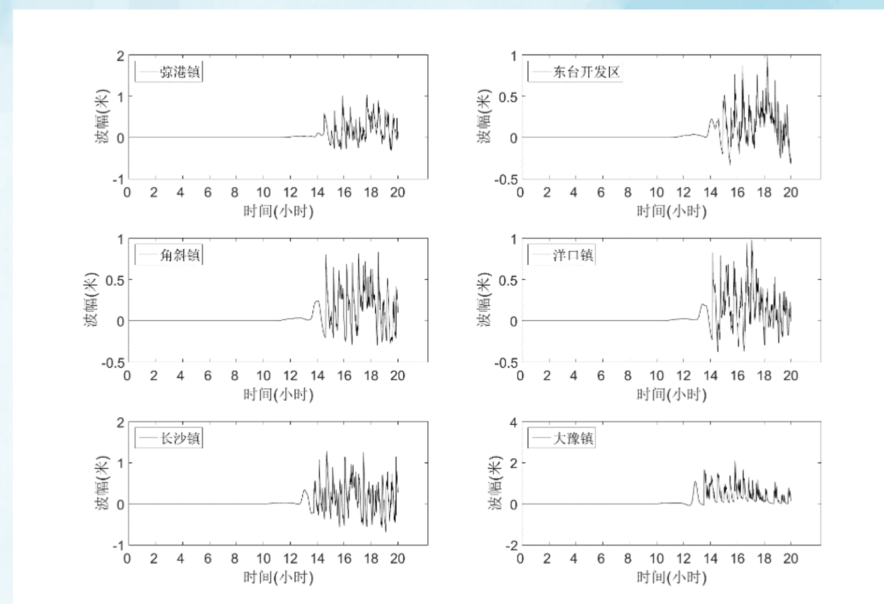
Tsunami Hazard

- Tsunami Maximum Amplitude
- Tsunami Travel Time
- Tsunami Current
- Tsunami Curve



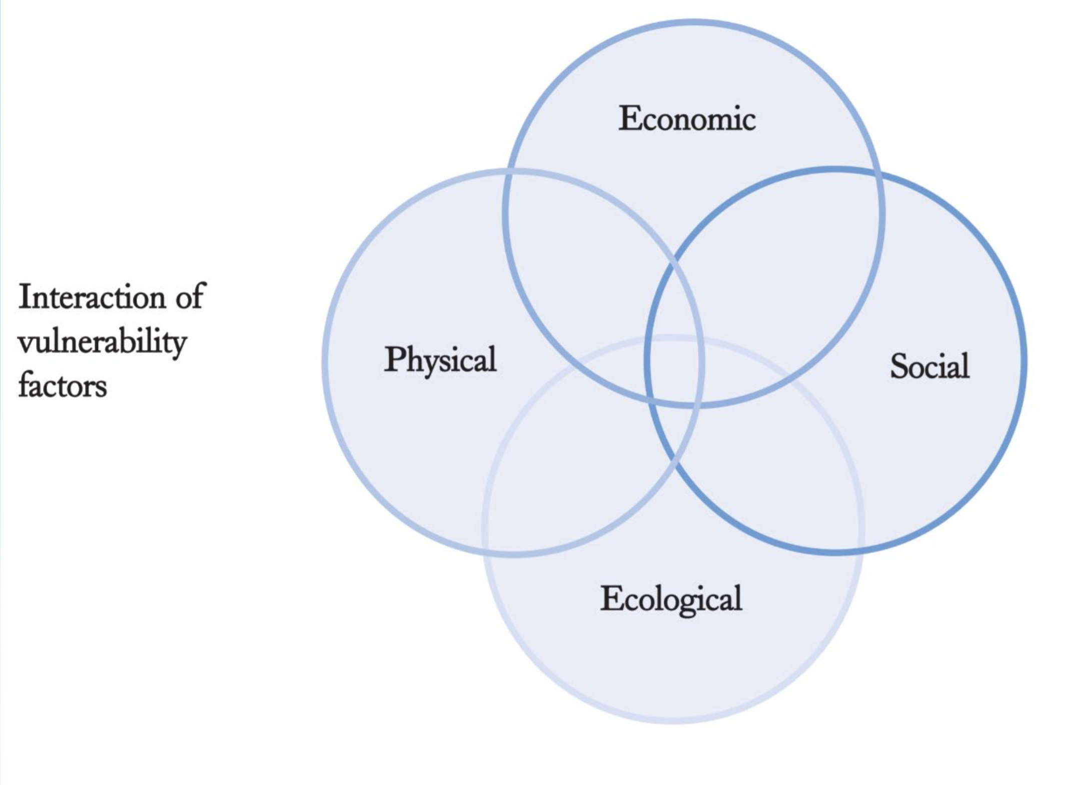






Related concept

Tsunami Vulnerability



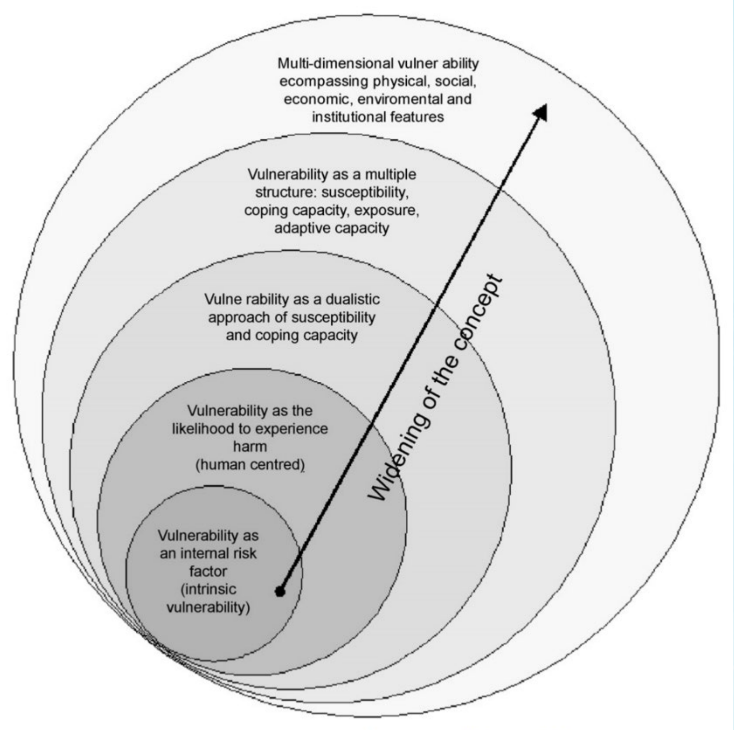


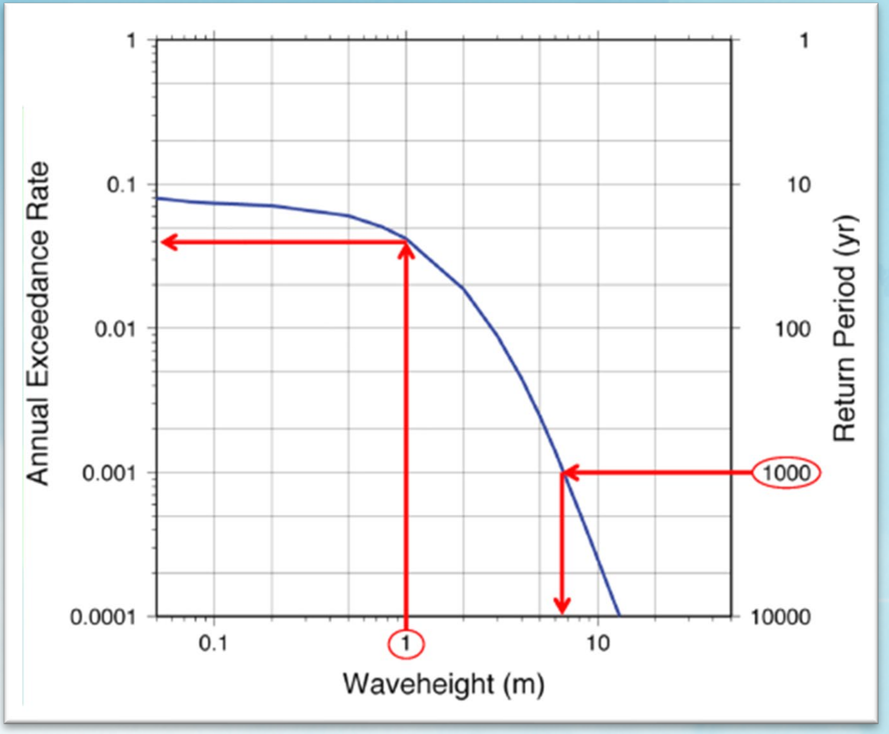
Fig. 1. The spheres of vulnerability. *Source*: Birkmann (2005).

The vulnerability to a tsunami is a function of a number of physical as well as social parameters that include amongst others: distance from the shore, depth of flood water, construction standards of buildings, preparedness activities, socio-economic status and means, level of understanding and hazard perception.

Contents

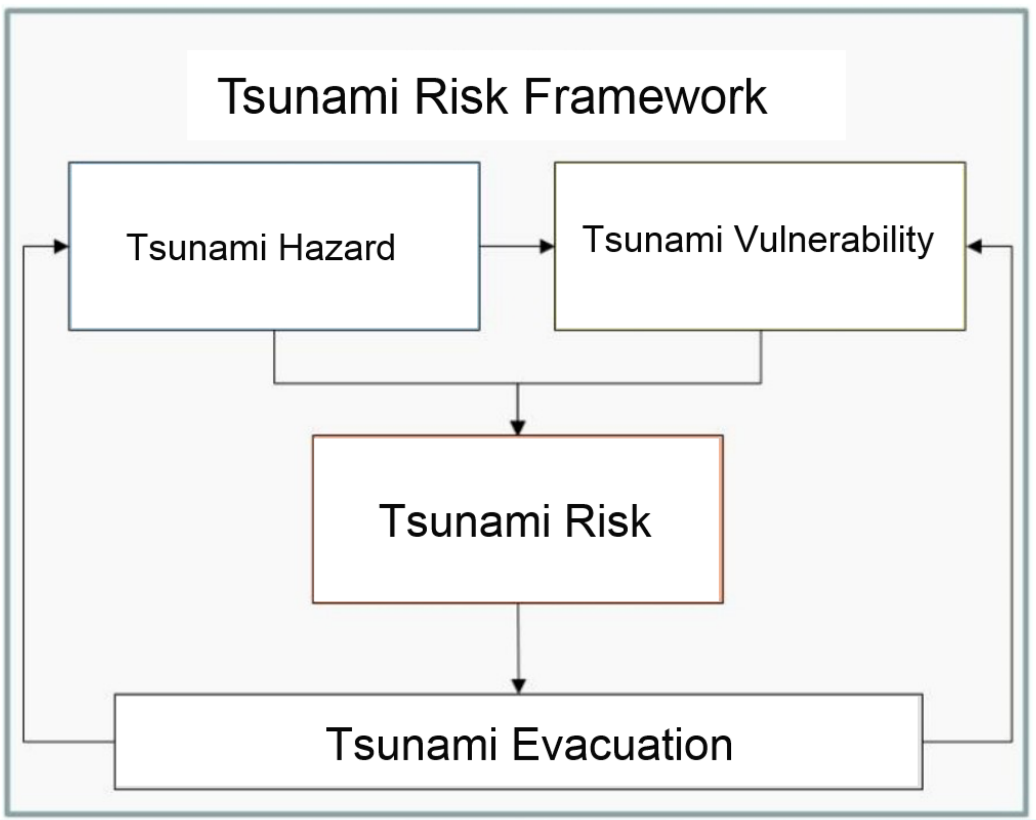
Tsunami assessment method

- **Scenario-based Tsunami Risk Assessment**
  - The key is to determine the source parameters of the potential worst tsunami and simulate of the tsunami wave near shore
  - Product: Maximum tsunami amplitude and inundation range (worst possibility)
- **Probabilistic Tsunami Risk Assessment**
  - The key is to determine the return period of different magnitudes of potential tsunamis and simulate the tsunami
  - Products: Maximum tsunami amplitude and inundation range during the typical return period; the spatial distribution of tsunami amplitude during a certain return period



Tsunami assessment method

Tsunami Risk Assessment Framework



(Clark *et al.* 2000)
(Turner et al. 2003)
(Hannes Römer 2011)

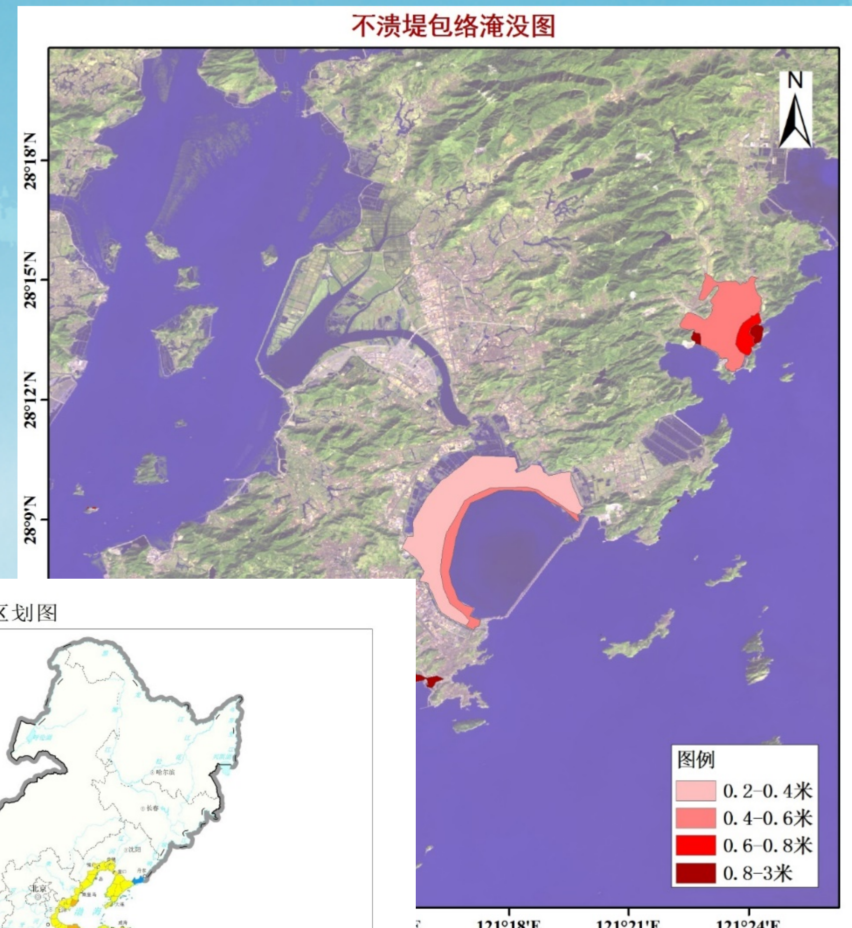
Tsunami assessment method

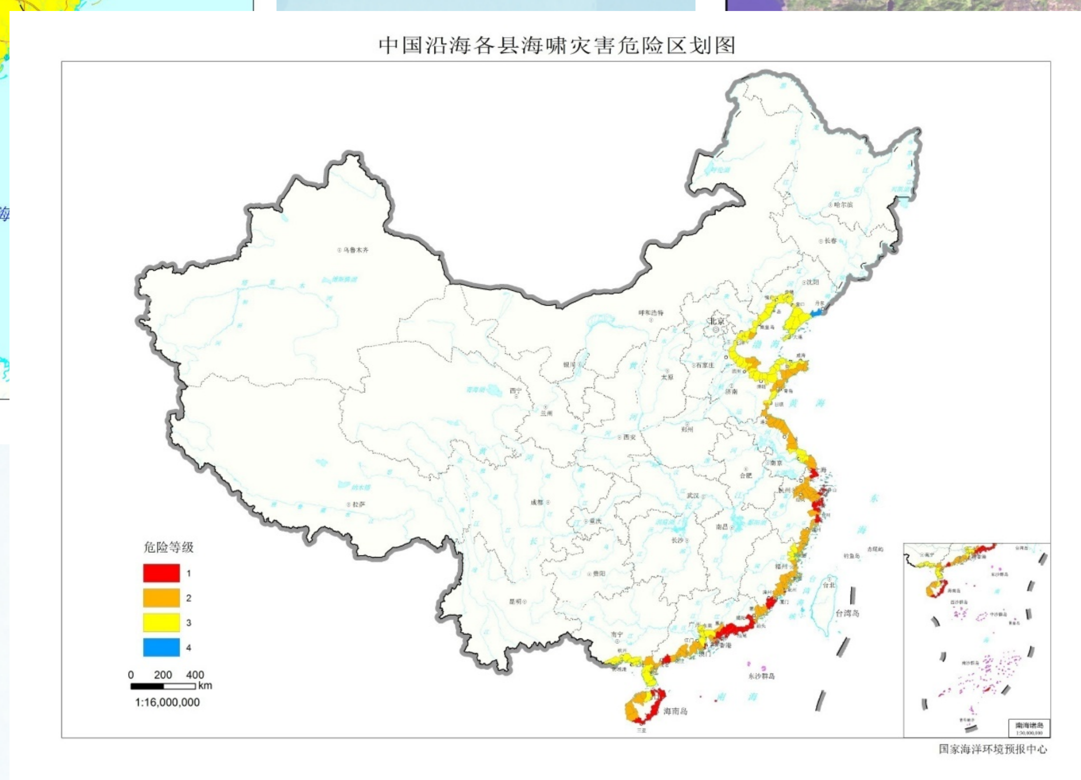
- The highest risk level of the grids in a unit is the risk level of the unit.
- Based on the results of the tsunami hazard and vulnerability levels, the risk levels of the unit is determined according to the risk matrix.

Risk matrix （Hazard, Vulnerability and Risk）

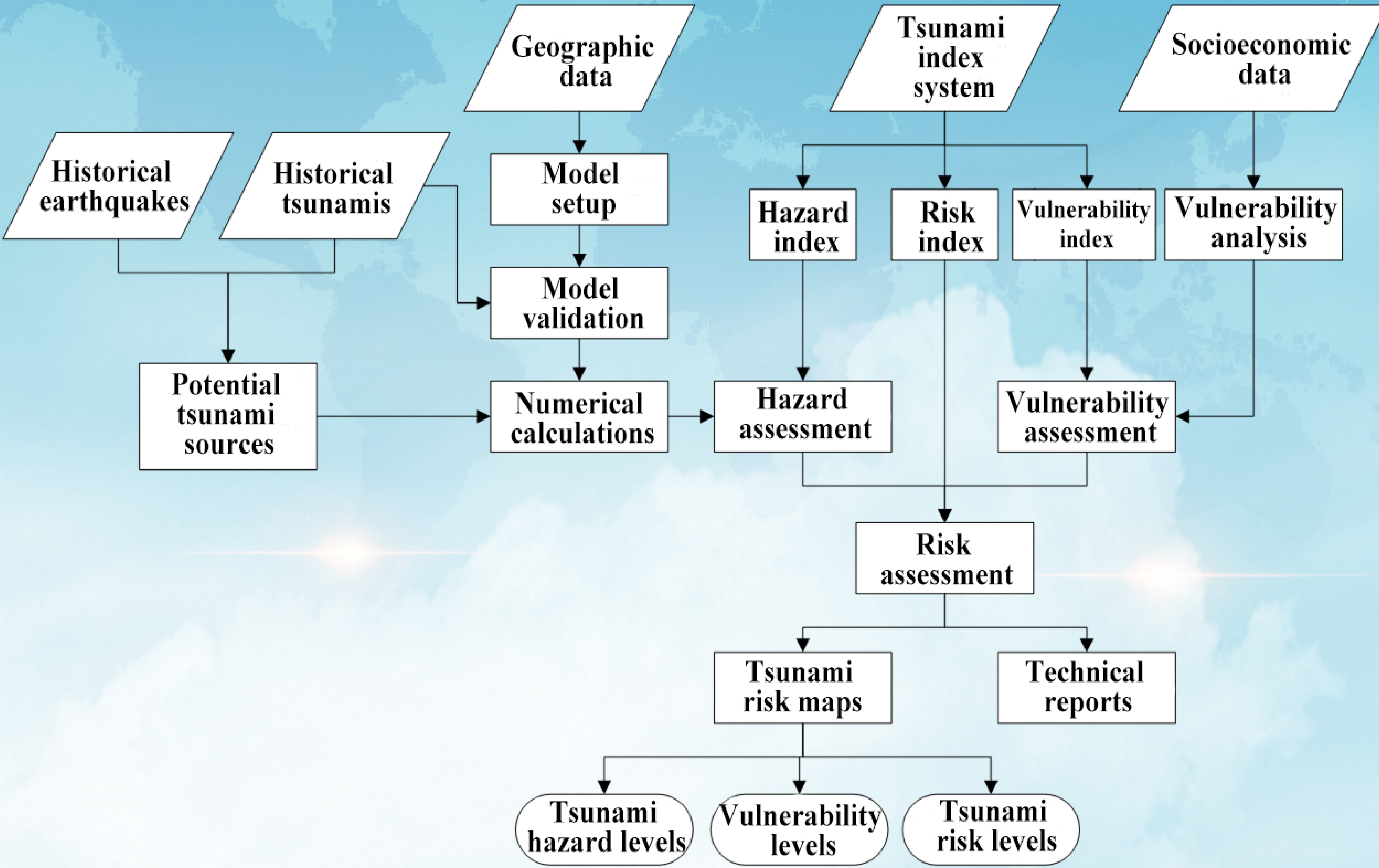
Hazard	Vulnerability			
	Low（IV）	Below Normal（III）	Above Normal（II）	High（I）
Low（IV）	**Low (IV)**	**Low (IV)**	**Below Normal (III)**	**Below Normal (III)**
Below Normal（III）	**Low (IV)**	**Below Normal (III)**	**Above Normal (II)**	**Above Normal (II)**
Above Normal（II）	**Below Normal (III)**	**Above Normal (II)**	**Above Normal (II)**	**High (I)**
High（I）	**Below Normal (III)**	**Above Normal (II)**	**High (I)**	**High (I)**

Tsunami assessment method





Tsunami assessment method



Tsunami assessment method

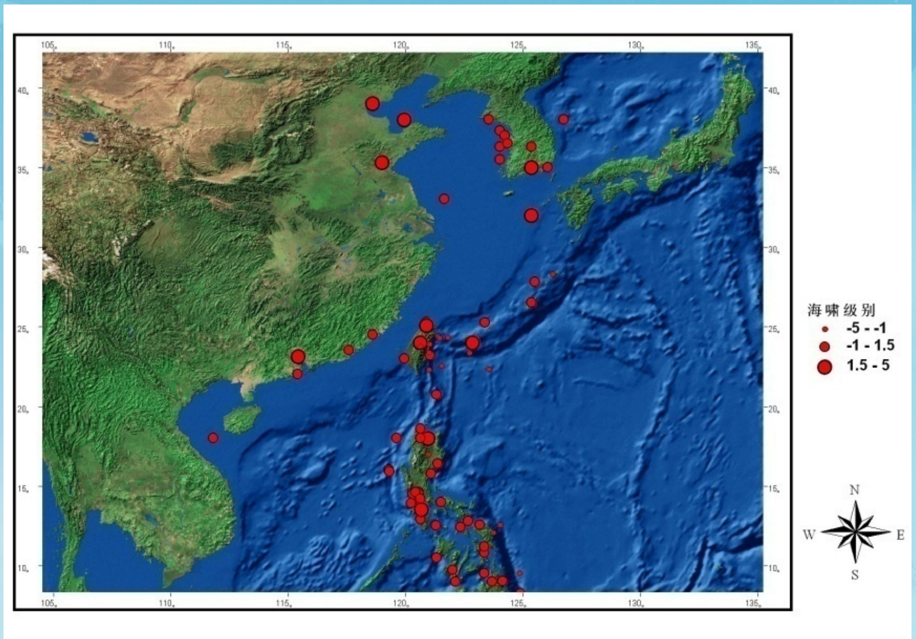
1 Survey of study area
2 Historical tsunamis analysis
3 Bathymetric and topographical data
4 Numerical simulation
5 Hazard, vulnerability, risk analysis
6 Evacuation analysis
7 Technical report

Contents

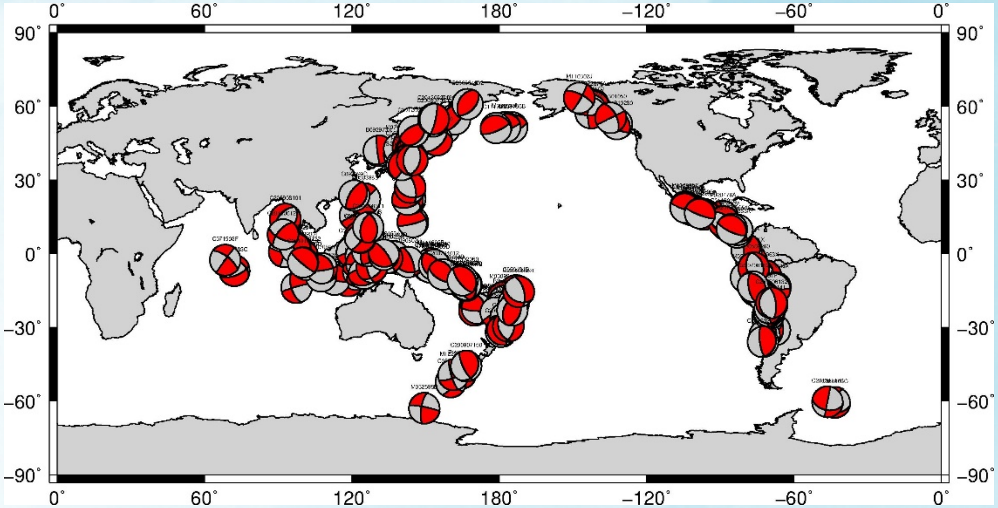
Tsunami assessment process

Data collection

- Historical tsunamis (NGDC, etc.)
- Historical earthquakes (CMT focal mechanism, etc.)
- Coastal tide gauge data
- Basic geographic data (DEM, DOM, DLG, water depth, important disaster-bearing bodies, land use, population, administrative division, transportation, etc.)
- Remote sensing data (Landsat, etc.)

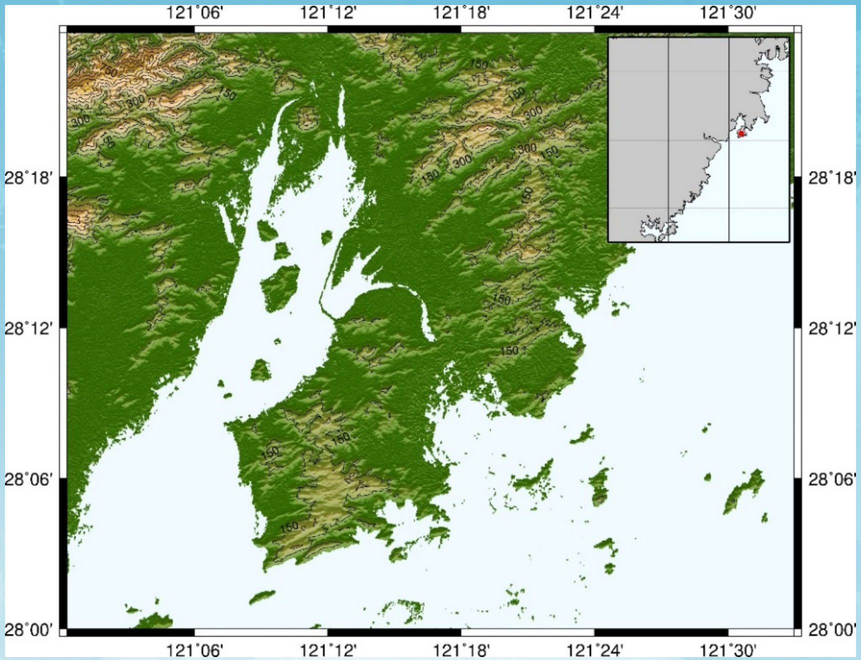


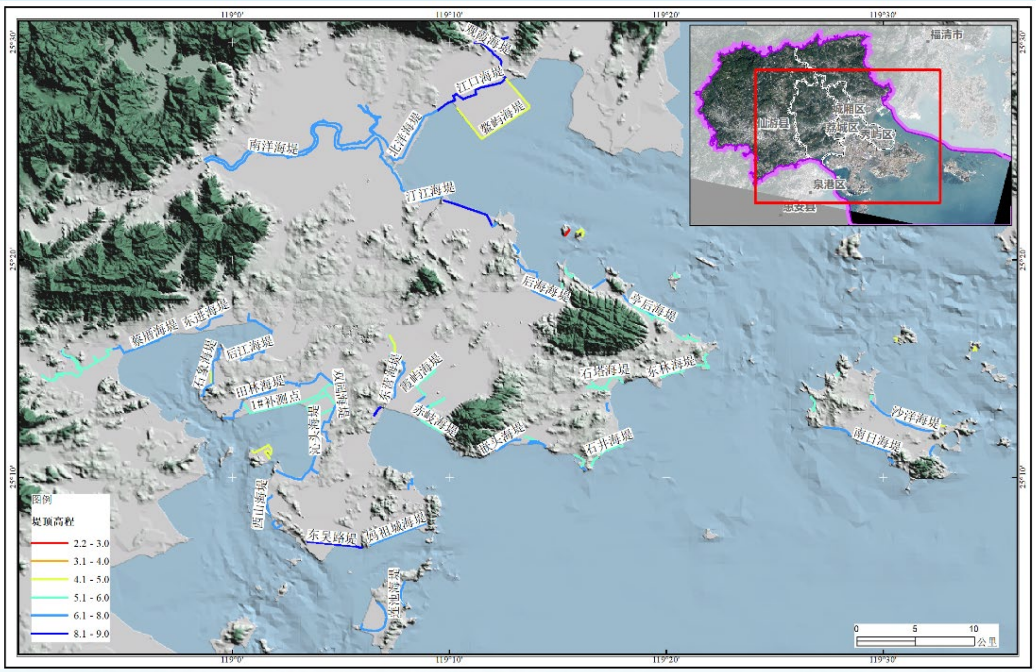
Historical tsunamis

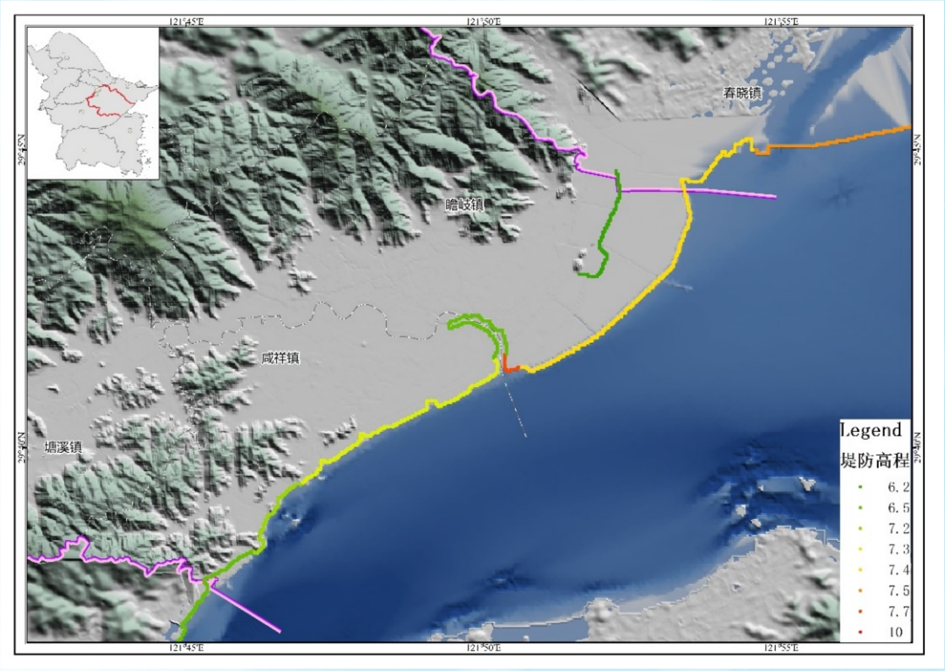


Historical earthquakes

Tsunami assessment process

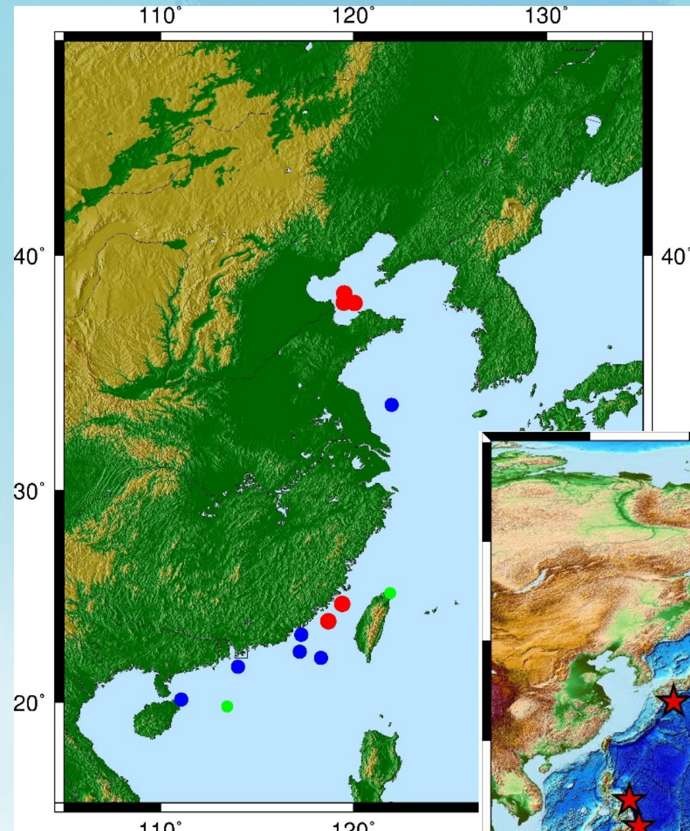




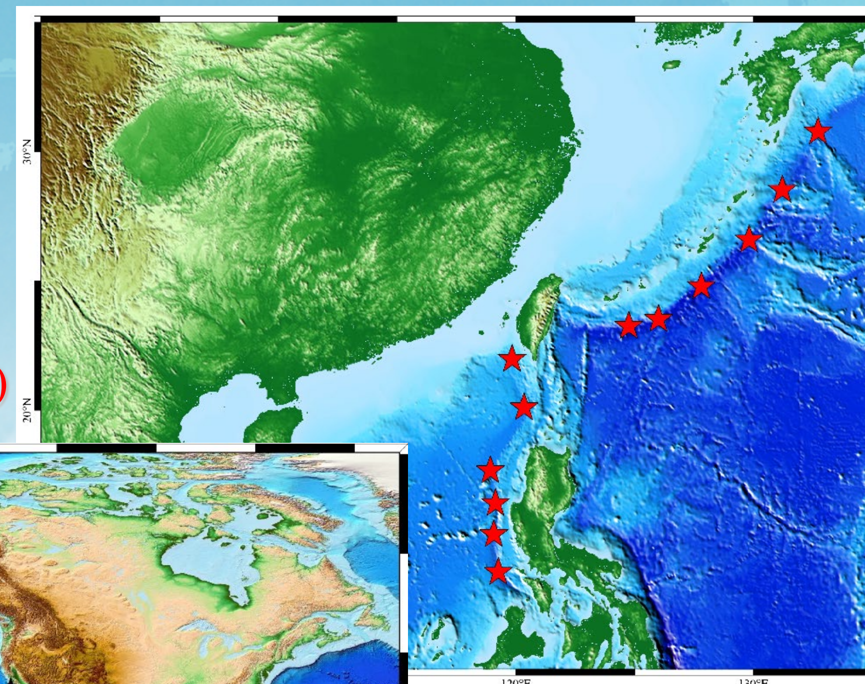


Tsunami assessment process

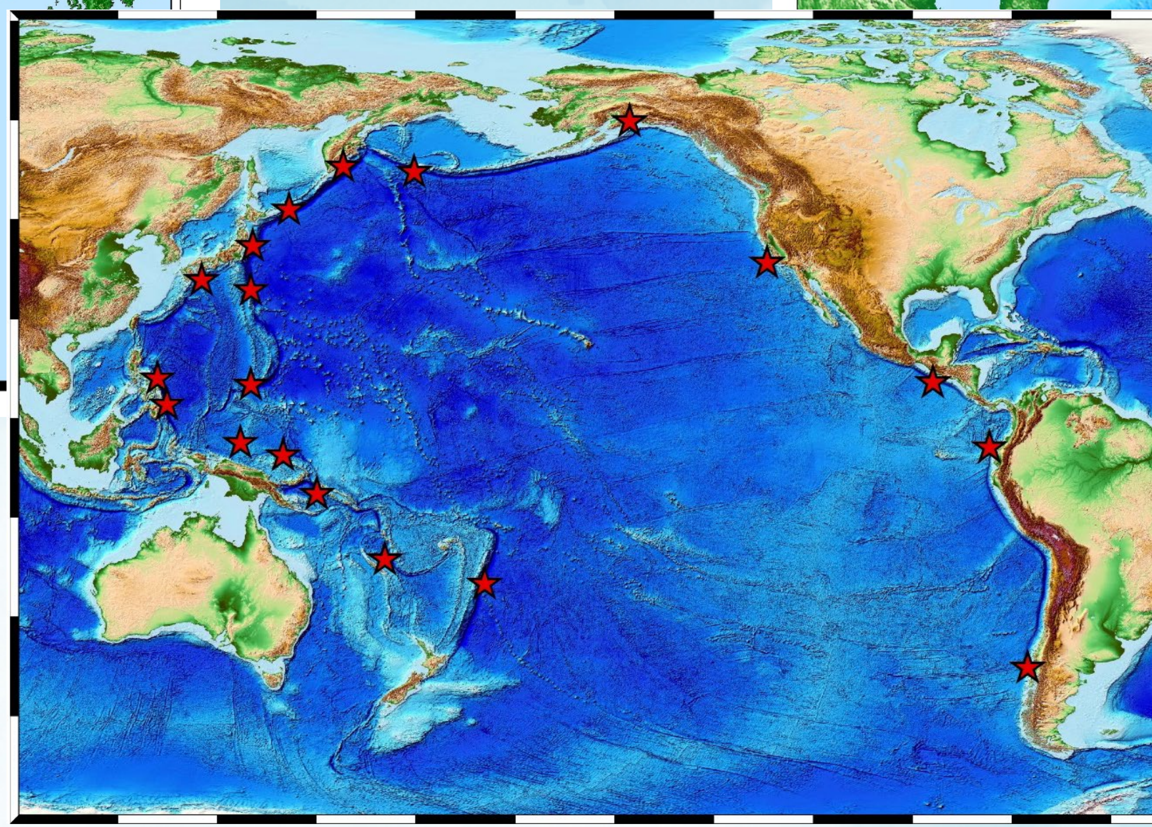
Local tsunami sources(13)



Regional tsunami sources (16)



Distant tsunami sources(22)



Numerical calculation

☐Model setup

☐**Geographic information data：**

- ✓ **Topographic data**
  - **ETOPO**
  - **GEBCO**
  - **DEM**
  - **Nautical chart**
  - **……**
- ✓ **Seawall data**
- ✓ **Shoreline data**
- ✓ **Satellite image data**
- ✓ **DLG**

Establishment of model grids

☐**Hydrological data：**

- ✓ **Astronomical tidal data**

The high tide level is considered in the model

☐**Land data：**

- ✓ **Land use data**

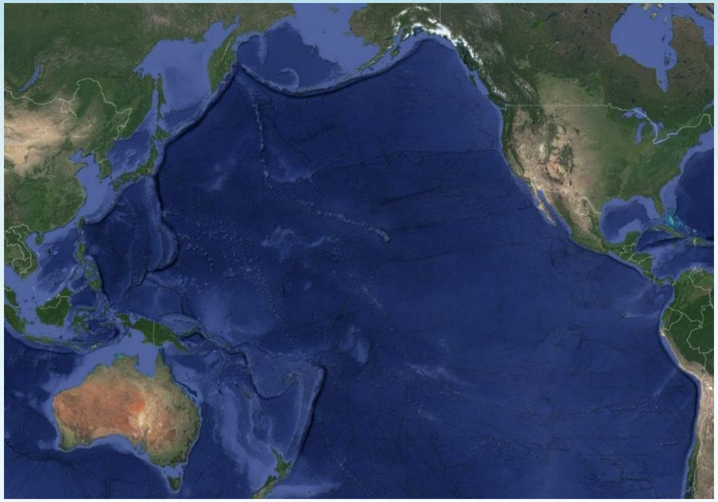
The bottom friction coefficient is set

Tsunami assessment method

Numerical calculation

□Nested grids

Layers	Longitude and Latitude	Resolution	Grids
Layer 1	5°- 52° N，99°- 157° E	2′	1741*1711
Layer 2	27°- 32° N，119°- 123° E	1/4′	952*1192
Layer 3	29.5°- 30.1° N，121.9°- 122.5° E	1/32′	1008*1064



Layer 1

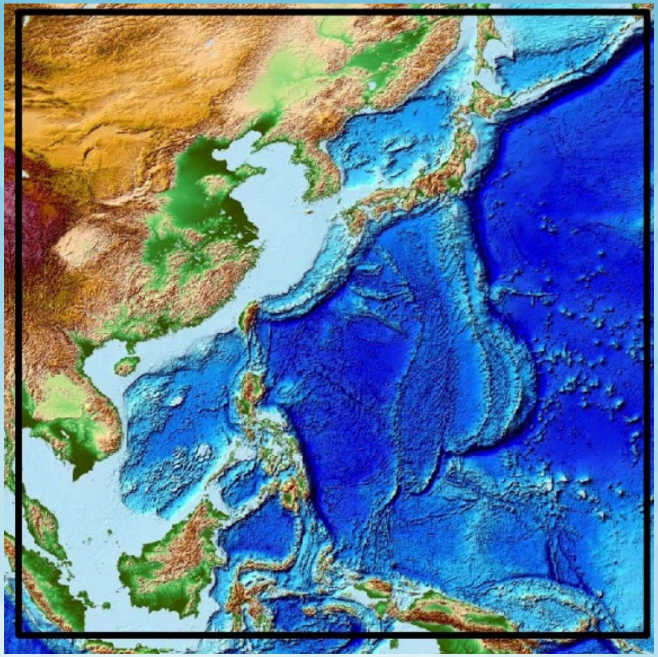
Layer 2

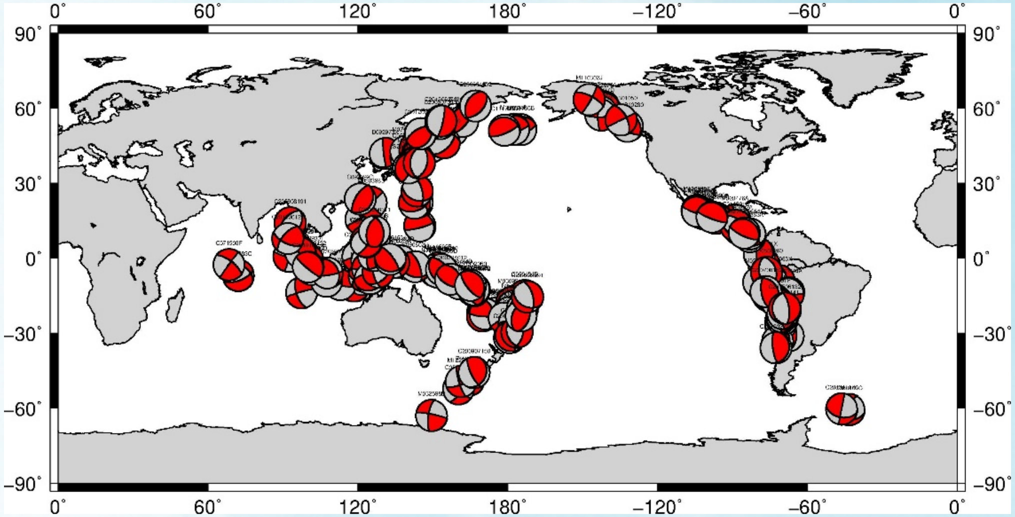
Layer 3

Tsunami assessment method

◻Numerical model

- Numerical model: COMCOT
    - Nested grids covering **the whole Pacific**
    - Max. resolution: ~ 50m
    - Flooding and inundation modeling
    - leap-frog scheme modeling
    - Parallel computing
- Initial water surface displacement: Okada
- Advantage:
    - High resolution to distinguish coastal topography and bathymetry
    - High efficiency of computing
    - Inundation processes





Tsunami assessment method

□Governing equations

$$\frac{\partial\eta}{\partial t}+\frac{1}{R\cos\varphi}+\left[\frac{\partial P}{\partial\psi}+\frac{\partial}{\partial\varphi}(\cos\varphi\, Q)\right]=-\frac{\partial h}{\partial t}\quad(1)$$

$$\frac{\partial P}{\partial t}+\frac{gh}{R\cos\varphi}\frac{\partial\eta}{\partial\psi}-fQ=0,\quad(2)$$

$$\frac{\partial Q}{\partial t}+\frac{gh}{R}\frac{\partial\eta}{\partial\varphi}+fP=0\quad(3)$$

Linear shallow water equation

$$\frac{\partial\eta}{\partial t}+\frac{1}{R\cos\varphi}+\left[\frac{\partial P}{\partial\psi}+\frac{\partial}{\partial\varphi}(\cos\varphi\, Q)\right]=-\frac{\partial h}{\partial t}\quad(4)$$

$$\frac{\partial P}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\psi}\left(\frac{P^2}{H}\right)+\frac{1}{R}\frac{\partial}{\partial\psi}\left(\frac{PQ}{H}\right)+\frac{gH}{R\cos\varphi}\frac{\partial\eta}{\partial\psi}-fQ+F_x=0,\quad(5)$$

$$\frac{\partial Q}{\partial t}+\frac{1}{R\cos\varphi}\frac{\partial}{\partial\psi}\left(\frac{PQ}{H}\right)+\frac{1}{R}\frac{\partial}{\partial\varphi}\left(\frac{Q^2}{H}\right)+\frac{gH}{R}\frac{\partial\eta}{\partial\varphi}+fP+F_y=0\quad(6)$$

NON-Linear shallow water equation

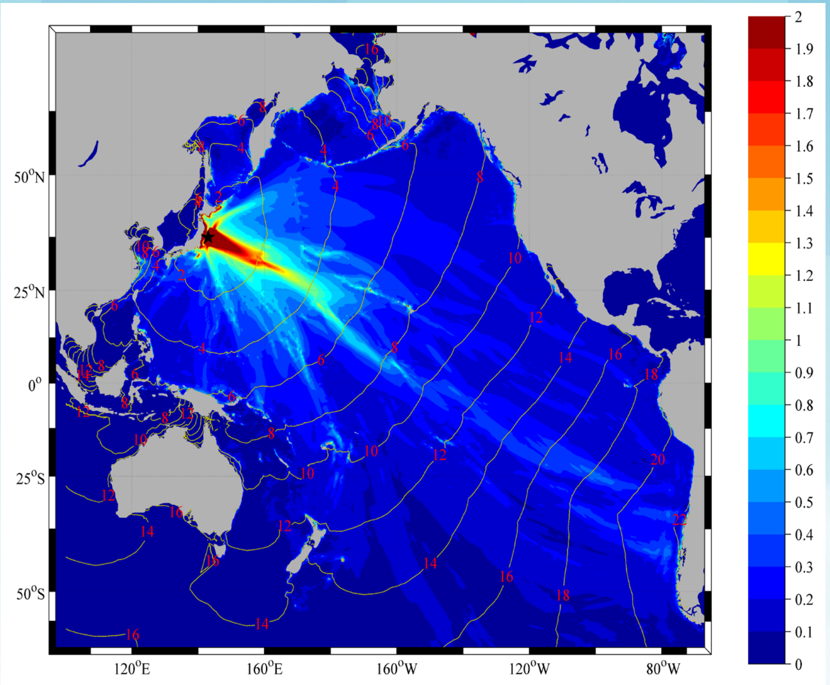
□When a tsunami wave propagates in the ocean, the dispersion and Coriolis force are relatively important. A linear shallow water equation in spherical coordinates is used to simulate the propagation of tsunami waves in the ocean.

□When the tsunami reaches the continental shelf, approaching the coast, the linear shallow water equation is no longer suitable. The nonlinear equations are used to simulate the tsunami wave.

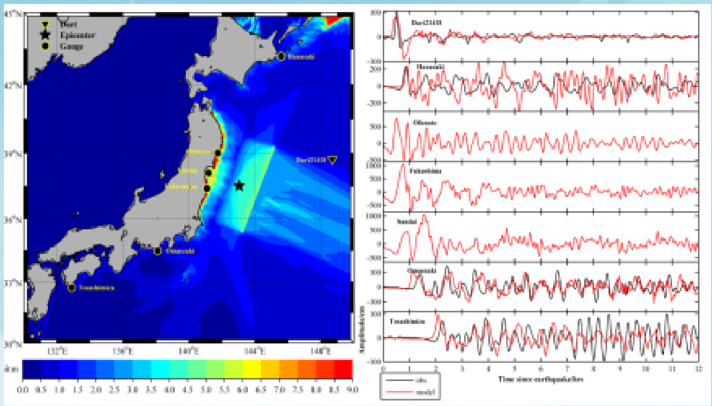
Tsunami assessment method

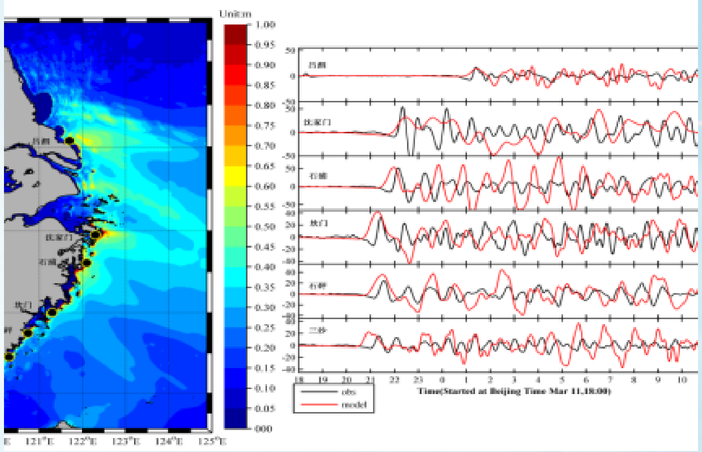
Numerical calculation

□Model validation



The simulation results are in good agreement with the monitoring results.





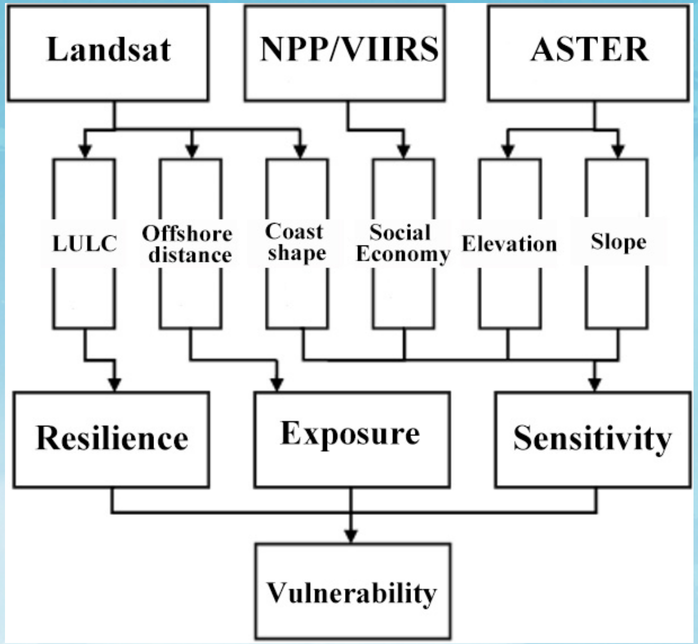
□A tsunami wave of about 50 cm was detected along the southeast coast of China.

□After ravaged the coast of Japan, the tsunami quickly reached the island countries and coastal countries in the Pacific.

Background and Concept

❖ **Tsunami vulnerability assessment analysis**

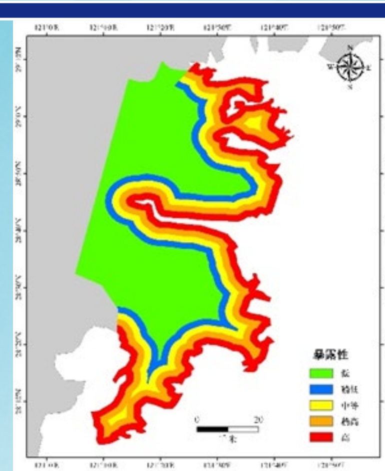
- Exposure: defined as the degree to which the disaster-bearing body is exposed to the tsunami disaster;
  Offshore Distance
- Sensitivity: refers to the degree of sensitivity to which the disaster-bearing body may be affected;
  Elevation, Slope, Coast Shape, Social economy
- Resilience: the potential recovery of the disaster-bearing body after a loss.
  Land use



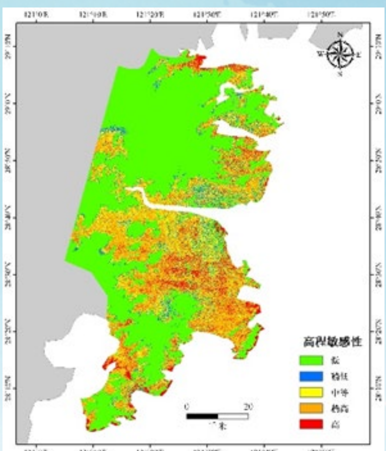
Resilience levels

LULC	Damage type	Resilience	Levels
Construction	Destruction	High	5
Wetland	Destruction, Salt invasion	Higher than medium	4
Natural water	Pollution	Medium	3
Woodland	Pollution, Salt invasion	Lower than medium	2
Cultivated land	Pollution, Salt invasion	Low	1

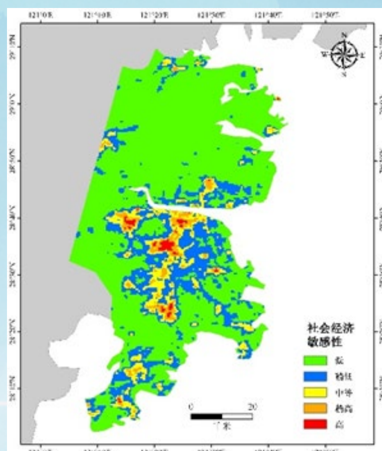
Background and Concept



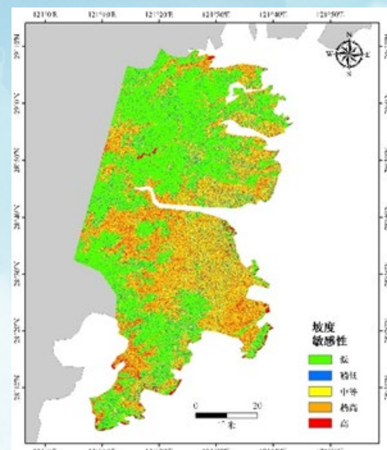
Offshore Distance



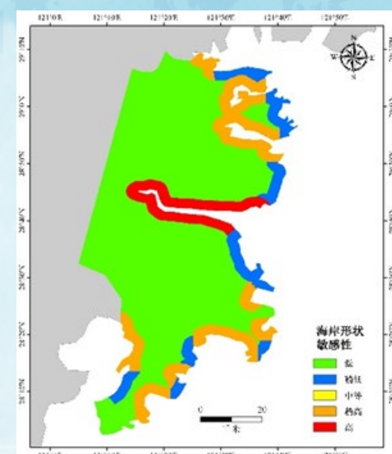
Elevation



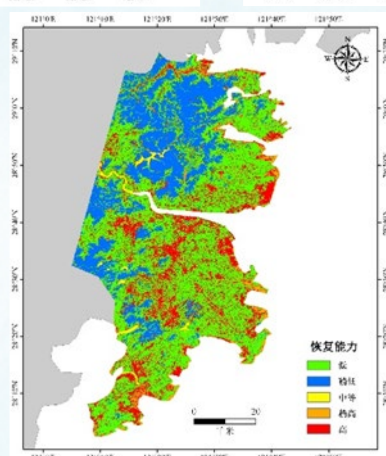
Slope



Social Economy



Coast Shape



Land Use

National level

- The purpose
  - To meet the macro needs such as national coastal strategic planning. The Scenario-based assessment method is used to assess the tsunami risk and provide scientific decision-making reference for national development.
- Data collection and processing
  - Basic geographic data (1:1 million), population data, seismic source information
- Analysis of potential tsunami sources
  - Submarine geological structure, regional seismic data; national seismic risk zoning results.
  - Based on historical replay and structural analogy principles, the upper limit of magnitude in the study area is evaluated.

National level

- Model setup
  - Numerical simulation method based on the shallow water equations
  - The resolution of the numerical model of national level is less than 1/10°
- Model validation
  - There are more than 5 historical tsunamis, and the average error of the maximum tsunami amplitude is less than 15%.
- Risk assessment and zoning
  - Hazard assessment:
    Assessment unit:
    County-level region

Level	Max Amplitude	Potential Impact
I	H > 3.0m	Large inundation
II	1.0m<H≤3.0m	Local inundation
III	0.3m<H≦1.0m	Strong current
IV	H≦0.3m	No threat

Tsunami assessment process

Province level

- Risk assessment and zoning

Vulnerability / Hazard	IV	III	II	I
IV	Risk (IV)	Risk (IV)	Risk (III)	Risk (III)
III	Risk (IV)	Risk (III)	Risk (II)	Risk (II)
II	Risk (III)	Risk (II)	Risk (II)	Risk (I)
I	Risk (III)	Risk (II)	Risk (I)	Risk (I)

- Assessment results
  - Tsunami hazard map
  - Tsunami vulnerability map
  - Tsunami risk map
  - Technical reports

Tsunami assessment process

County level

- The purpose
  - To meet the needs of local governments for disaster prevention and mitigation, the tsunami risk analysis is carried out to provide disaster prevention and mitigation decision-making support for the coastal emergency departments.
- Data collection and analysis
  - Digital elevation models (DEM), digital line drawings (DLG), digital orthographic images (DOM);
  - Socio-economic data (land use, population, villages, industry, etc.), hazard-affected bodies, etc.
- Modeling
  - The resolution of the nearshore model is less than 50 meters;
  - Considering facilities such as rivers, astronomical tides (high tides) and embankment gates

Tsunami assessment process

- Risk assessment and zoning
  - Tsunami inundation analysis: To meet the disaster prevention needs of nearshore ports, fisheries, water conservancy, civil affairs, transportation and other emergency management departments

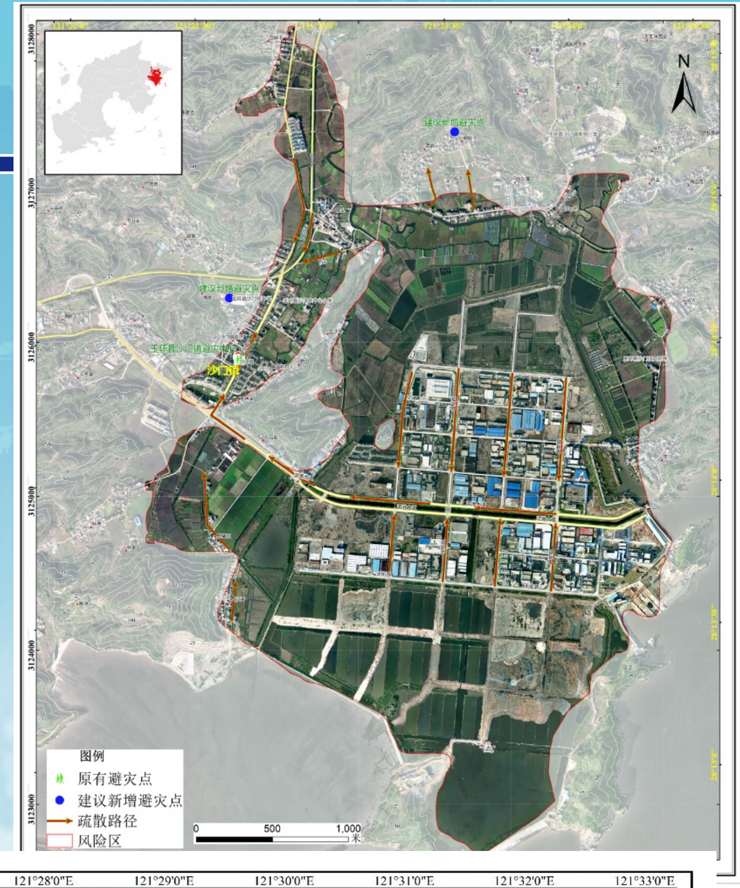
	Information should be included
Basic information	Inundation information (inundation high-risk area, initial time of inundation, inundation area)
	DEM
	Coastal protection facilities
	Regional overview (population distribution and land use)
	Emergency traffic routes, earthquake shelters and evacuation facilities
Information for inundation map	Historical tsunamis (inundation area and damage)
	Disaster prevention headquarters, police station, fire brigade, communication network, storage warehouse, water works
	Evacuation shelters such as square, school, stadium ,park
	Public facilities (transportation facilities such as roads, railways, ports and airports, shopping malls, power generation facilities, natural gas pipe network, schools, communities, hospitals, nursing homes, kindergartens and welfare facilities)
	Tsunami evacuation routes
	Coastal protection facilities (location and structure)

Tsunami assessment process

- Evacuation map
  - Basic information (inundation hazard, DEM, DLG, etc.)
  - Population distribution
  - Public facilities, shelters, etc.
  - Evacuation routes

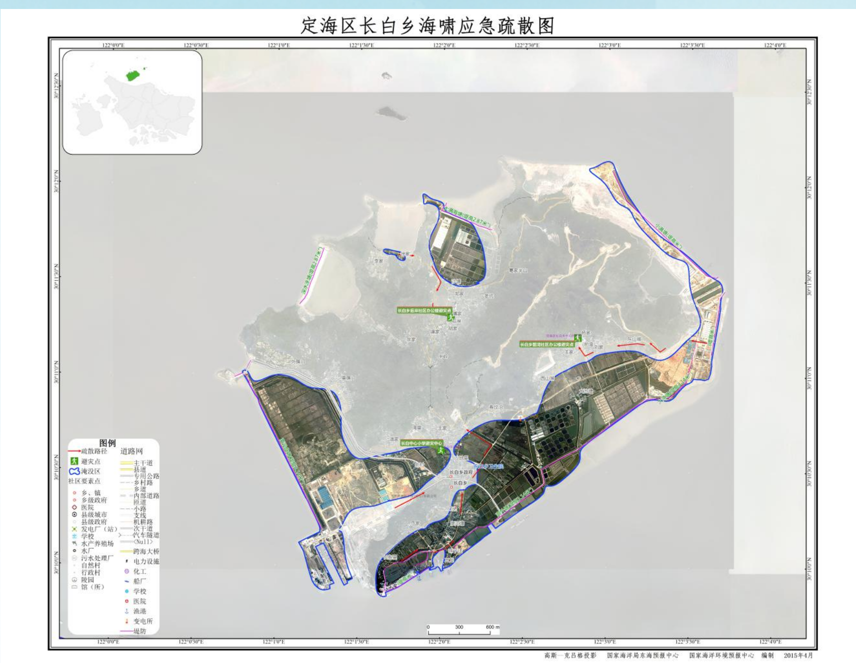
- County-level tsunami assessment results
  - tsunami inundation map
  - Tsunami vulnerability map
  - Tsunami risk map
  - Tsunami evacuation map
  - Technical report

Tsunami assessment process



- Calculate tsunami inundation of different tsunami sources
- Analyze the tsunami evacuation based on the calculation results

- Principle of shelter selection:
  - High altitude: places with high altitude
  - Accessibility: Road, bridge and other information
  - large capacity: schools, parks and other places



Contents

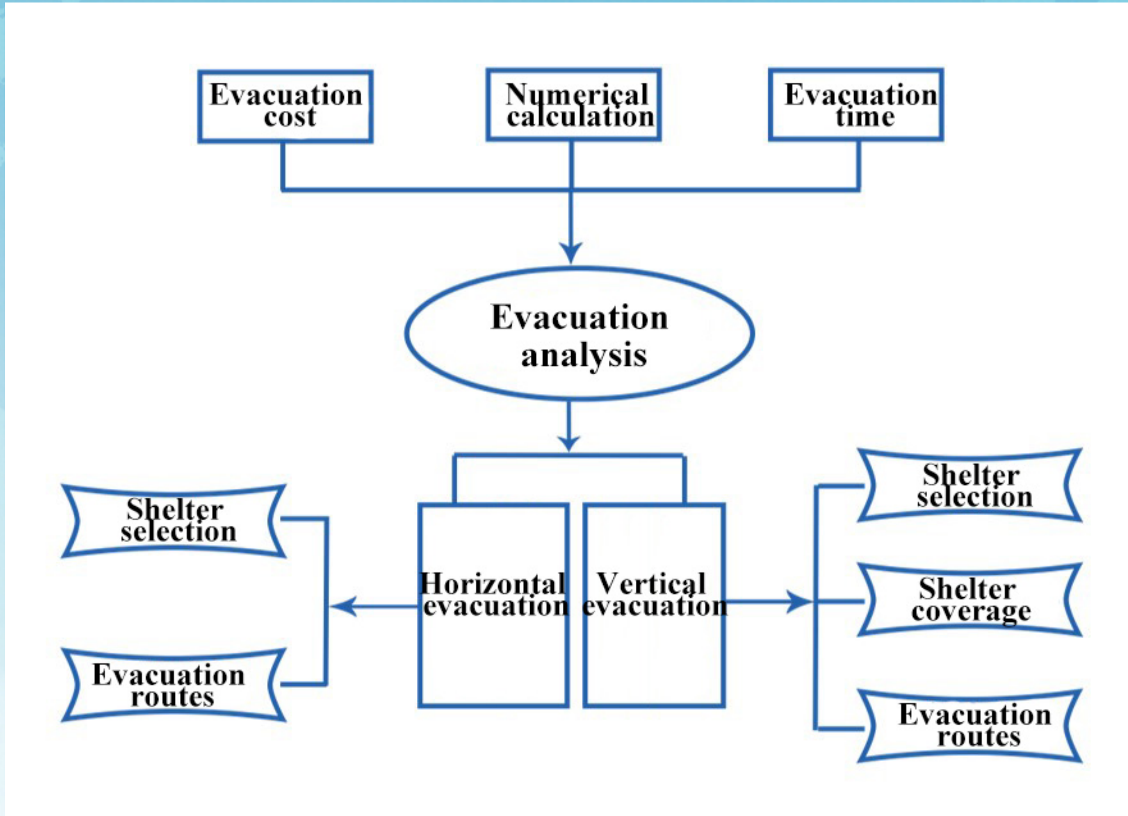
Tsunami evacuation

Macro Evacuation Model (**County level**)
- ✓ Static evacuation models of large areas
- ✓ Suitable for tsunami evacuation plans

Micro Evacuation model (**Community level**)
- ✓ Dynamic evacuation models of small areas
- ✓ Suitable for tsunami exercises

Horizontal evacuation

Vertical evacuation

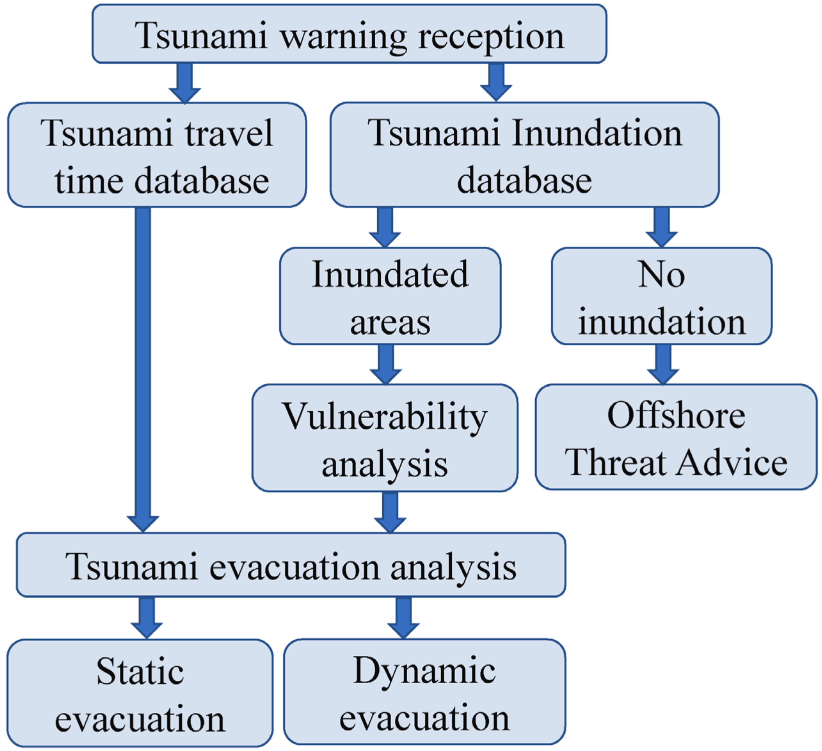


Hou J, Yuan Y, Wang P, et al. Development of a decision support system for tsunami evacuation: application to the Jiyang District of Sanya city in China[J]. Natural Hazards and Earth System Sciences, 2017, 17(3): 335-343.

Tsunami evacuation

- According to the analysis content of tsunami evacuation, Tsunami evacuation can be divided into dynamic evacuation and static evacuation

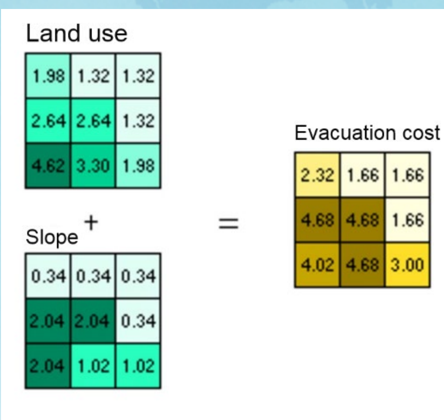
  - Tsunami numerical calculation and high-risk area identification
  - Static tsunami evacuation
  - Dynamic tsunami evacuation



The evacuation analysis results can be presented in the form of reports, pictures, or systems. When a tsunami occurs, emergency managers can apply the results of tsunami evacuation analysis in a certain area to make a quick evacuation decision.

Tsunami evacuation

Accessibility analysis is on the basis of a Cost Weighted Distance (CWD) approach



(González-Riancho *et al. 20*13)
(Post et al. 2009)
(Budiarjo, 2006)
(ArcGIS network analyst tutorial)

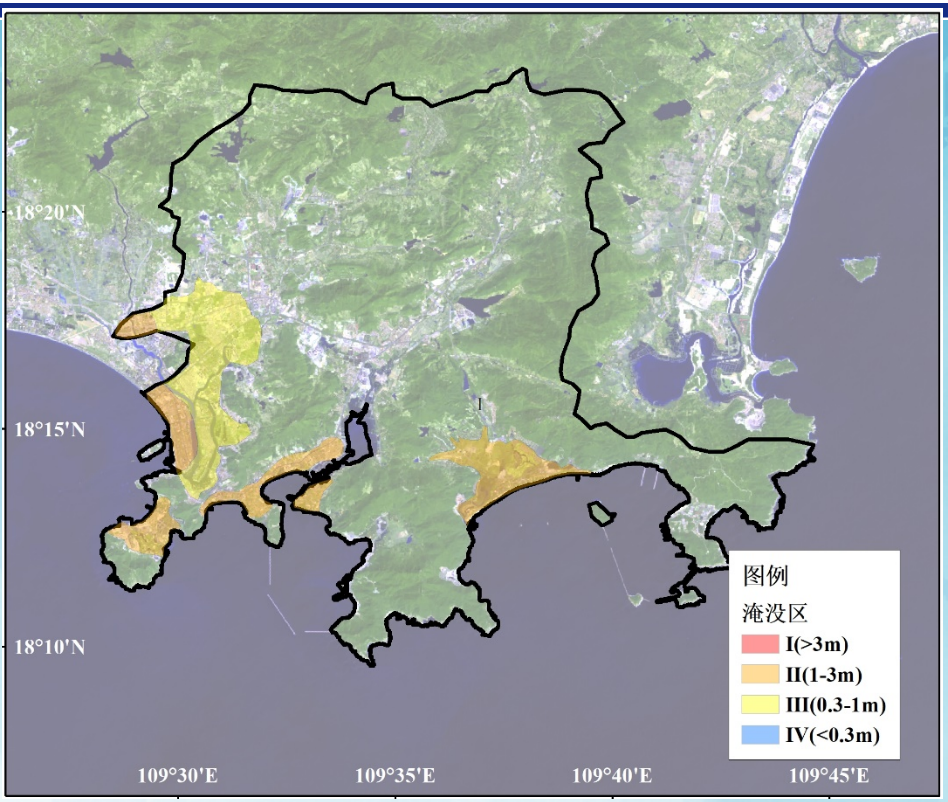
Makes a location-allocation network analysis layer and Network Dataset Analyst to determine suitable shelter location and routes.

Tsunami evacuation

- Tsunami hazard is analyzed firstly. The hazard analysis result can show tsunami impact area and identify the location of evacuation;
- The inundation of different tsunami scenarios are various;
- The effect of astronomical tide is considered in the calculation.

Magnitude	Fault length (km)	Fault width (km)	Strike(°)	Dip (°)	Slip (°)	Depth (km)
9.0	398.1	199.1	1	41	70	24.6
8.5	223.9	111.9	1	41	70	24.6
8.0	125.9	62.9	1	41	70	24.6
7.5	70.8	35.4	1	41	70	24.6
7.0	39.8	19.9	1	41	70	24.6

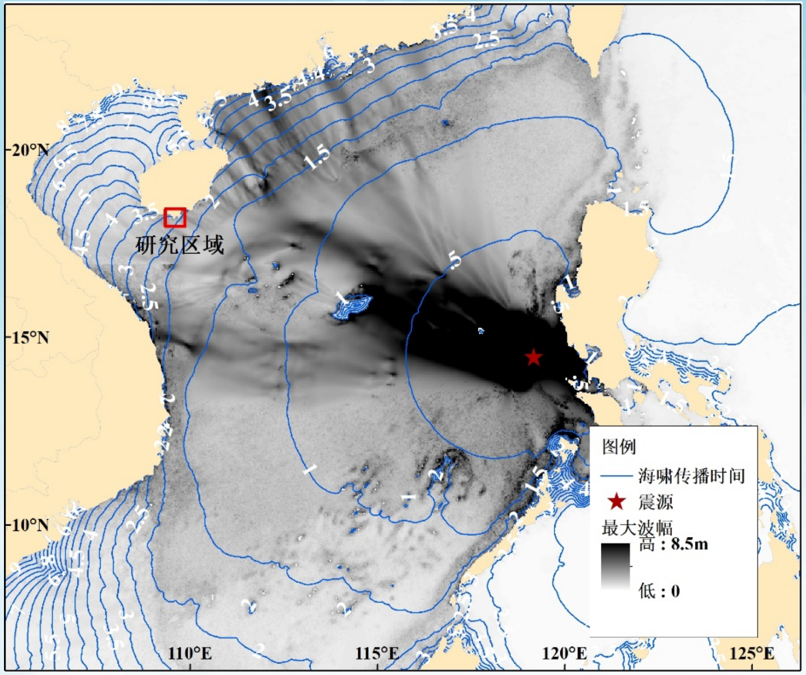
Hypothesized tsunami source parameters



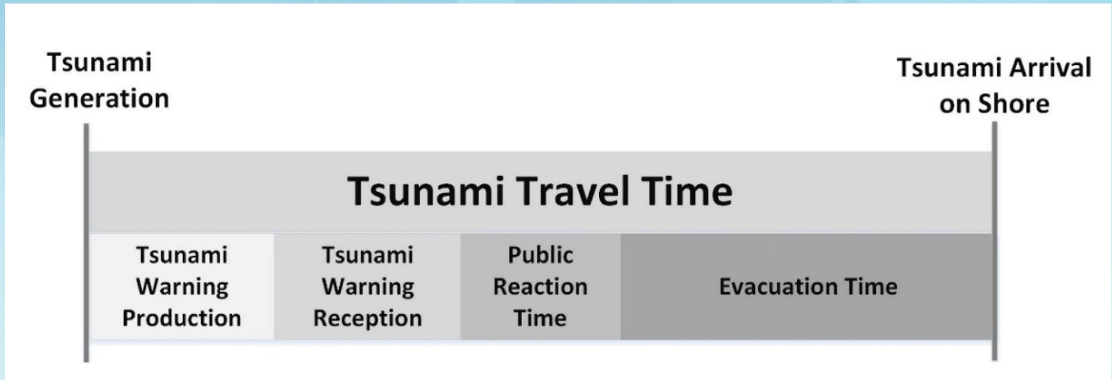
The Mw 8.5 earthquake tsunami caused the inundation area of 29 square kilometers, with a maximum depth of 1.8 meters. The inundation area covers hospitals, schools, shopping malls and hotels. Several communities, such as Yalong Bay, Hexi and Yulin, were inundated.

Tsunami evacuation

- The evacuation time determines the different evacuation methods. Under the premise of sufficient evacuation time, people can be evacuated horizontally to a safe area outside the tsunami-inundated area. If there is not enough evacuation time, people can evacuate to vertical shelter near their residences.



Tsunami travel time and max amplitude

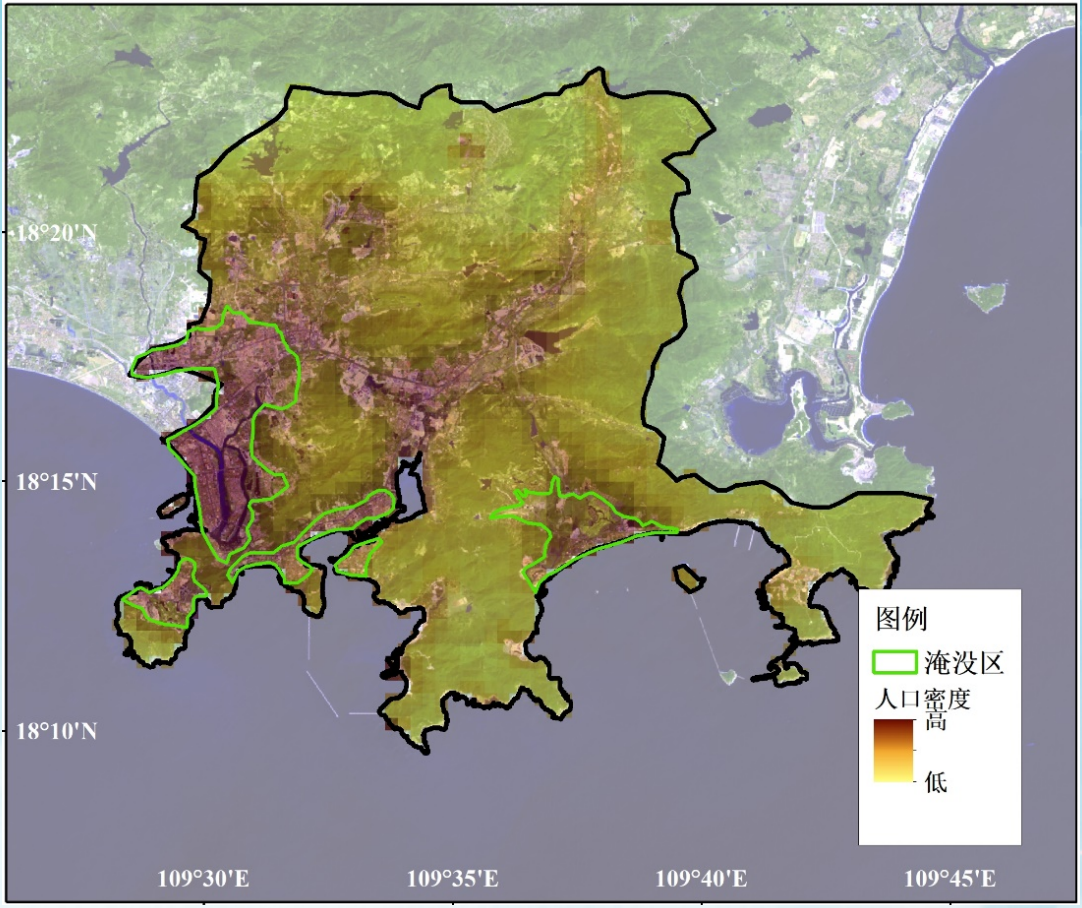


Based on past experience of issuing tsunami warning, the time of tsunami warning production and public reaction time were determined. As a result, the affected population needs to be evacuated within 1.9 hours. From the evacuation time, people can use horizontal evacuation and vertical evacuation to evacuate.

Tsunami evacuation

❑ Population analysis

❑By analyzing the population distribution in the inundation area, the areas that need to be evacuated are determined



It can be seen from the figure that some densely populated areas of Jiyang District are located in tsunami-inundated areas. There are 114086 people in the inundation areas, 52 percent of whom are men and 48 percent are women. The elderly (65 years and older) account for 15 percent of the total, the middle-aged (18-65 years) for 65 percent and the young (under 18 years of age) for 20 percent.

Tsunami evacuation

Horizontal evacuation

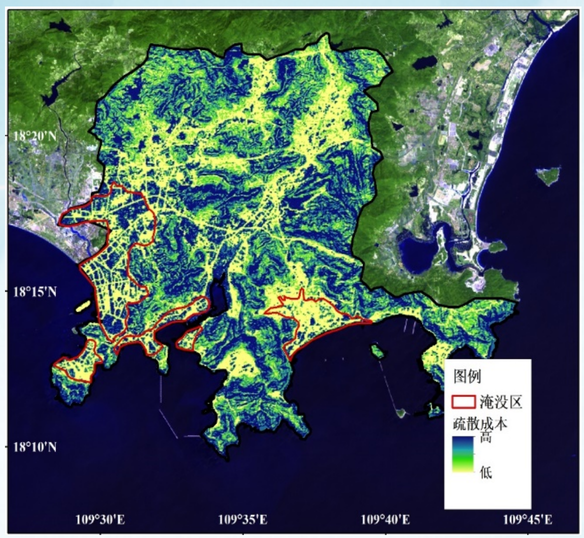
- The Horizontal evacuation method is used to optimize the location of shelters and evacuation routes
- The horizontal evacuation is analyzed according to evacuation cost.

- Evacuation cost
  (1) Slope
  (2) Landuse

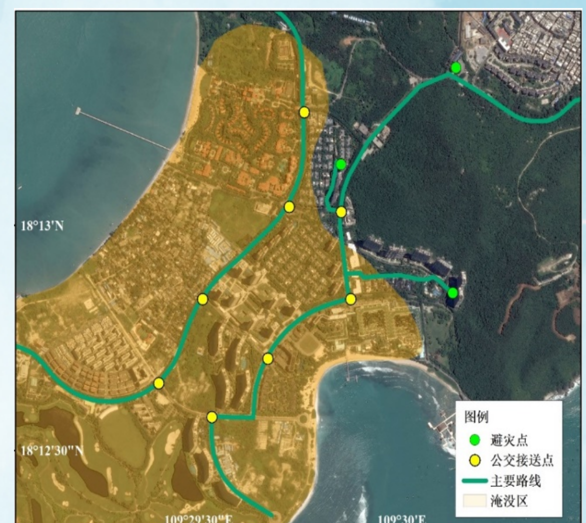
Land use	Time (s/m)
Building	16.67
Forest	2.11
Open area	0.88
Agricultural land	2.08
Rivers/ponds	16.67
Road	0.83

	Horizontal evacuation	Vertical evacuation
Tsunami travel time	Long	Short
Location	Close to high altitude	Low-lying flat ground
Tsunami runups	Slowly climbs	Fast climbs
Conditions	Traffic conditions	Strong high-rise buildings

Slope (%)	Weight of evacuation time
0–3	1.0
3–6	1.2
6–9	1.4
9–12	1.8
12–15	2.2
15–18	2.5
18–21	2.9
21–24	3.3
24–27	4.0
27–30	5.0
30–33	6.7
33–36	7.1
36–39	7.7
39–42	8.3
42–45	9.1
>45	10.0



Evacuation cost



Routes of horizontal evacuation

Tsunami evacuation

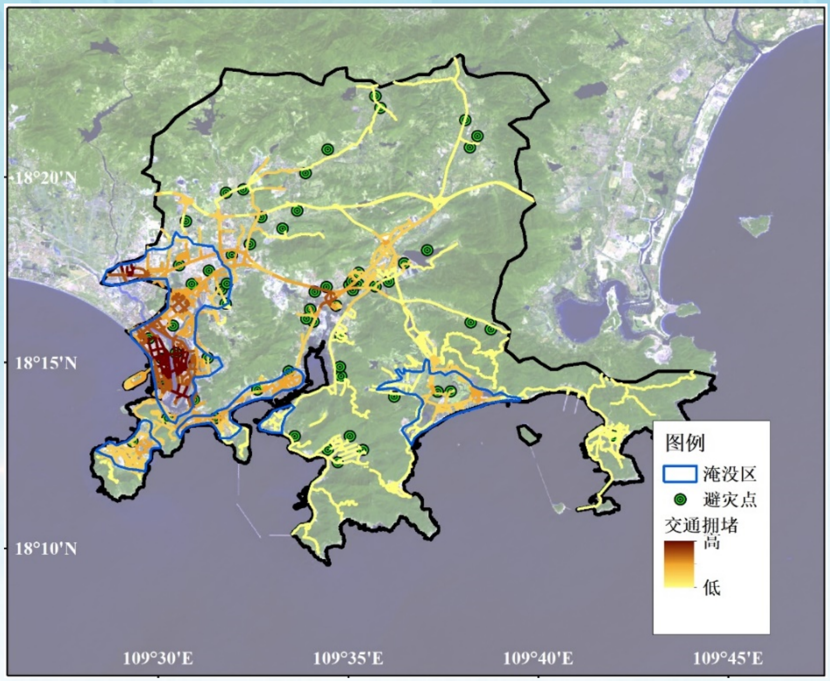
Why vertical evacuation:

□Evacuation operations are affected and restricted by a variety of factors.

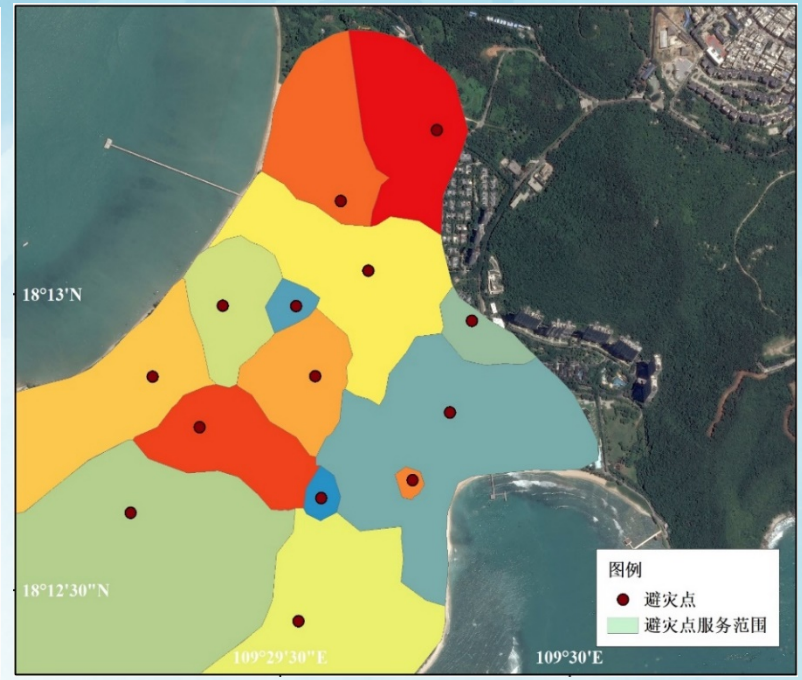
□Long-distance evacuations of large groups of people can cause road congestion, so people could adopt vertical evacuation.

Vertical evacuation

❑ Analysis content:
(1) Which areas need vertical evacuation;
(2) Which shelters can be used for evacuation.



Map of congestion prone roads



Shelter service area for vertical evacuation

Hou J M, Li X J, Yuan Y, et al. Scenario-based tsunami evacuation analysis: A case study of Haimen Town, Taizhou, China[J]. Journal of Earthquake and Tsunami, 2017, 11(1), 1750008.

Tsunami evacuation

What's in the dynamic evacuation:

(1) Configuration of vertical and horizontal evacuation;

(2) Roads that are prone to congestion;

(3) Ratio of the car during the evacuation;

(4) Impact of walking speed on evacuation.

Dynamic evacuation

Area of dynamic evacuation analysis

Bottleneck found in dynamic evacuation analysis

- The traffic bottleneck was found in the simulation.
- With the increase of car use, the mortality rate increases.
- The number of shelters is effective in reducing mortality

THANK YOU !

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