Compound coastal inundation modeling on Typhoon Jebi (2018) induced wave overtopping and sewer reverse flow at Kansai Airport, Japan

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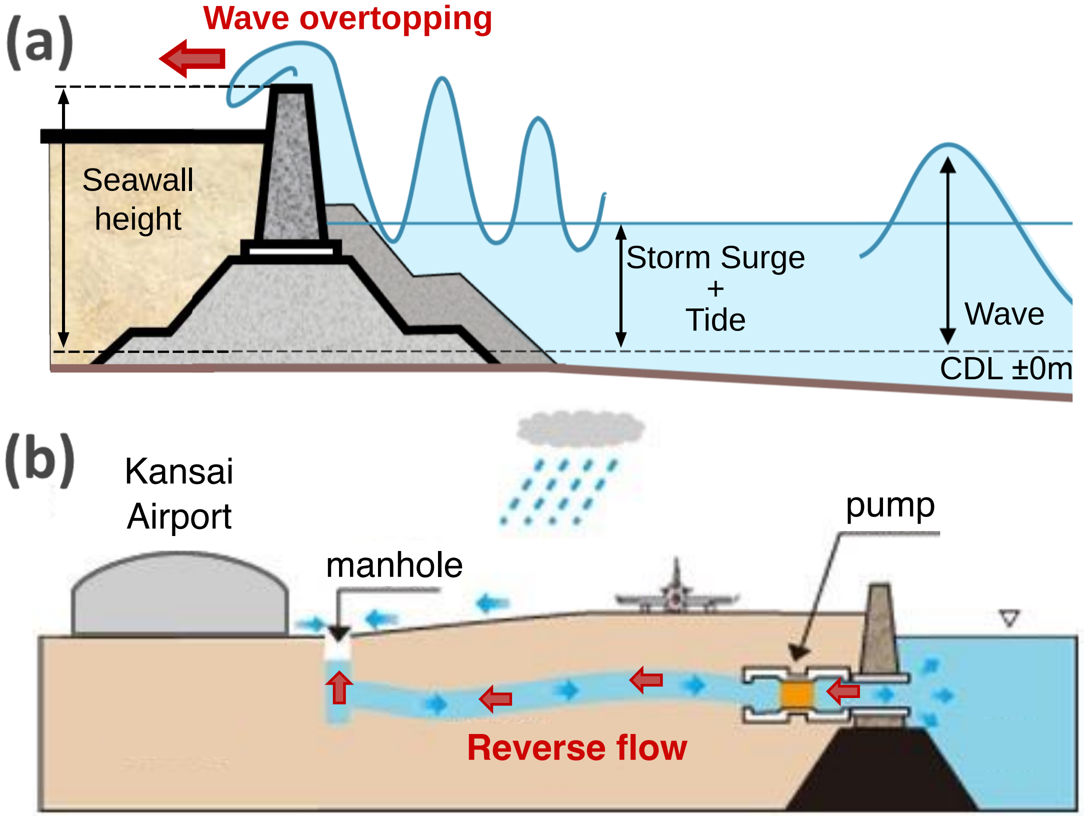
Compound flooding at Kansai Airport by wave overtopping and reverse flow

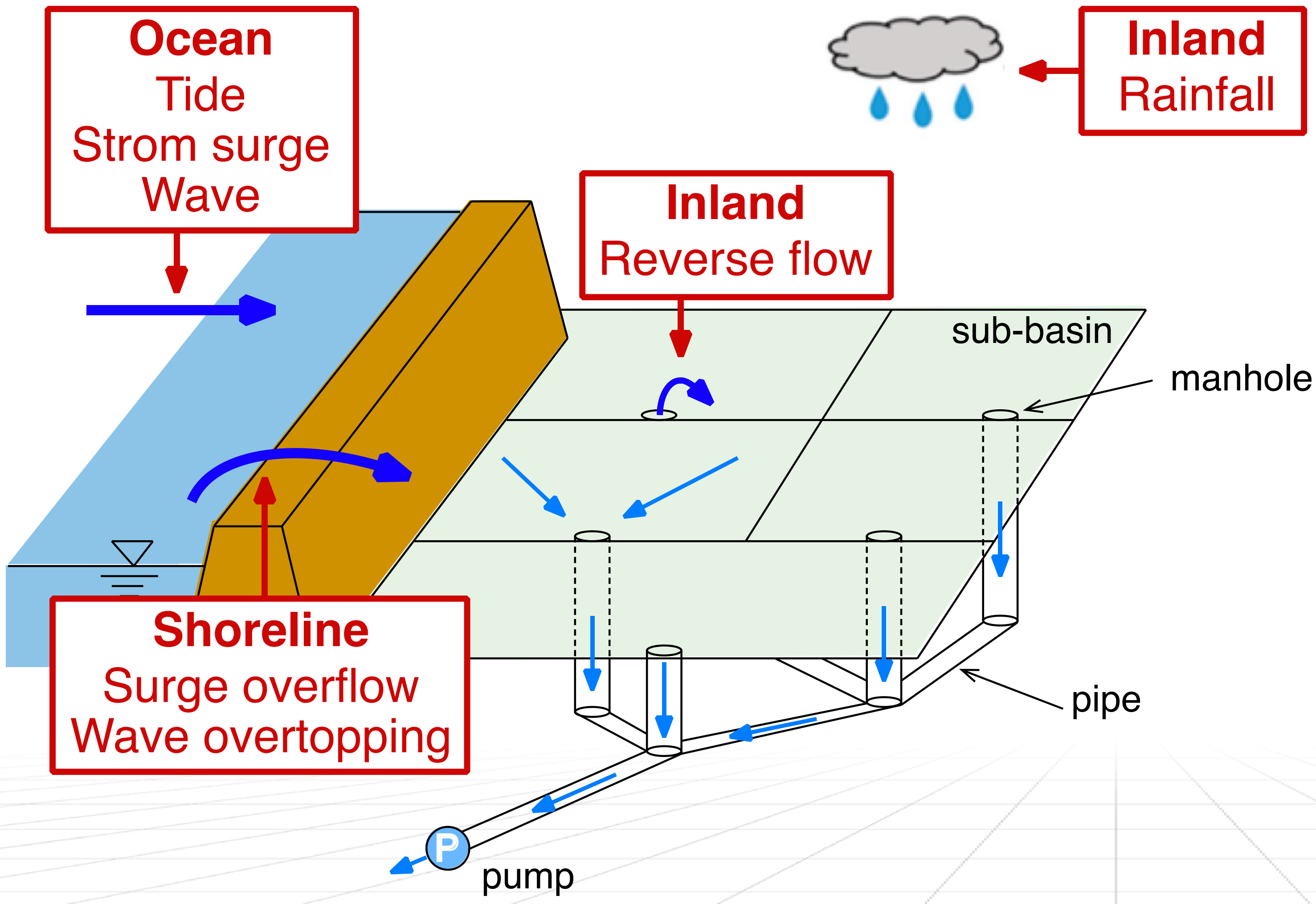
< Heavy flooding at Kansai Airport, Japan (2018) >



< Typhoon Jebi-induced flood cause >

- Typhoon Jebi-induced heavy flood occurred at Kansai Airport in 2018.
- The cause of flood is assumed to be **wave overtopping**(a) and **sewer reverse flow**(b).

Flood characteristics in coastal urban areas



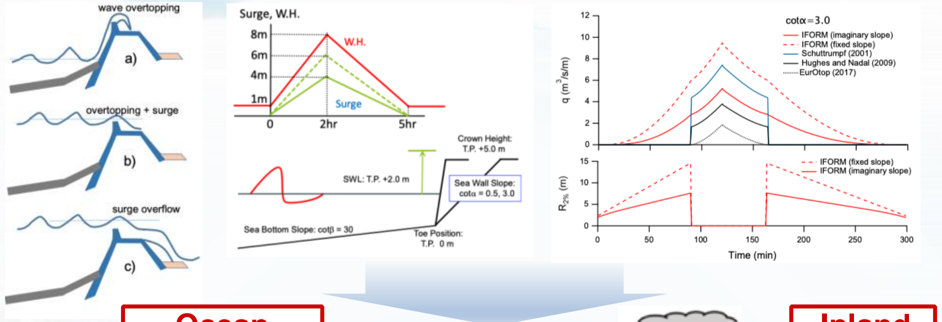
< Concept of compound flood in coastal areas >

Flood in the coastal urban area due to **multiple physical processes**.

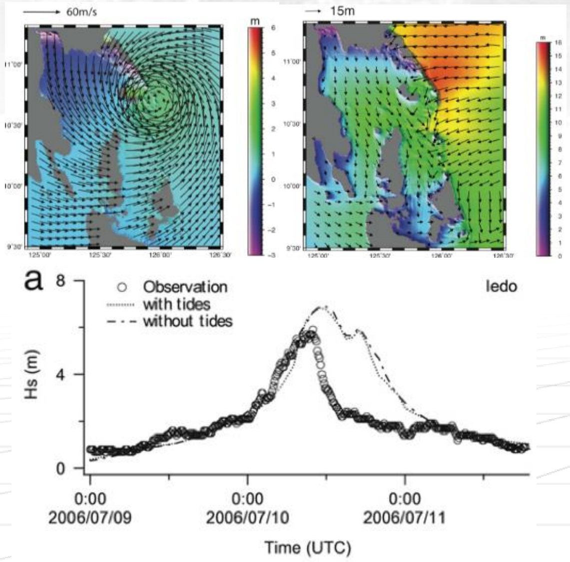
- **In ocean**
  - Tide
  - Storm surge
  - Wave
- **Along shoreline**
  - Surge overflow
  - Wave overtopping/runup
- **In inland**
  - Rainfall-runoff
  - Sewer reverse flow

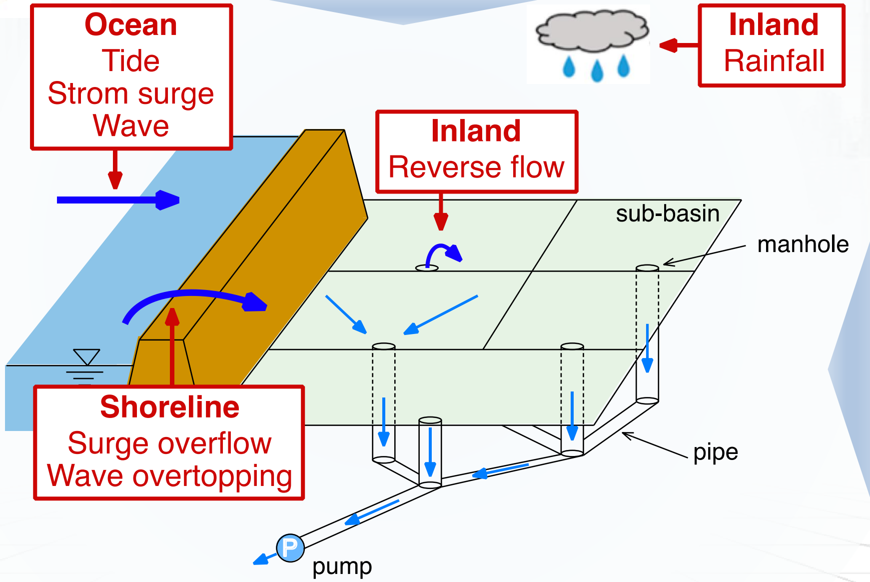
Development of fully coupled flood simulation model for compound flood

Shoreline
Surge overflow and wave overtopping/runup calculation

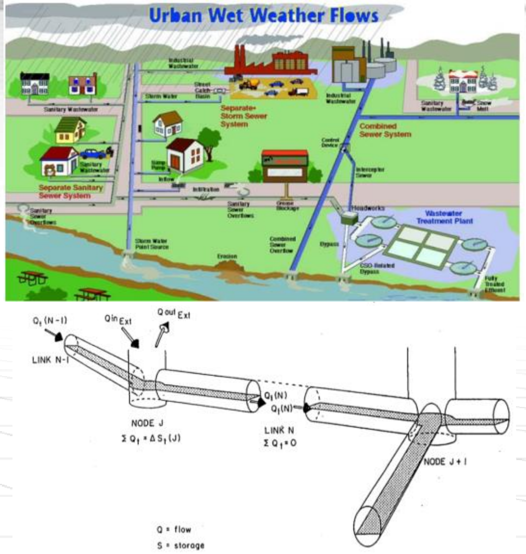


Ocean
Tide-surge and wave calculation



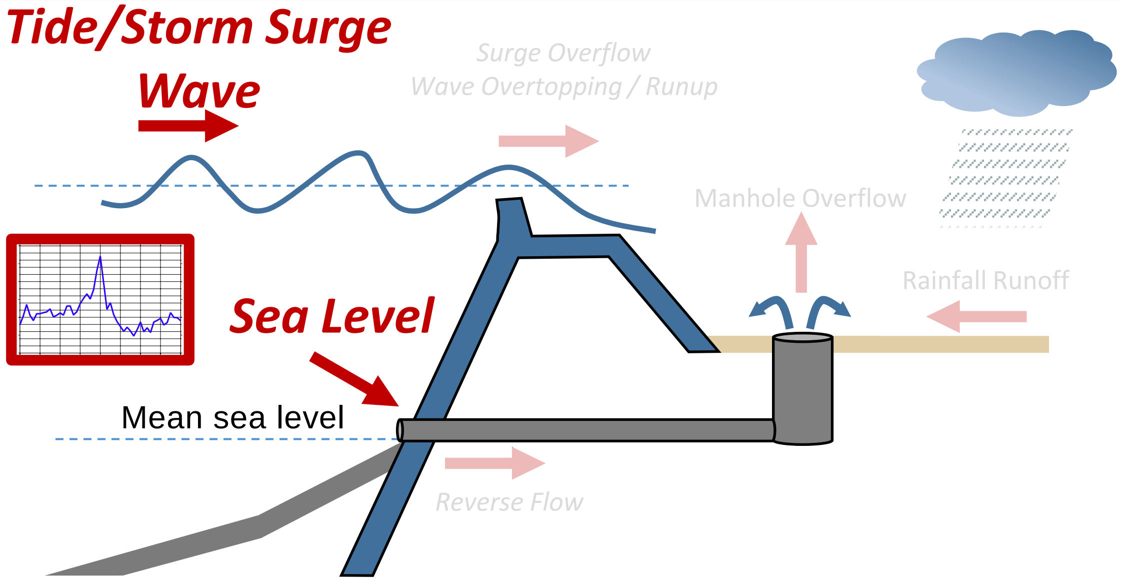


Inland
Rainfall-runoff and sewer reverse flow calculation



Compound flood risk assessment considering multiple factors

Fully coupled flood simulation model for the compound flood: SuWAT



The **tide** is given by the water surface level on open boundaries.

$$\eta = \eta_{tide} + \eta_{storm\ surge} = \eta_{tide} + P_d / g\rho_w$$

$\{ P_d$: pressure depression by typhoon $\}$

The **wave** is calculated by the wave action balance equation.

(*Booij et al.*, 1999)

$$\frac{\partial}{\partial t}N + \frac{\partial}{\partial x}C_x N + \frac{\partial}{\partial y}C_y N + \frac{\partial}{\partial \sigma}C_\sigma N + \frac{\partial}{\partial \theta}C_\theta N = \frac{S}{\sigma}$$

The **storm surge** is calculated by the depth integrated nonlinear shallow water equations. (*Kim et al.*, 2008)

1) equation of conservation of mass (2D)

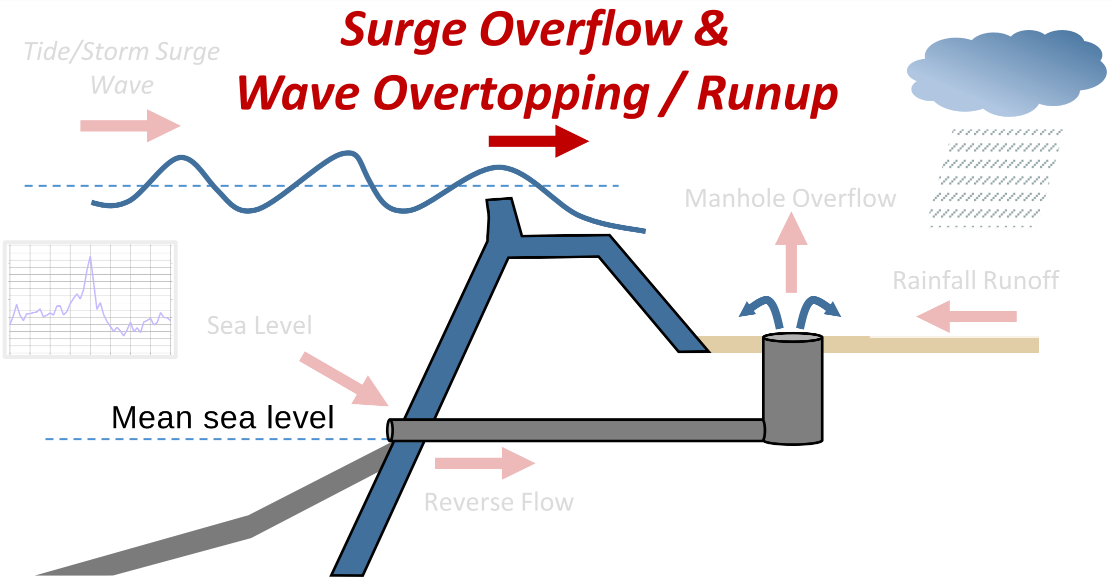
$$\frac{\partial \eta}{\partial t} + \frac{\partial M}{\partial x} + \frac{\partial N}{\partial y} = 0$$

2) equation of conservation of momentum (2D)

$$\frac{\partial M}{\partial t} + \frac{\partial}{\partial x}\left(\frac{M^2}{d}\right) + \frac{\partial}{\partial y}\left(\frac{MN}{d}\right) + gd\frac{\partial \eta}{\partial x} = fN - \frac{1}{\rho_w}d\frac{\partial P}{\partial x} + \frac{1}{\rho_w}(\tau_s^x - \tau_b^x + F_x) + A_h\left(\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2}\right)$$

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}\left(\frac{NM}{d}\right) + \frac{\partial}{\partial y}\left(\frac{N^2}{d}\right) + gd\frac{\partial \eta}{\partial y} = -fM - \frac{1}{\rho_w}d\frac{\partial P}{\partial y} + \frac{1}{\rho_w}(\tau_s^y - \tau_b^y + F_y) + A_h\left(\frac{\partial^2 N}{\partial x^2} + \frac{\partial^2 N}{\partial y^2}\right)$$

Fully coupled flood simulation model for the compound flood: SuWAT-IFORM



The **surge overflow** is calculated by the weir formula.

$$q_{overflow} = 0.54 \cdot \sqrt{g \cdot |-d_c^3|}$$

g : gravity acceleration
d_c: overflow depth at the crest

The volume of **wave overtopping** and **runup** is calculated by the Formula of wave overtopping and runup (IFORM).

(*Yuhi et al.*, 2020, 2022)

1) Wave overtopping formula

$$q_{overtopping} = C\left[\Gamma\left(\frac{R_{max}}{H_0'}\right)^{\frac{3}{2}}\left\{1 - \frac{R_c}{H_0'}\Big/\left(\frac{R_{max}}{H_0'}\right)^{\frac{3}{2}}\right\}^{\Omega}\right]$$

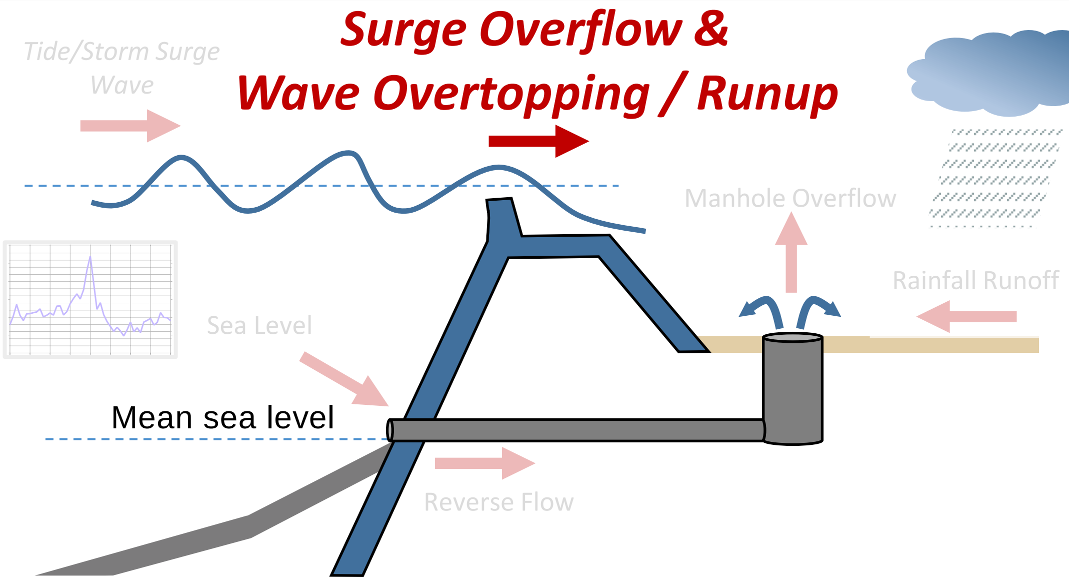
$$R_{max} = 1.54\, R_{2\%}$$

2) Wave runup formula

$$R_{2\%} = H_0\left[2.99 - 2.73\exp\left(-0.57\tan\beta \,/\sqrt{H_o/L_o}\right)\right]$$

R_{max} : maximum runup
$R_{2\%}$: runup exceeded by 2% of the incident waves
H_o : **offshore** significant wave height
L_o : **offshore** wavelenght

Fully coupled flood simulation model for the compound flood: SuWAT-IFORM



$$q_t = q_s + \gamma_t q_w$$

$$\gamma_t = 1 \quad \left(for \frac{R_c}{H_{m0}} \leq 0 \right)$$

$$\gamma_t = 1.0 - R_c/H_o \ (for\ 0 < R_c/H_{m0} \leq 1.0)$$

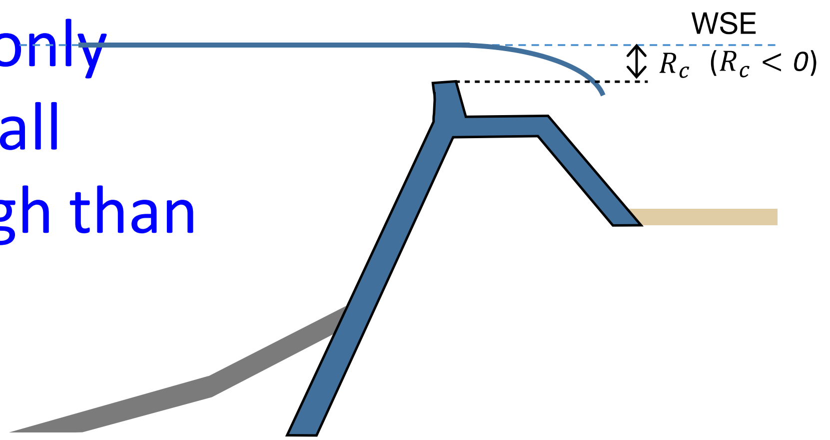
$$\gamma_t = 0 \quad \left(for\ 1.0 < \frac{R_c}{H_{m0}} \right)$$

R_c = seawall freeboard

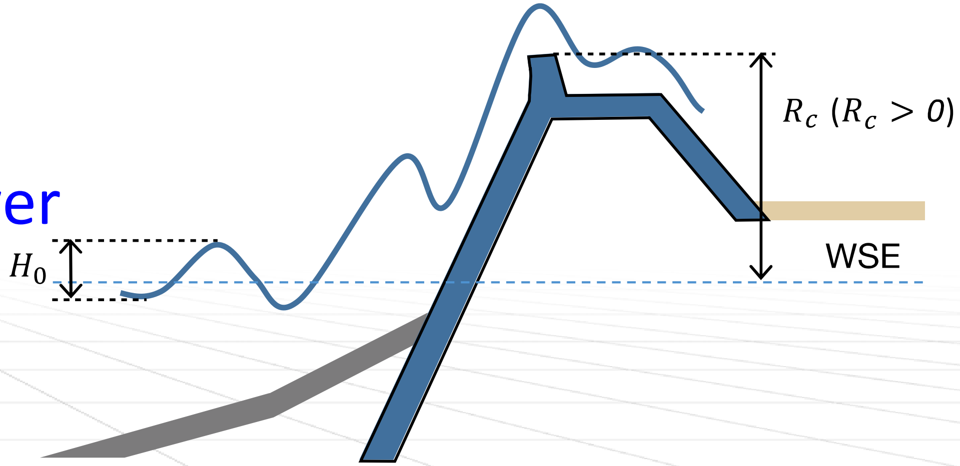
H_{m0} = wave height in front of the seawall

- A) Surge Overflow only
  - Typhoon landfall
  - SSL high enough than top
  - No waves
- B) Wave Overtopping
  - Typhoon is located far away
  - Swell etc.
  - SSL still lower

Transient processes

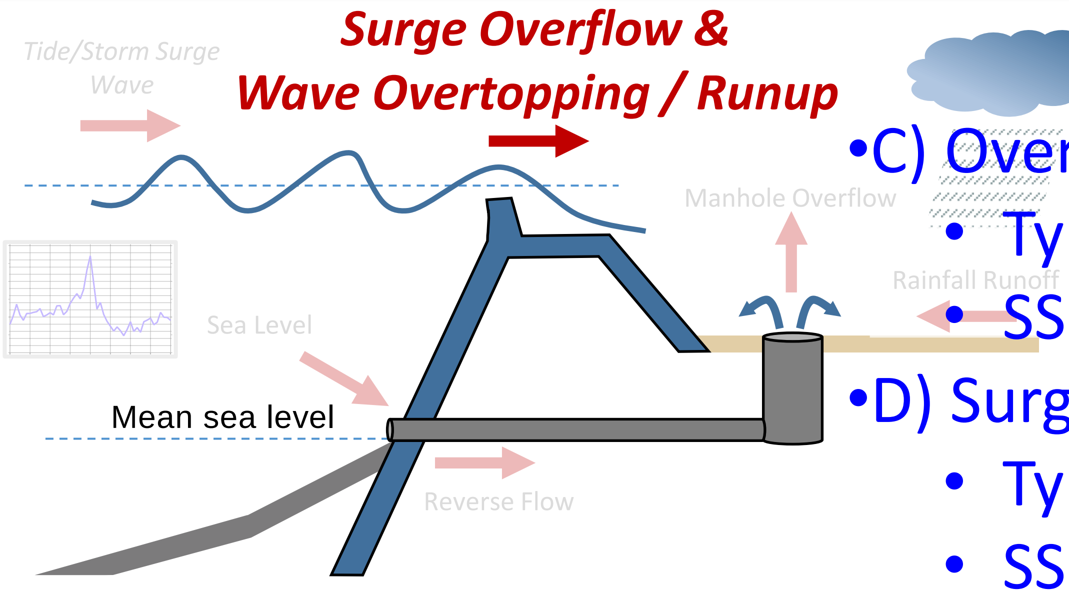


(a) Steady surge overflow without waves

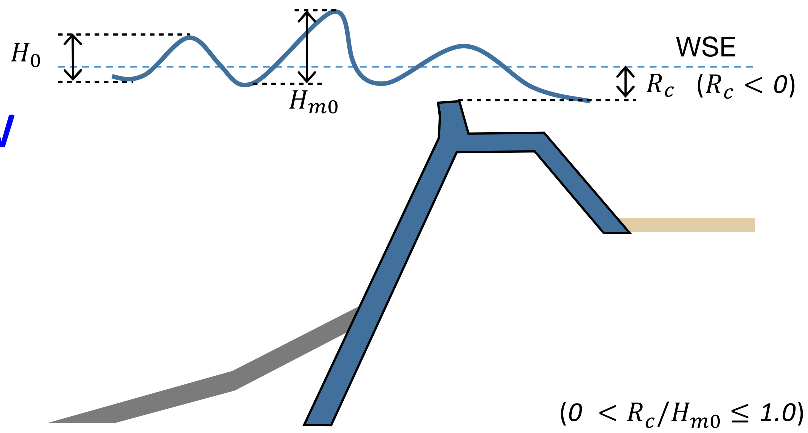


(b) Wave overtopping/runup

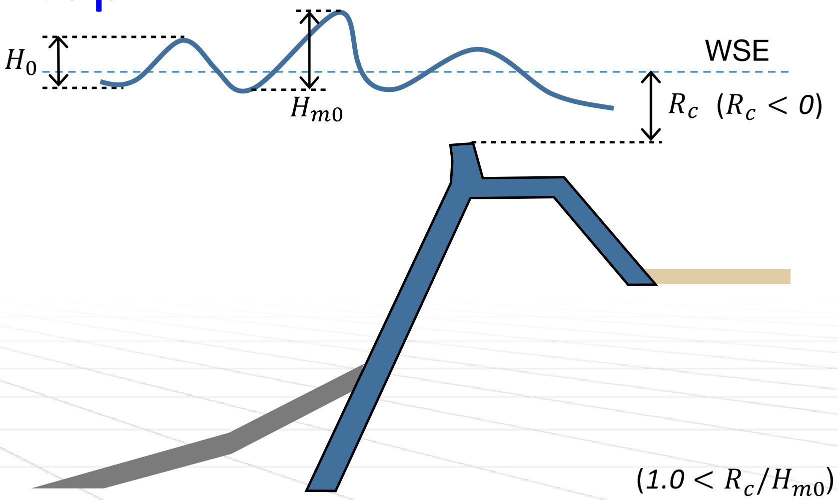
Fully coupled flood simulation model for the compound flood: SuWAT-IFORM



- C) Overtopping + Overflow
  - Typhoon is closer
  - SSL near top
- D) Surge Overflow
  - Typhoon landfall
  - SSL higher enough than top
  - Overtopping ignorable



(c) Combined surge overflow and wave overtopping



(d) Surge overflow with waves

$$q_t = q_s + \gamma_t q_w$$

$$\gamma_t = 1 \left(for \frac{R_c}{H_{m0}} \leq 0 \right)$$

$$\gamma_t = 1.0 - R_c/H_o \ (for\ 0 < R_c/H_{m0} \leq 1.0)$$

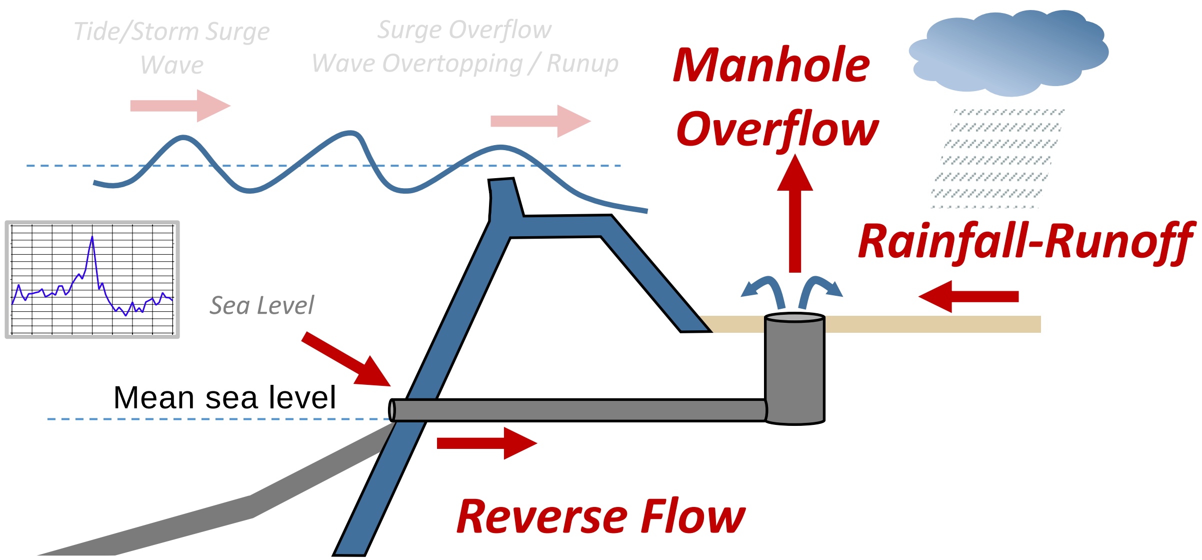
$$\gamma_t = 0 \left(for\ 1.0 < \frac{R_c}{H_{m0}} \right)$$

R_c = seawall freeboard

H_{m0} = wave height in front of the seawall

Transient processes

Fully coupled flood simulation model for the compound flood: SuWAT-IFORM-SWMM (**Storm Water Management Model**)



The **reverse flow** is calculated by the shallow water equation.

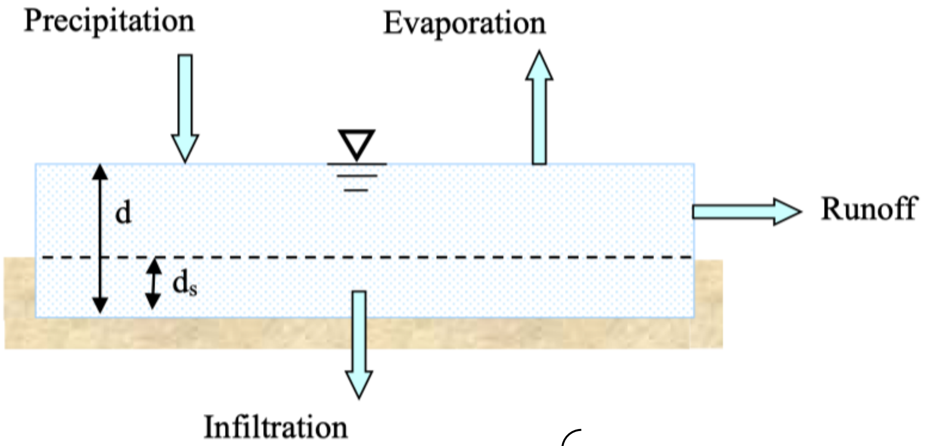
1) Conservation of mass (1D)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

2) Conservation of momentum (1D)

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}(Q^2 / A) + gA\frac{\partial H}{\partial x} + gAS_f = 0$$

The **rainfall runoff** is calculated by the non-linear reservoir equation.



1) Surface depth per unit of time

$$\frac{\partial d}{\partial t} = i - e - f - q$$

- i : precipitation rate
- e : surface evaporation rate
- f : infiltration rate
- q : runoff rate

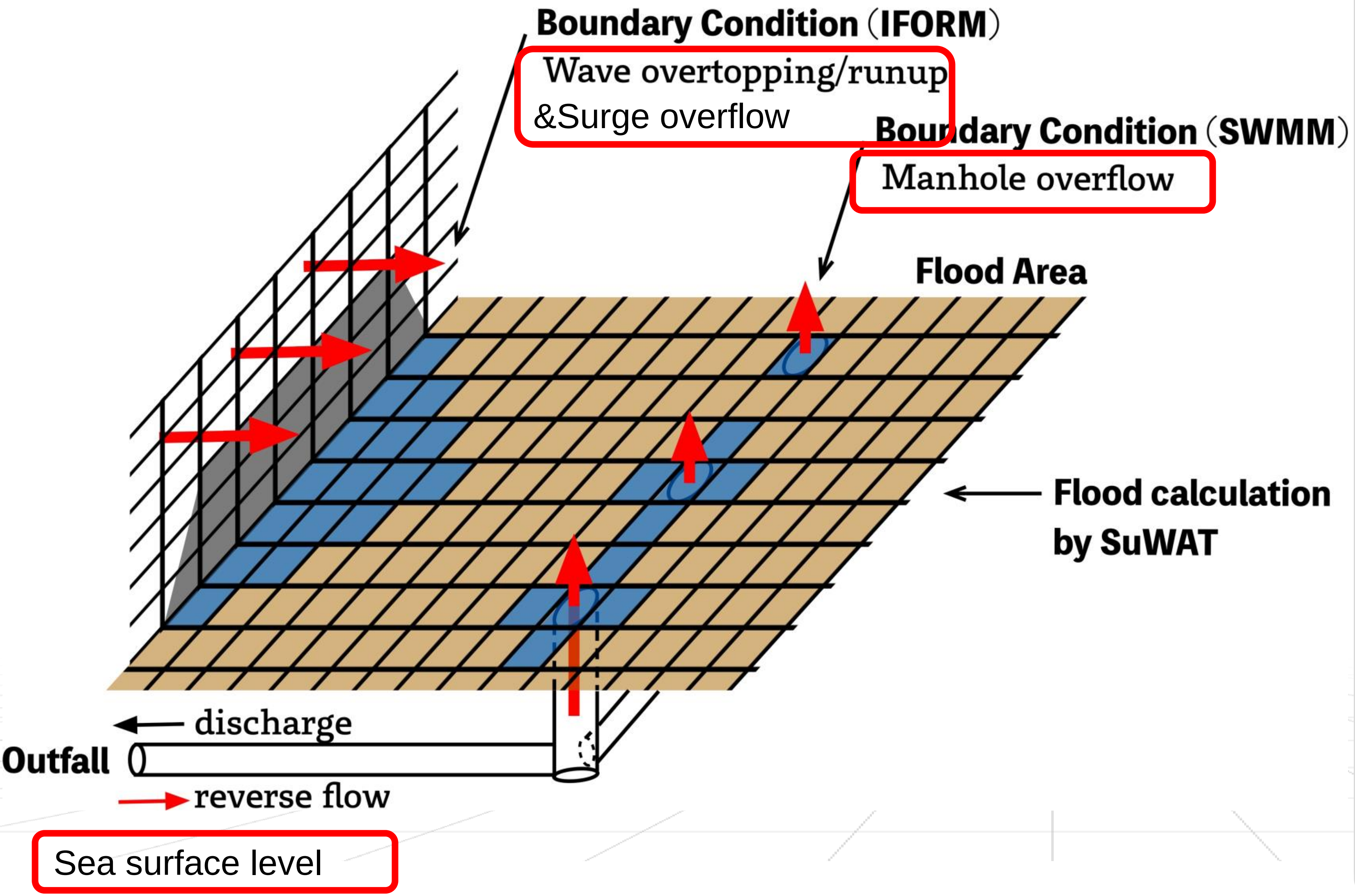
2) the volume of runoff by Manning equation

$$q_{runoff} = \frac{1.49}{n} S^{1/2} R_x^{2/3} A_x$$

- S : average slope of the surface
- R_x : hydraulic radius
- A_x : runoff area (= $W(d - d_s)$)
- W : width of surface
- d : surface depth
- d_s : storage depth

Modeling Pipe lines in the sewer system

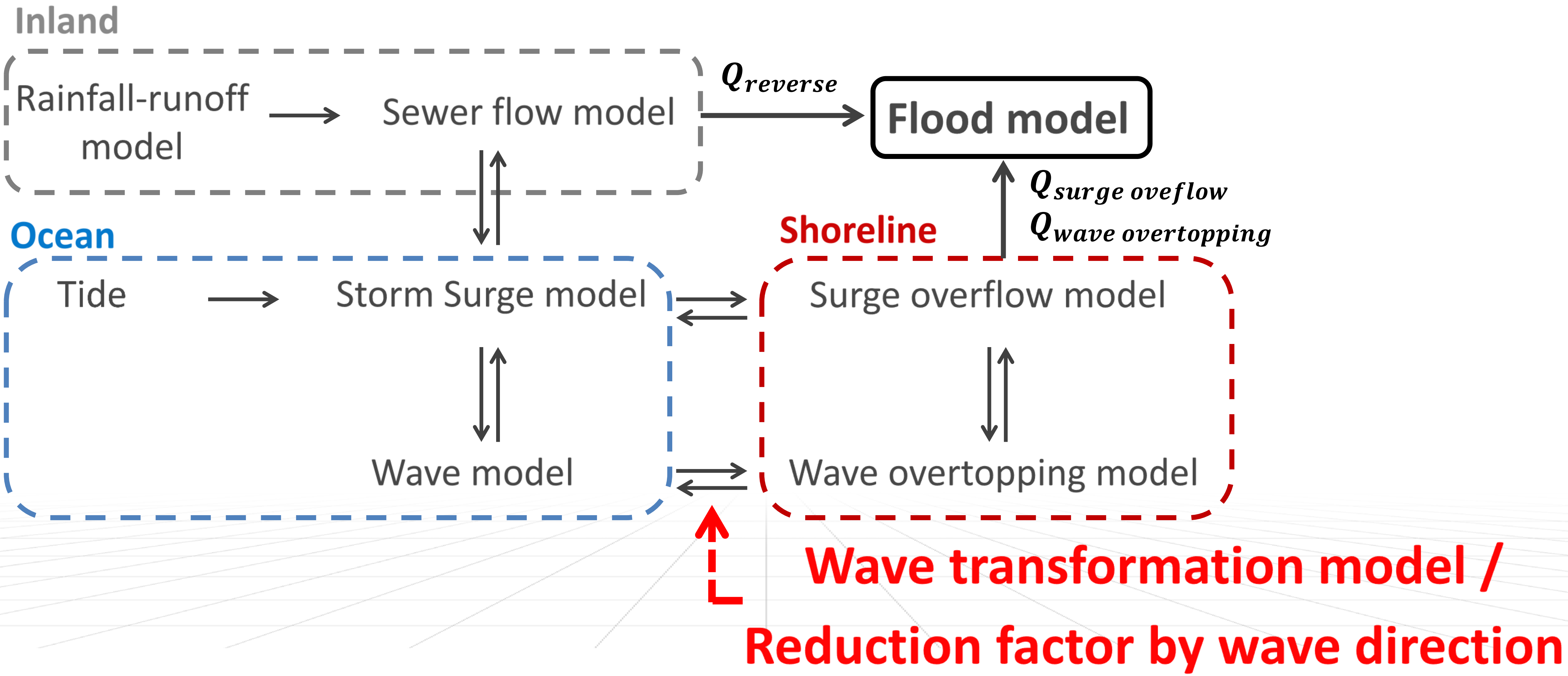
Boundary conditions for flooding



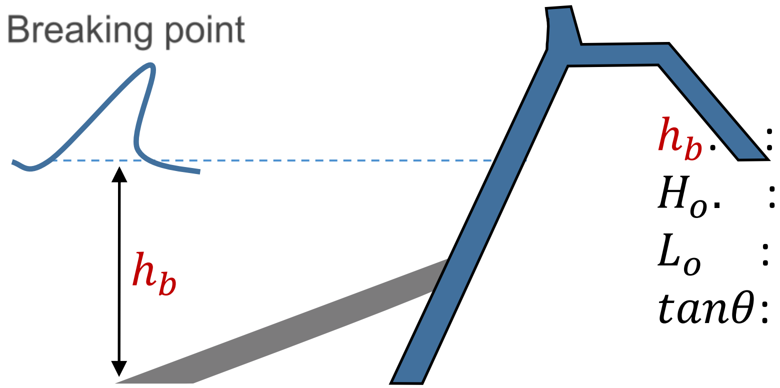
- **SuWAT**
  - Surge
  - Wave
  - 0.4 sec for surge
  - 600 sec for wave
- **IFORM -> flooding area (SuWAT)**
  - Surge overflow
  - Wave overtopping
  - One way
  - 0.4 sec for IFORM
- **SWMM -> flooding area (SuWAT)**
  - Overflow from manhole
  - Runoff
  - One way
  - 10 sec in SWMM

Framework of fully coupled flood simulation model for compound flood

$$Q_{total} = Q_{surge\ overflow} + Q_{wave\ overtopping} + Q_{reverse}$$



Wave transformation model for estimating breaking point



h_b : **breaker depth**
H_o : **offshore** wave height
L_o : **offshore** wavelength
$tan\theta$: bottome slope from shoreline to breaking point ($1/100 < tan\theta < 1/10$)

Breaker depth formula (*Mase et.al.,* 2016)

$$\frac{h_b}{H_o} = a_0 + a_1 \exp\left[-\left(\frac{\ln\{(H_o/L_o)/a_2\}}{a_3}\right)^2\right]$$

$$a_0 = 30.2470 - 27.3440 \exp[-\{\frac{\ln(22.9130tan\theta)}{5.4509}\}^2]$$

$$a_1 = -9.9467 + 8.9213 \exp[-\{\frac{\ln(29.3880tan\theta)}{3.1264}\}^2]$$

$$a_2 = 0.0302 - 0.0023 \exp[-\{\frac{\ln(25.9160tan\theta)}{1.7065}\}^2]$$

$$a_3 = 6.1291 - 3.5001 \exp[-\{\frac{\ln(36.3660tan\theta)}{1.3457}\}^2]$$

- **Breaking point** changes every moment due to waves and sea level variations.
- Offshore location for wave properties can not be fixed during simulation.
- At every time step, H_o on a grid is used to calculate h_b
  - If h_b > the water depth on a grid, move toward the offshore grid. Then, repeat it.
  - If h_b < the water depth on a grid, the water depth = h_b

Reduction of overtopping by incident wave directions

Influence factor for wave runup

$$\gamma_{runup} = 1 - 0.0022|\beta| \qquad (\text{for } 0° \le |\beta| \le 80°)$$

$$\gamma_{runup} = 0.824 \qquad (\text{for } |\beta| \ge 80°)$$

Wave runup formula

$$R'_{2\%} = H_o[2.99 - 2.73\exp(-0.57\tan\beta/\sqrt{H_o/L_o})] \times \gamma_{runup}$$

Wave overtopping formula

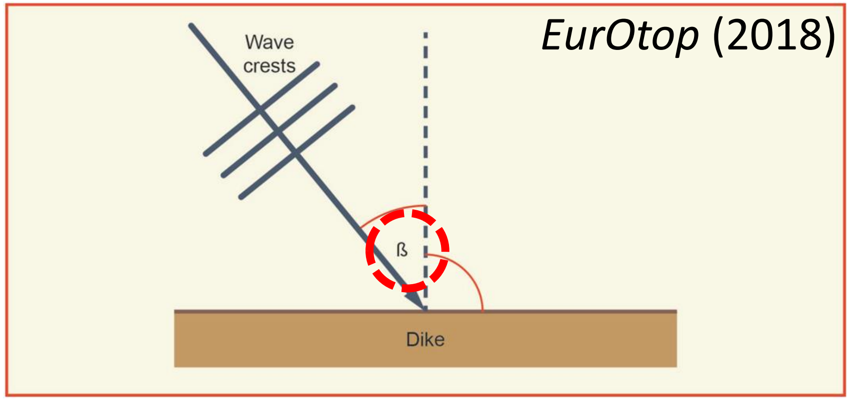
$$R'_{max} = 1.54\,H_0\,[2.99 - 2.73\exp(-0.57\tan\beta/\sqrt{H_o/L_o})] \times \gamma_{runup}$$

$$\rightarrow R'_{max} = 1.54\,R'_{2\%} = 1.54\,\gamma_{runup}\,R_{2\%}$$

$$Q_{over} = C\left[\Gamma\left(\frac{R'_{max}}{H_0}\right)^{\frac{3}{2}}\left\{1-\left(\frac{R_c}{H_0}\right)/\left(\frac{R'_{max}}{H_0}\right)\right\}^{\Omega}\right] \qquad (\text{for } 0 \le R_c < R_{max})$$

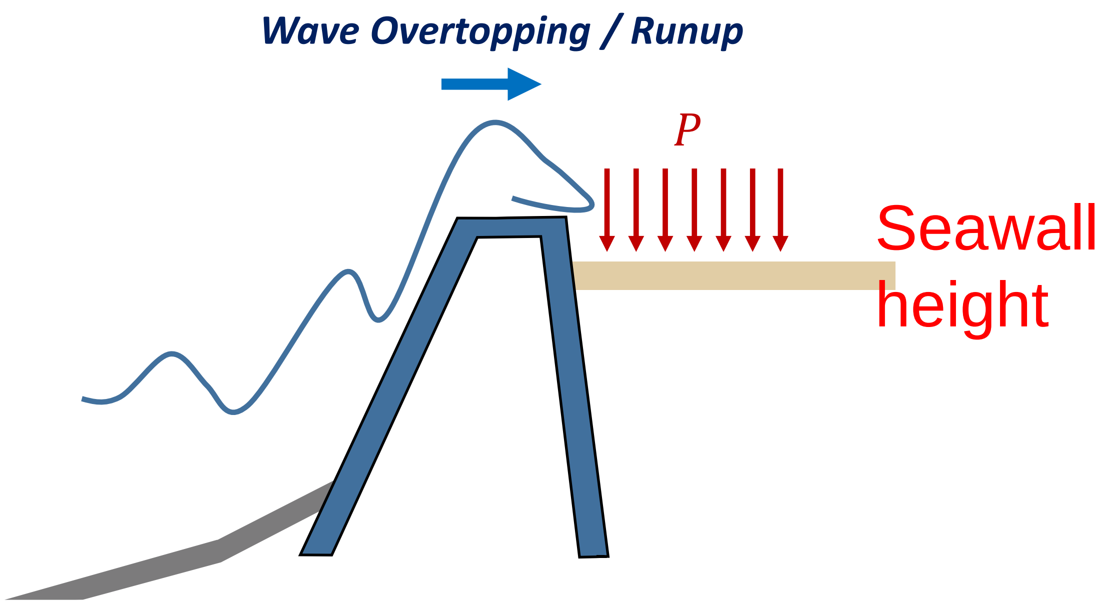
$$Q_{over} = 0 \qquad (\text{for } R_{max} \le R_c)$$

* Definition of wave attack angle



- H_o : **offshore** wave height
- L_o : **offshore** wavelength
- $tan\beta$: front slope of seawall
- $R'_{2\%}$: runup exceeded by 2% of the incident waves **with applying reduction factor**
- R'_{max} : maximum runup **with applying reduction factor**
- R_c : freeboard height
- Q_{over} : overtopping discharge

Seawall collapse due to wave-induced pressure



Seawall collapse is caused by damage to seawall **due to wave-induced pressure.**

< Collapse section at Kansai Airport >

Allowable pressure and overtopping discharge

$$P_a = 10{,}828\ Q_{over\_a}$$

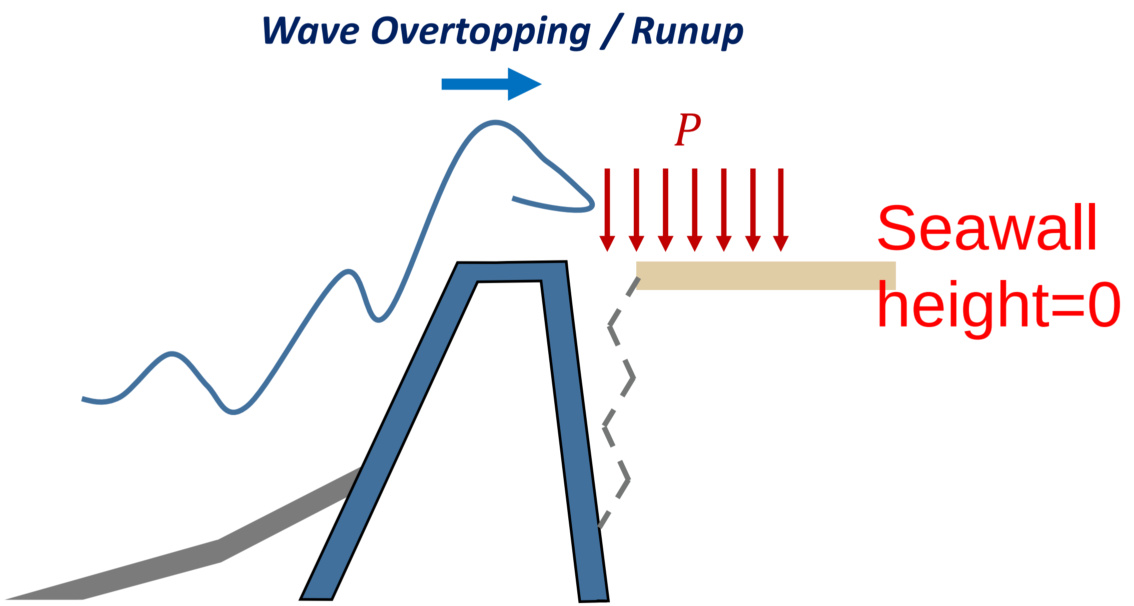
where,

P_a : allowable pressure

Q_{over_a} : allowable overtopping discharge $(m^3/s/m)$

Covering	Q_{over_a}
Concrete three-side wrapping	0.05
Top surface paving · No backfill construction	0.02
No top surface paving	less than 0.005

Seawall collapse due to wave-induced pressure



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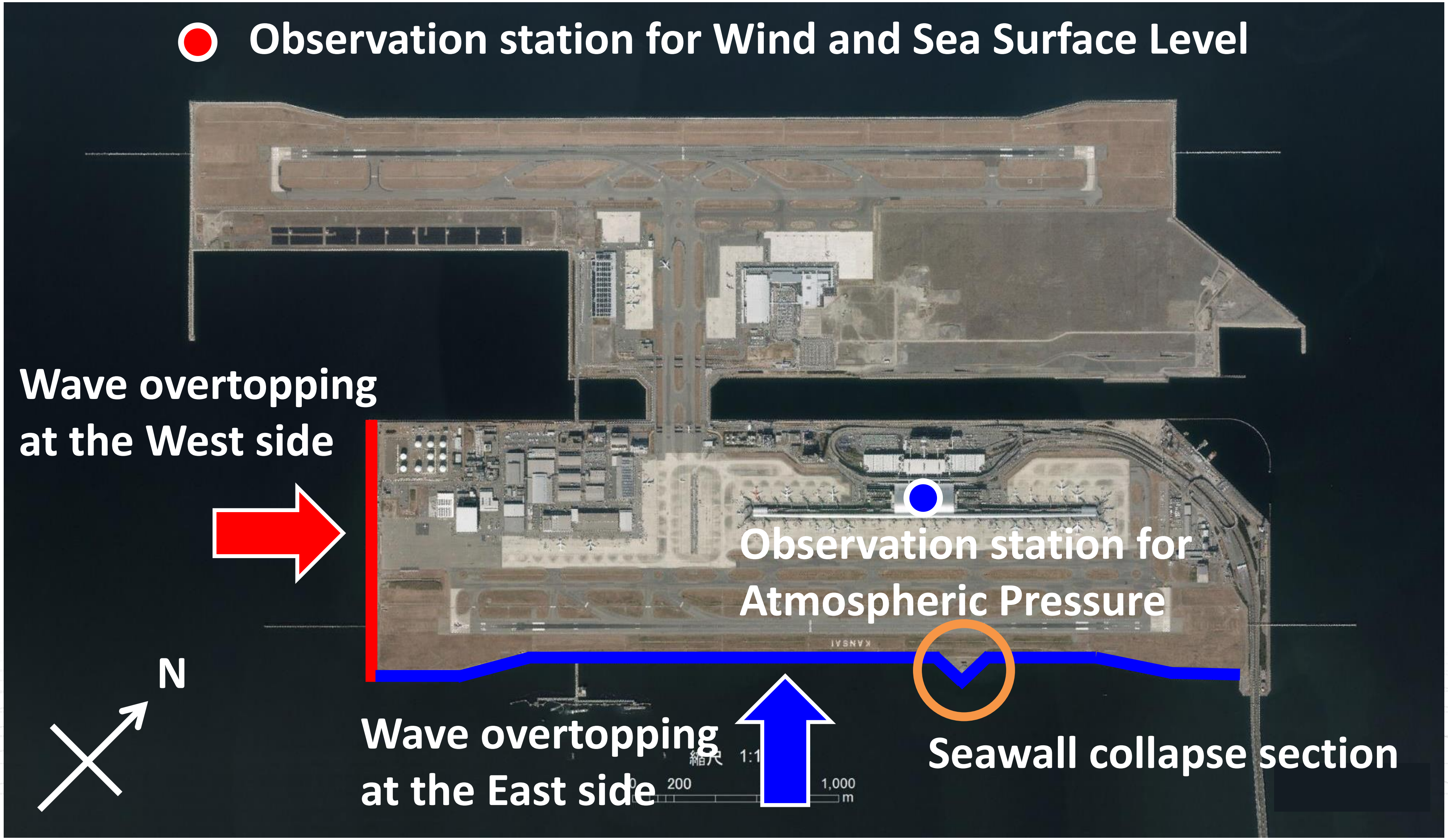
Covering	Q_{over_a}
Concrete three-side wrapping	0.05
Top surface paving · No backfill construction	0.02
No top surface paving	less than 0.005

Numerical experiments – Study area: Kansai Airport, Japan



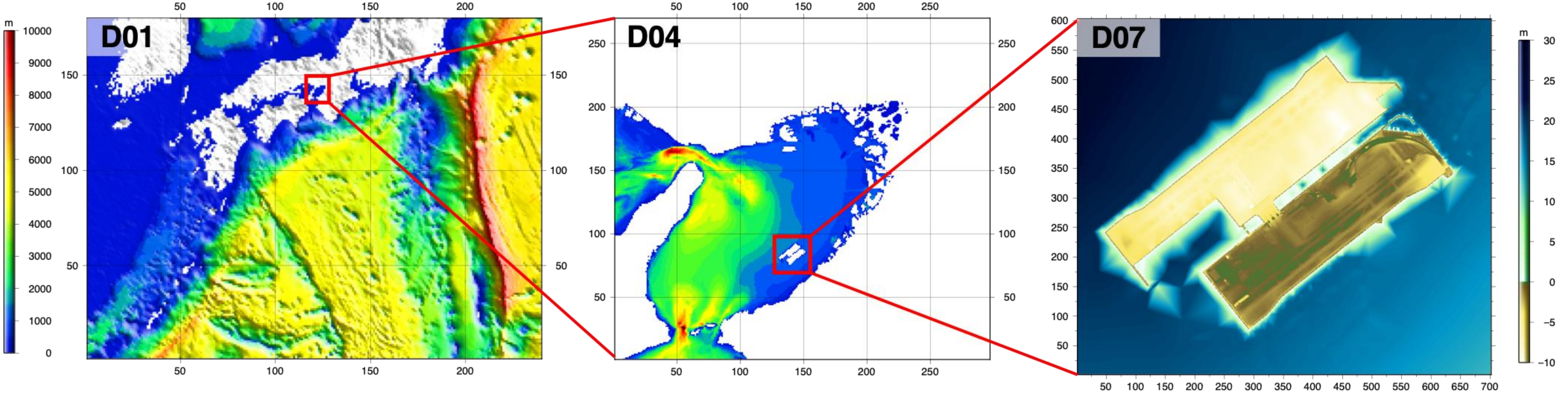
Seawall status

West side
- 6.6 m height
- 1,357 m length
- Vertical slope

East side
- 4.5 m height
- 5,060 m length
- Vertical slope

Collapse section

Numerical experiments – Geophysical regions for simulation



- The simulation area is consisted of **seven domains** downscaled from **7 km to 10 m grid size**.
- **Kansai Airport** is in the **7th domain** with the **10 m grid size**.
- The **numerical experiments** were carried out:
  1) **individual flood** (i.e., wave overtopping and reverse flow)
  2) **compound flood by all flood factors**

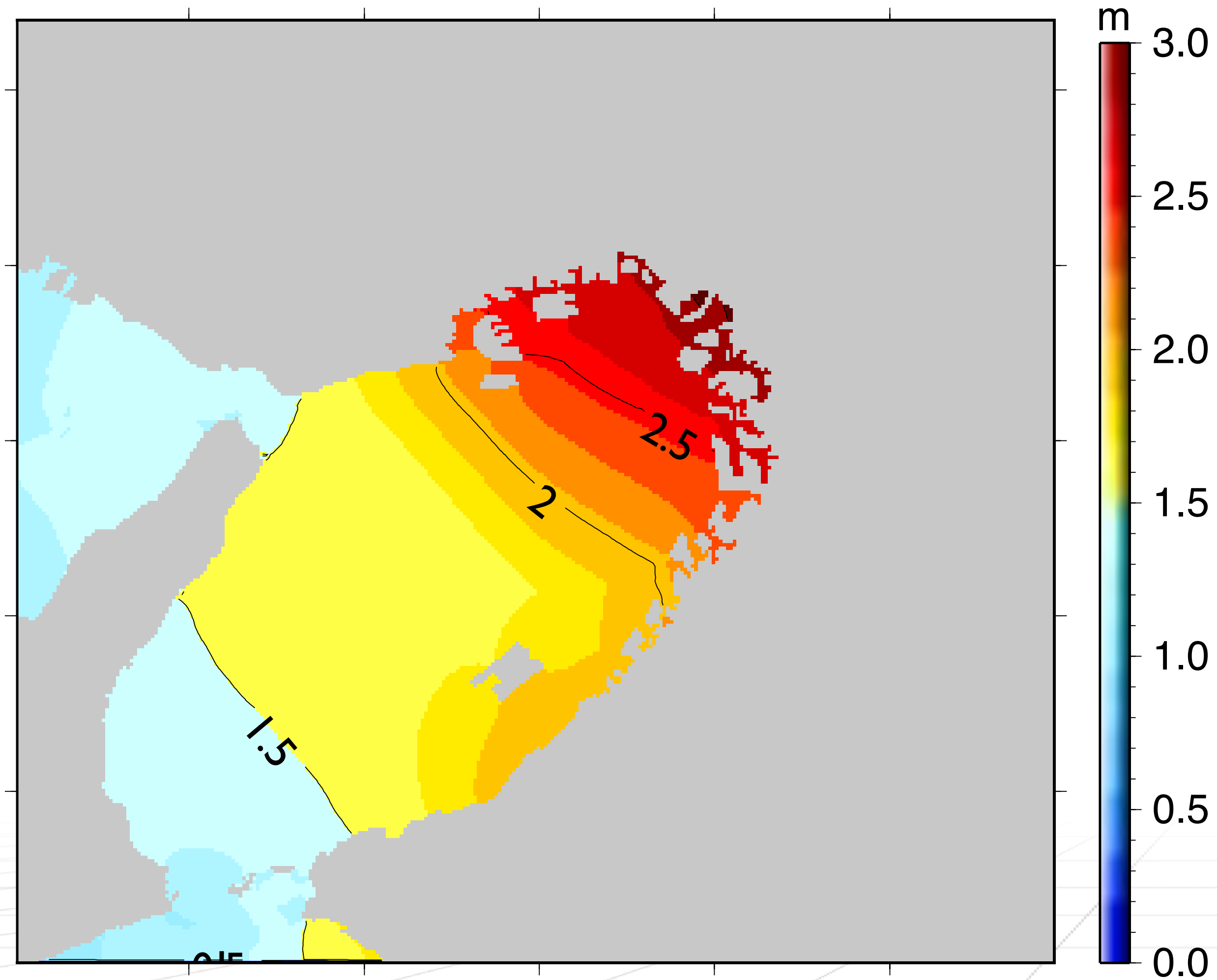
Numerical experiments – Flood calculation cases

Case No.	Wave overtopping		Sewer reverse flow	Seawall collapse	
	Breaking point	Reduction factor			
1	fix	X	-	-	Wave overtopping
2	flexible	X	-	-	
3	flexible	O	-	-	
4	flexible	O	-	O (only occur)	
5a	-	-	O (with Flap gate)	-	Sewer reverse flow
5b			O (without Flap gate)		
6	flexible	O	-	O	Partial compound flood
7	flexible	O	O	-	
8	fix	X	O	O	Full compound flood
9	flexible	X	O	O	
10	flexible	O	O	O	

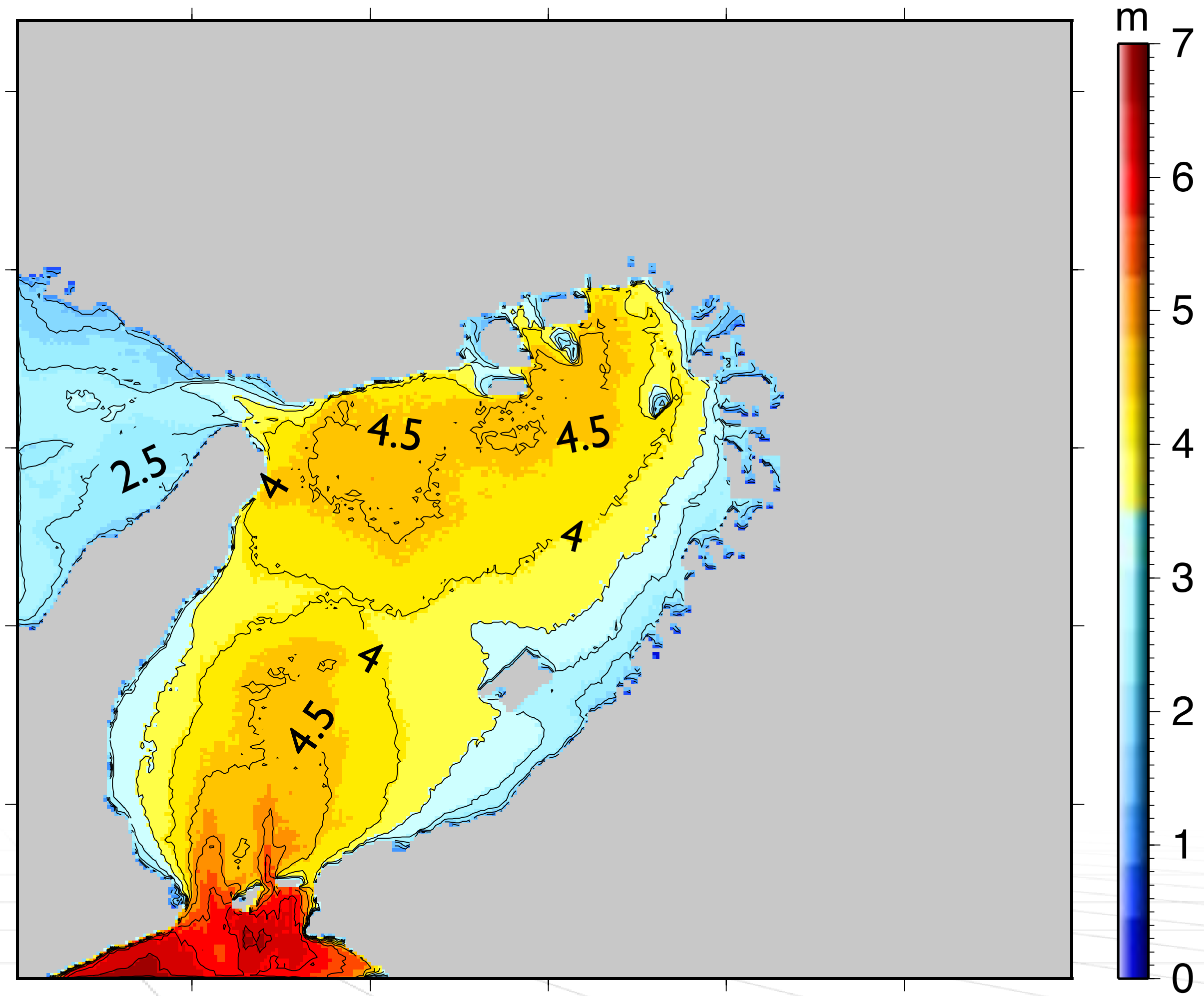
: Individual flood cases (orange box: cases 1–5b) **: Compound flood cases** (red box: cases 6–10)

- **Typhoon Jebi validation: Hs, Surge, wind**

Reproducing typhoon Jebi – Maximum surge and Hs at Osaka Bay

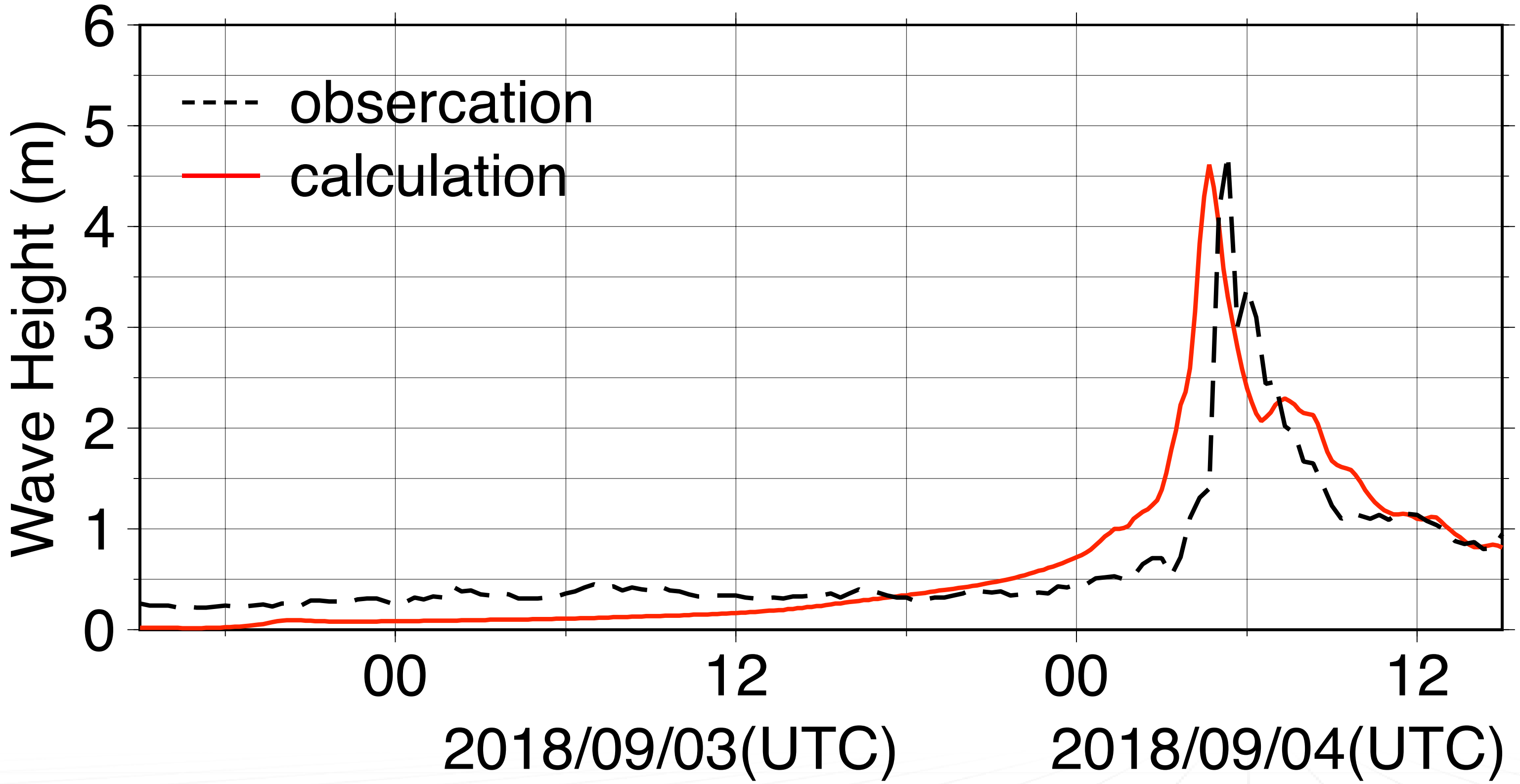


< Maximum surge height >

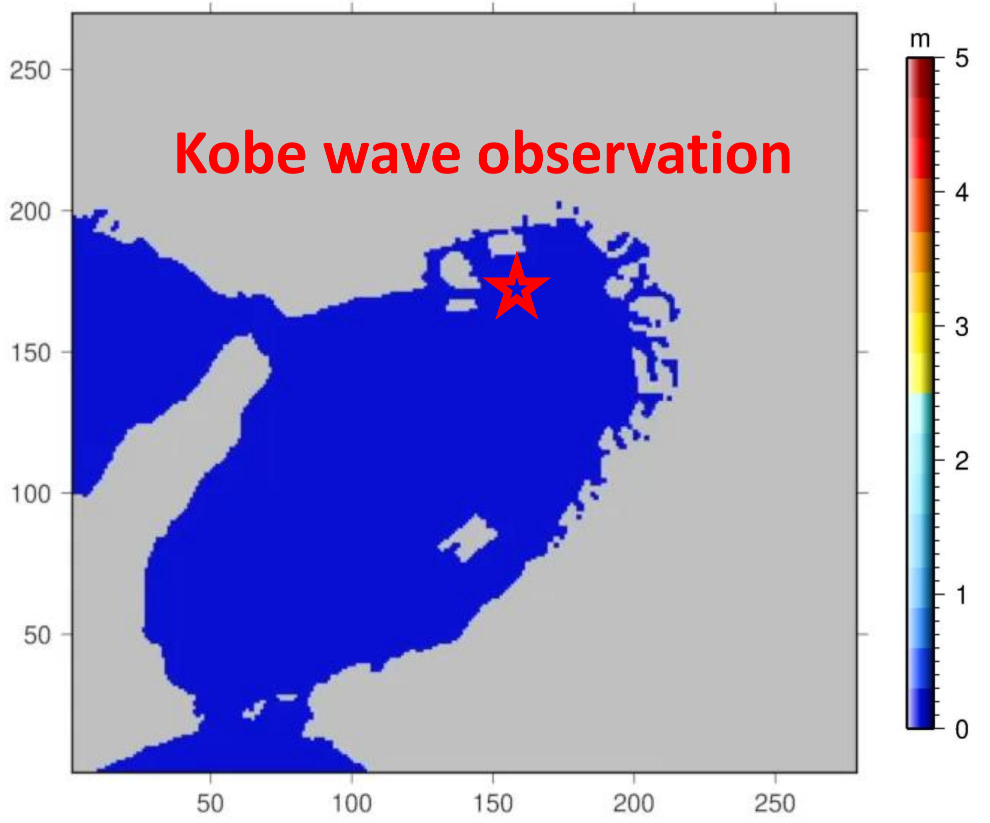


< Maximum Hs >

Reproducing typhoon Jebi – Wave height



< Comparison of calculated and observed wave height >

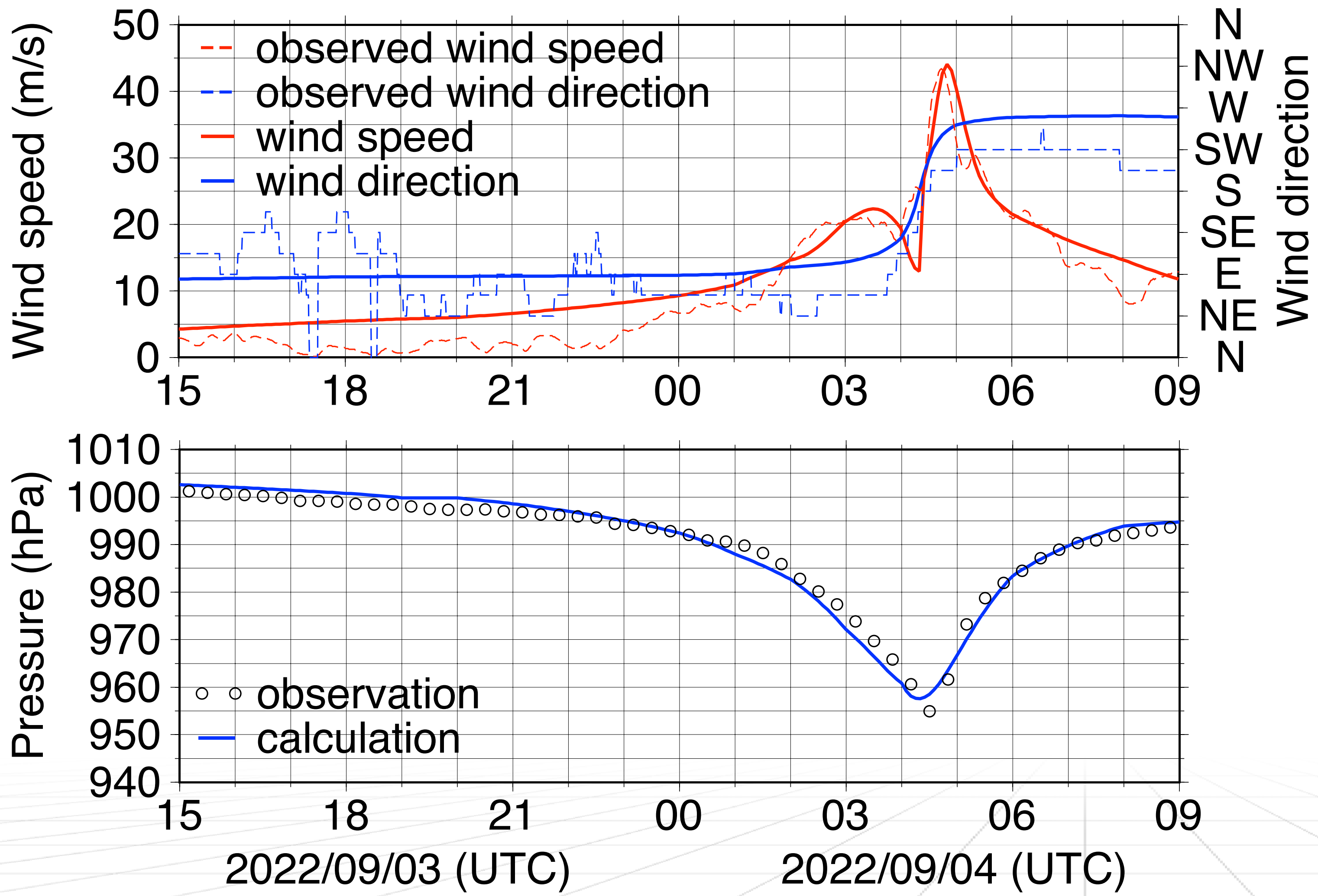


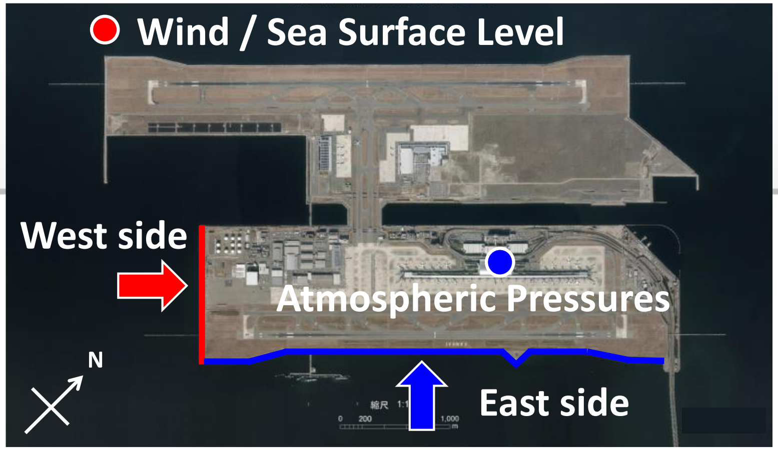
- **Peak wave height at ☆point**

  observation: 4.72 m at 5:20

  simulation : 4.62 m at 4:40

Reproducing typhoon Jebi – Wind/Pressure

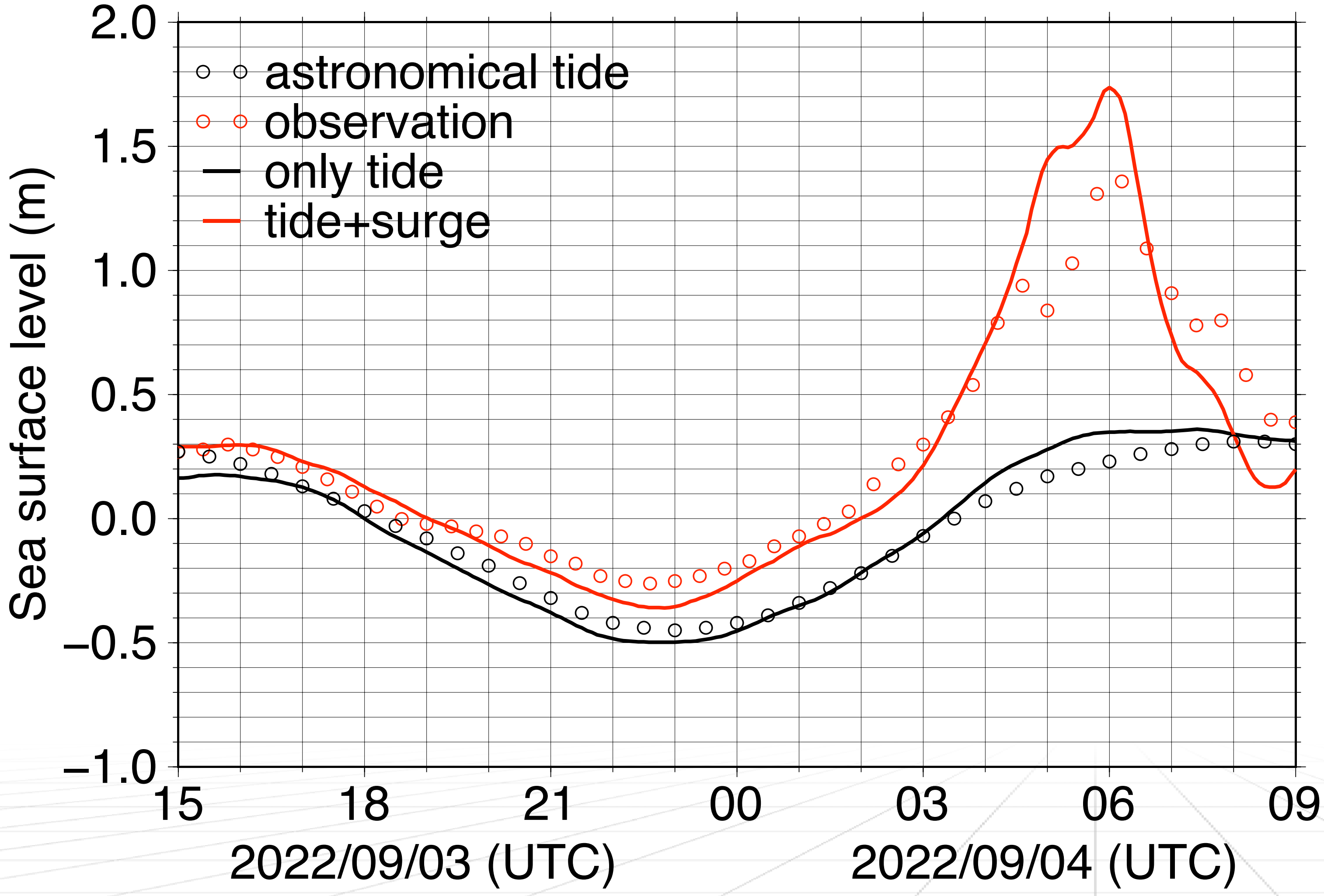


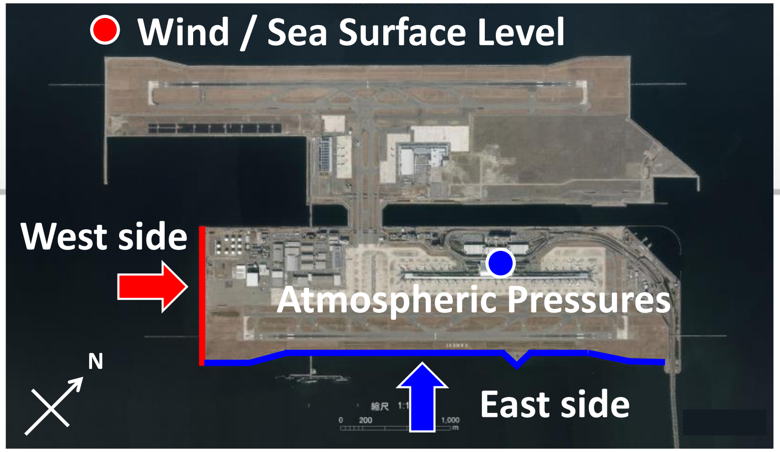


- **Peak wind speed at ● point**
  observation: 46.3 m/s at 4:44
  simulation : 44.0 m/s at 4:50
- **Maximum depression at ● point**
  observation: 954 hPa at 4:40
  simulation : 957 hPa at 4:25
- **Typhoon Jebi was well reproduced.**

< Comparison of calculated and observed wind/pressure >

Reproducing typhoon Jebi – Sea surface level

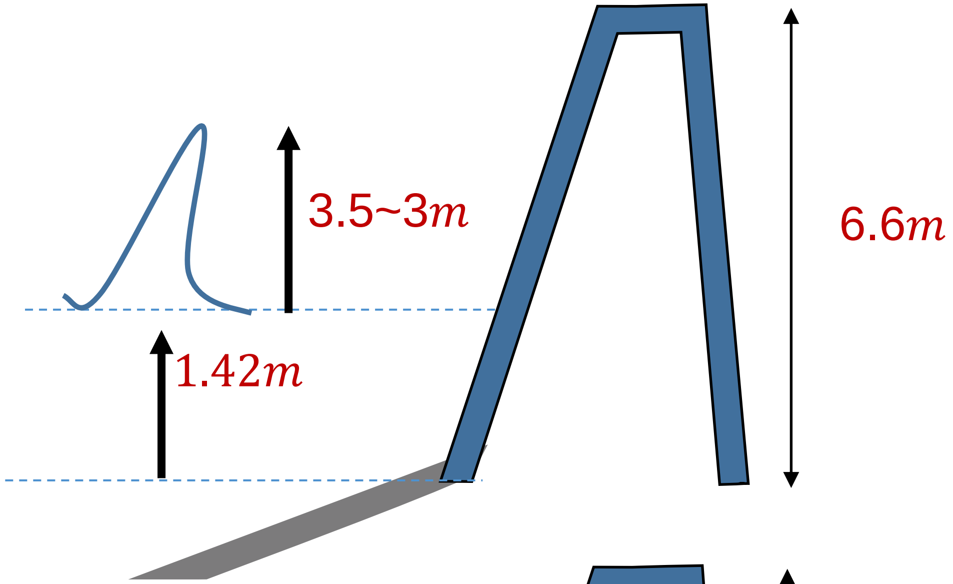




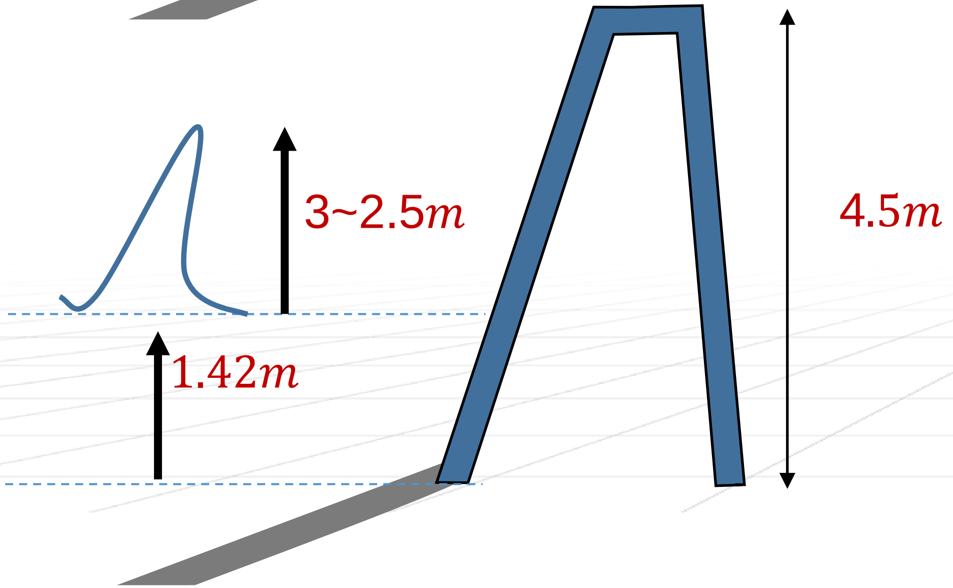
- **Peak surge height considering tidal variation at ● point**
  observation: 1.42 m at 6:15
  simulation : 1.73 m at 6:00
- **The calculated results** were **validated** in good agreement with **the observation.**

< Comparison of calculated and observed sea surface level >

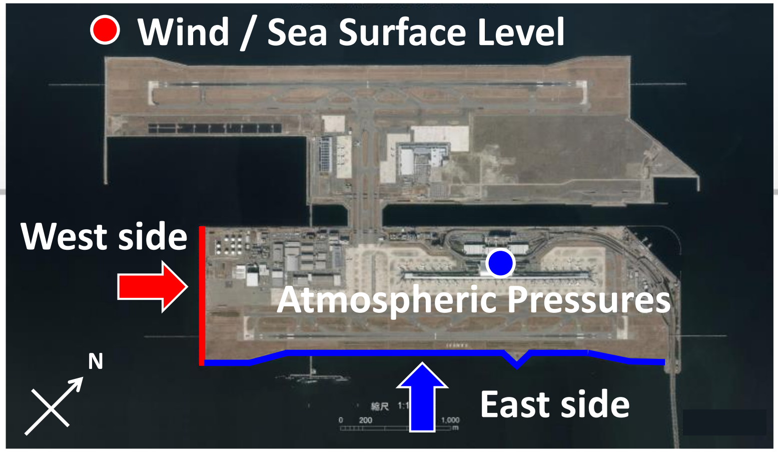
Peak surge + Peak Hs + Seawall height



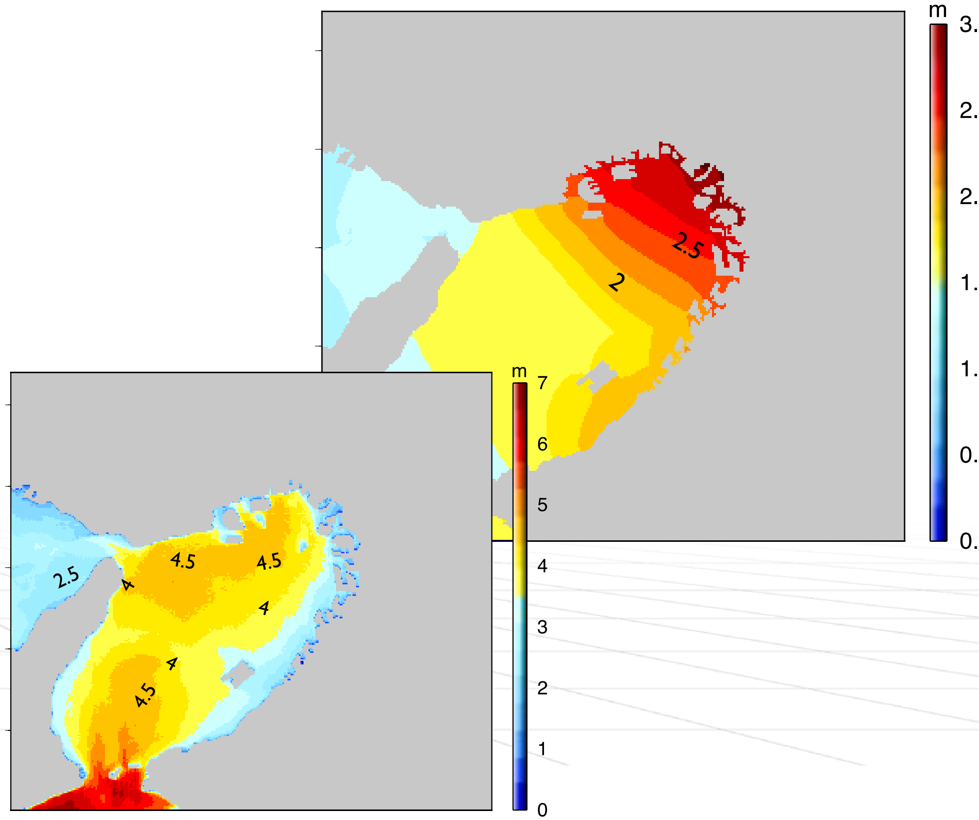
- West side
- 6.6 m height
- 1,357 m length
- Vertical slope



- East side
- 4.5 m height
- 5,060 m length
- Vertical slope

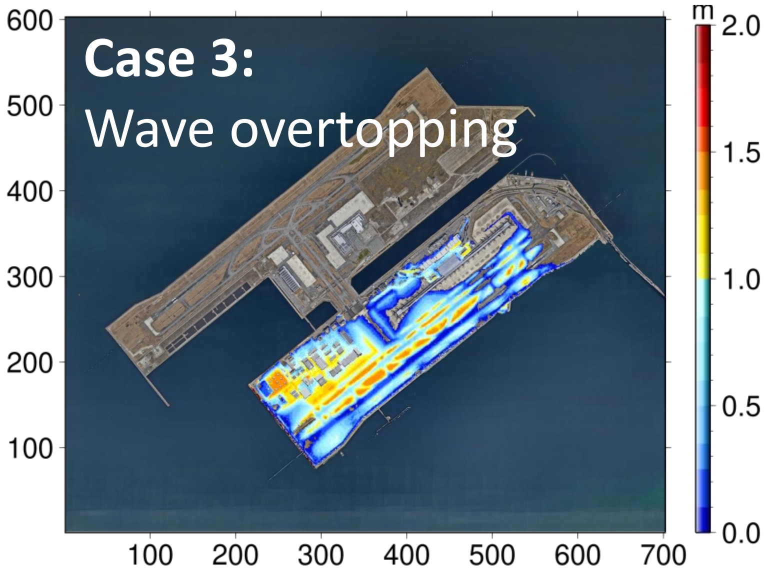


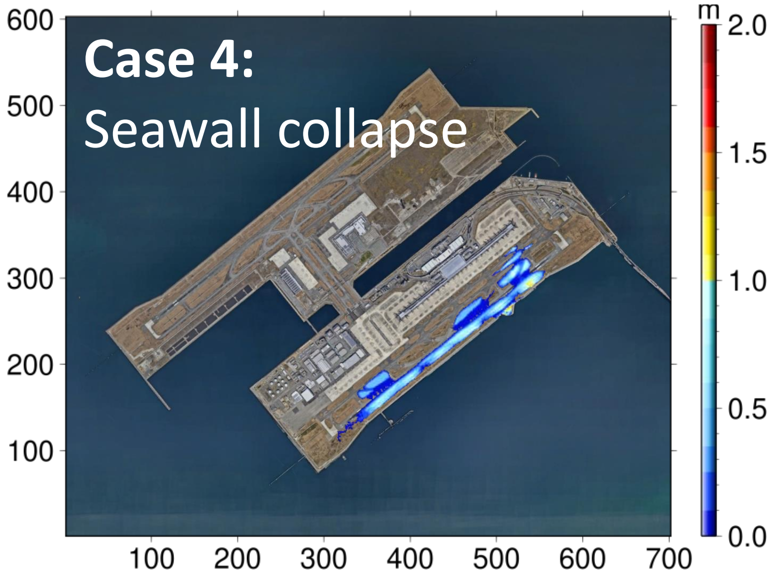
Seawall status

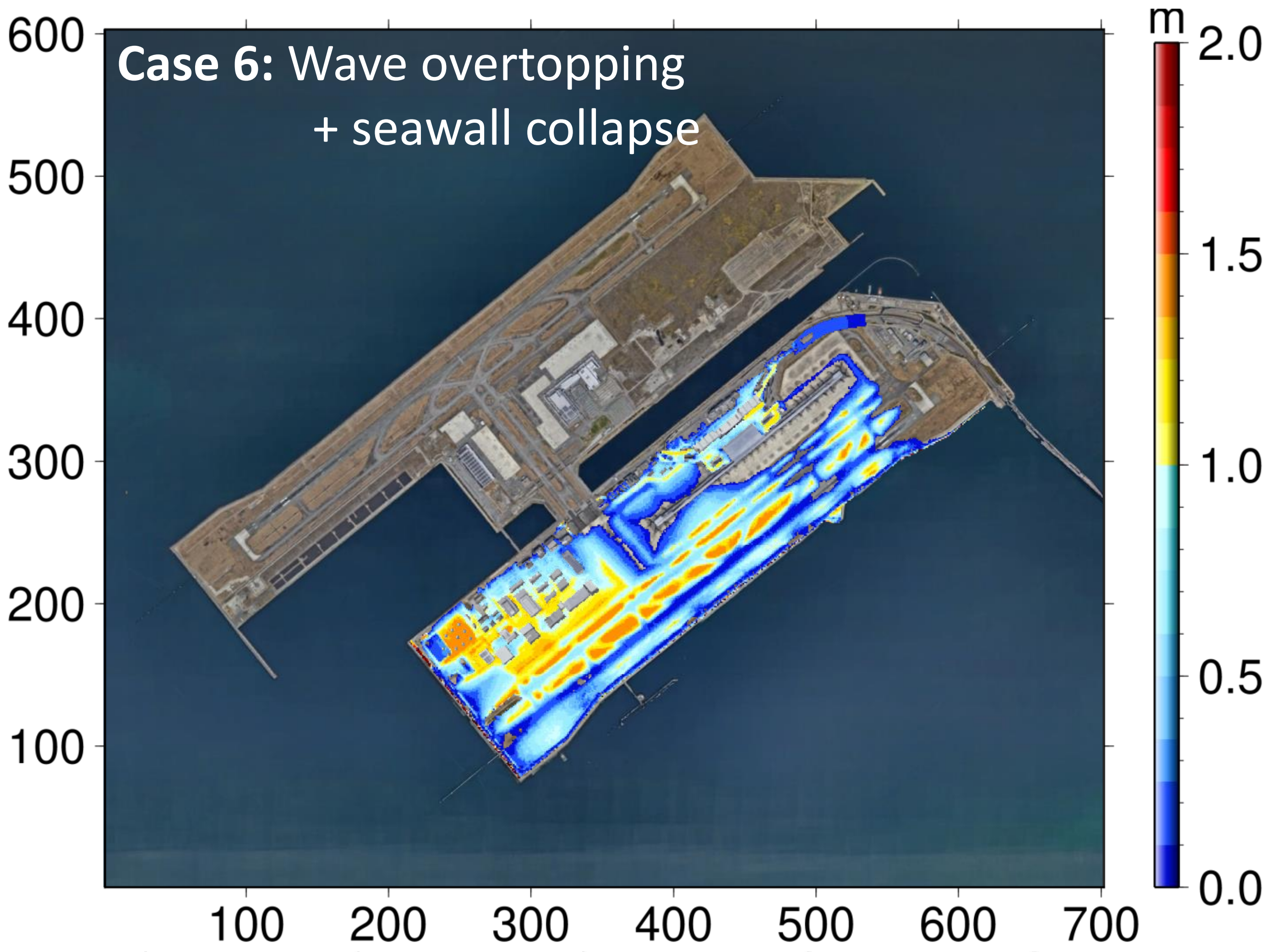


- **Results:**
  partial compound flood

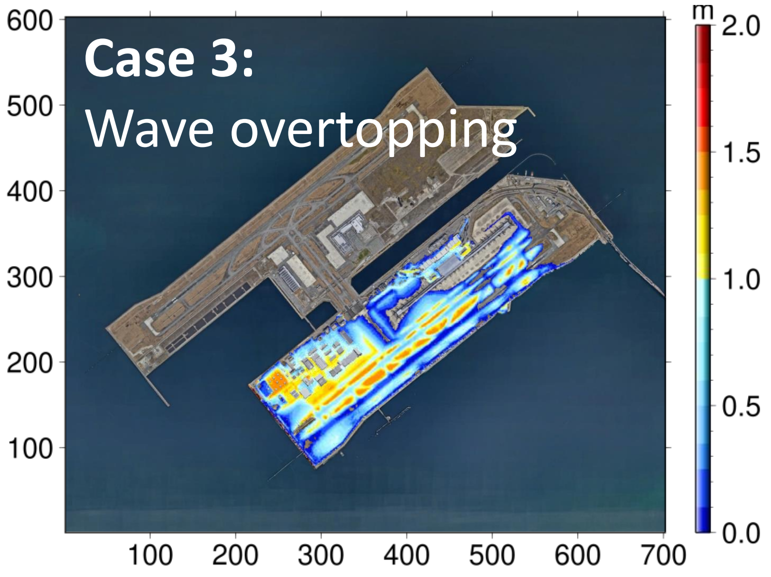
Flood discharge by failure & Overtopping (Case 6)

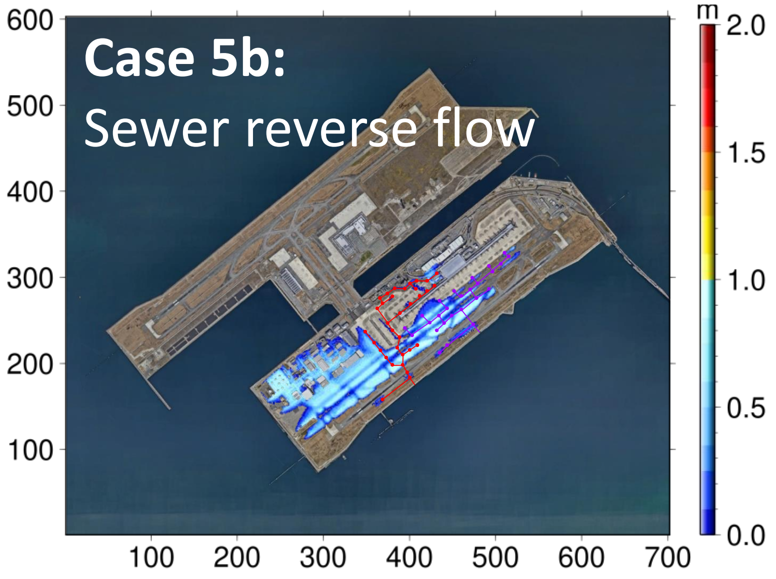


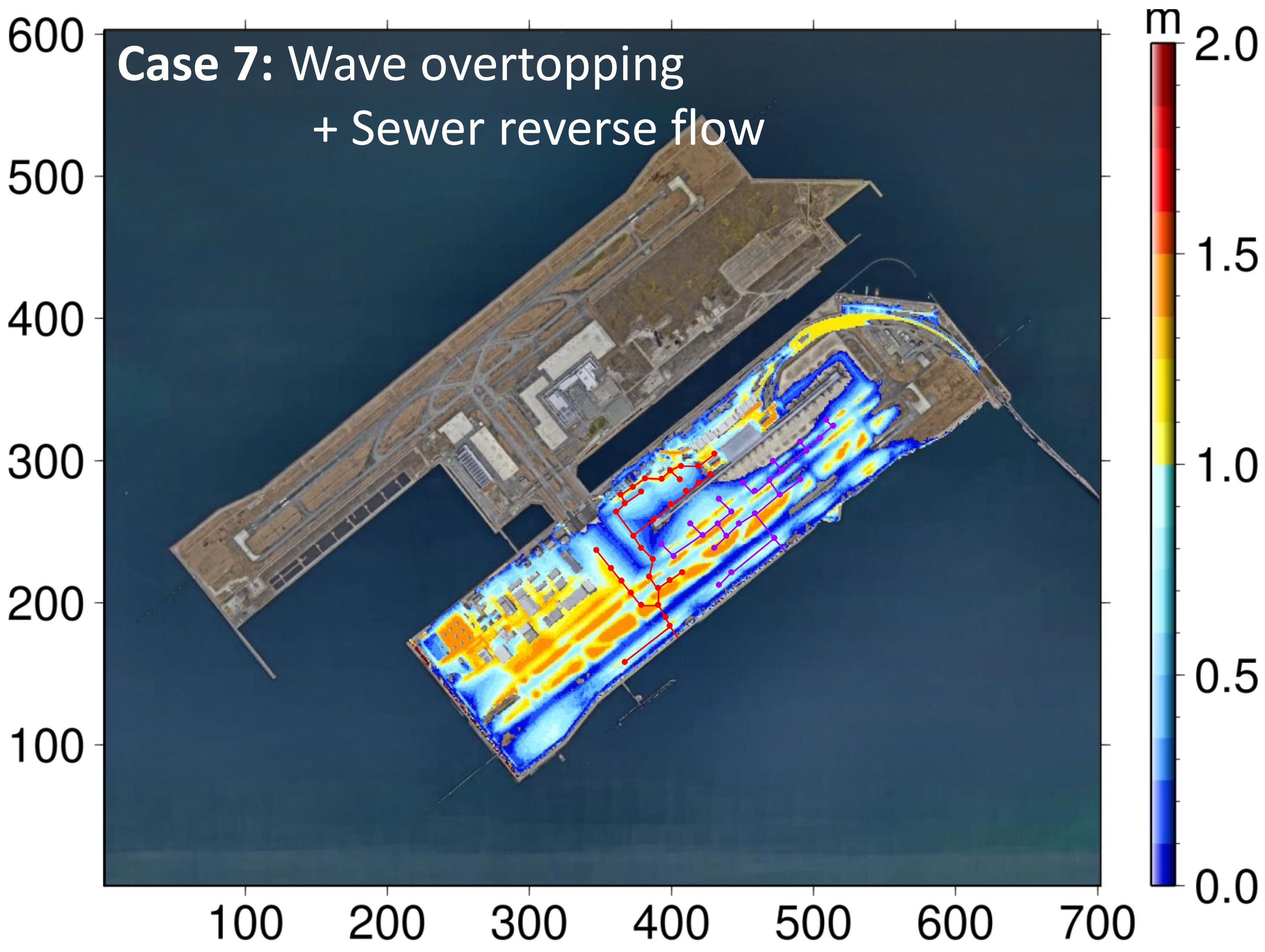




Flood discharge by Flood discharge by Reverse flow & Overtopping (Case 7)

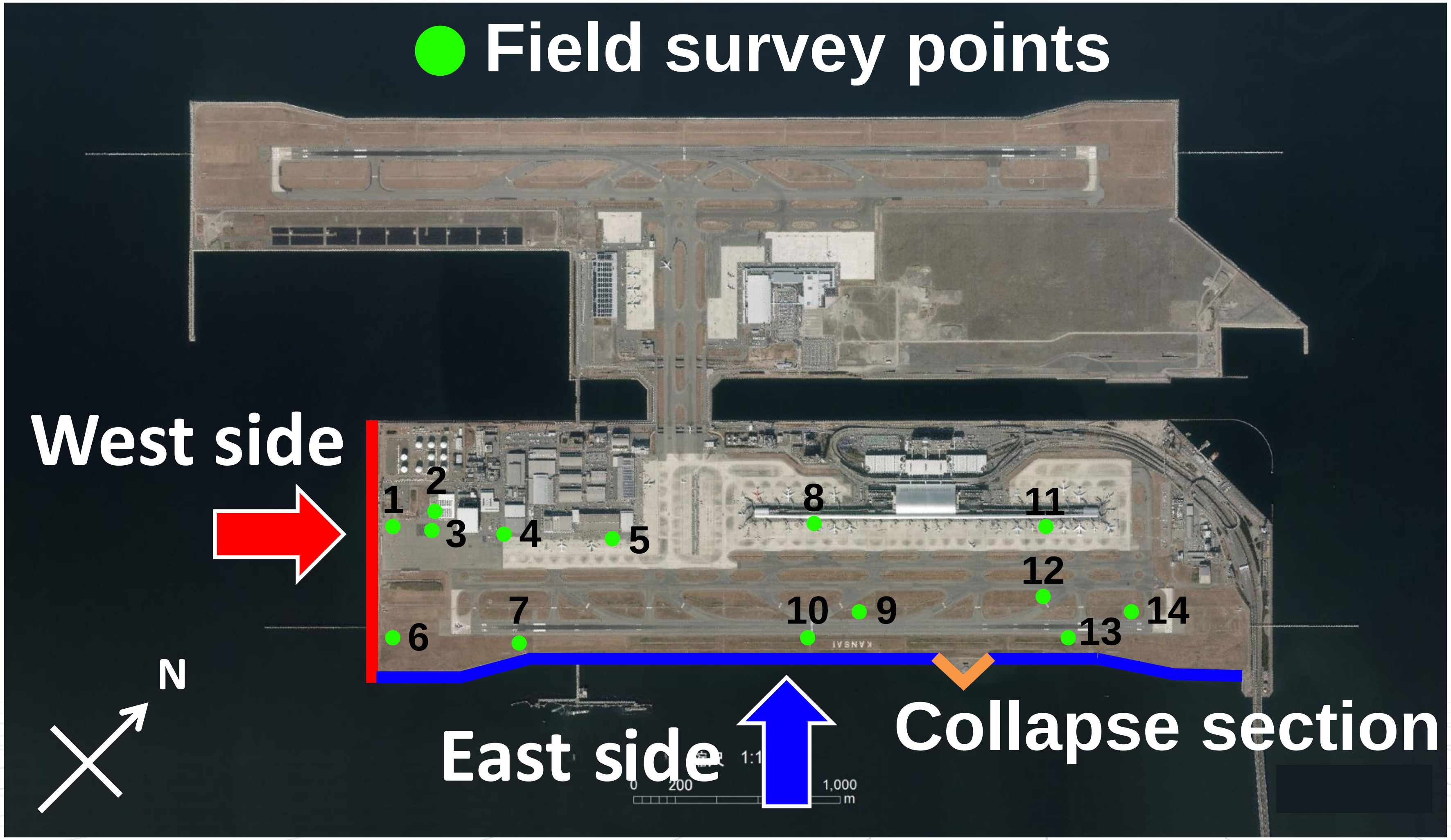




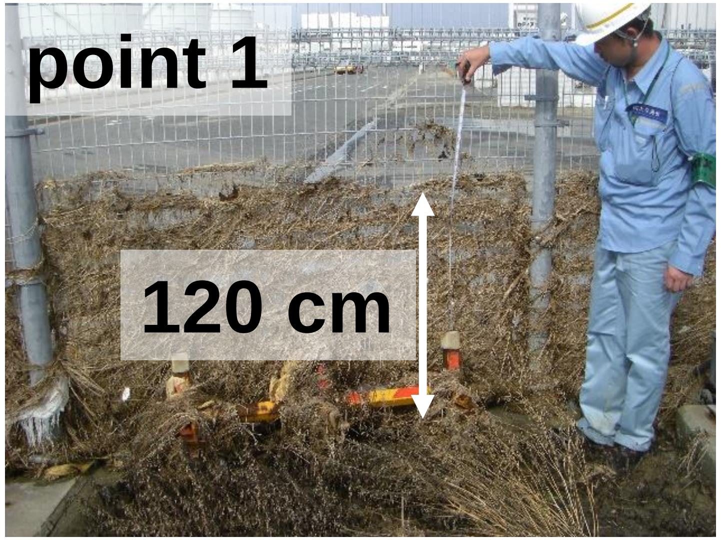


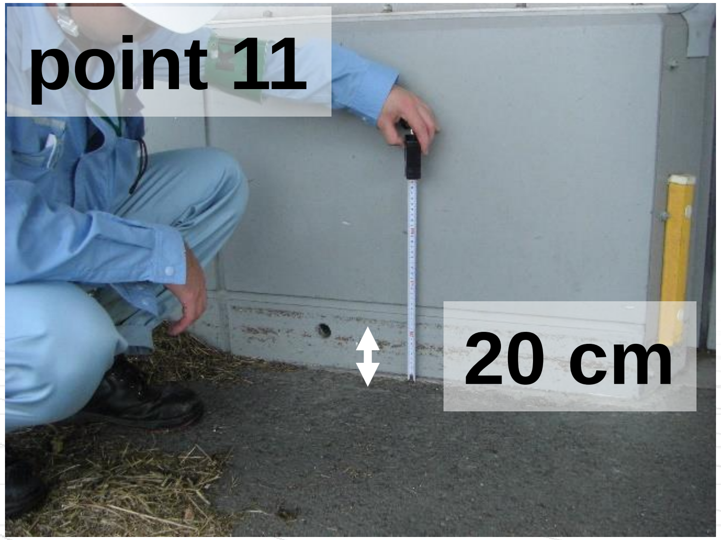
- **Comparisons to survey**

Comparison of peak flood depth with field survey



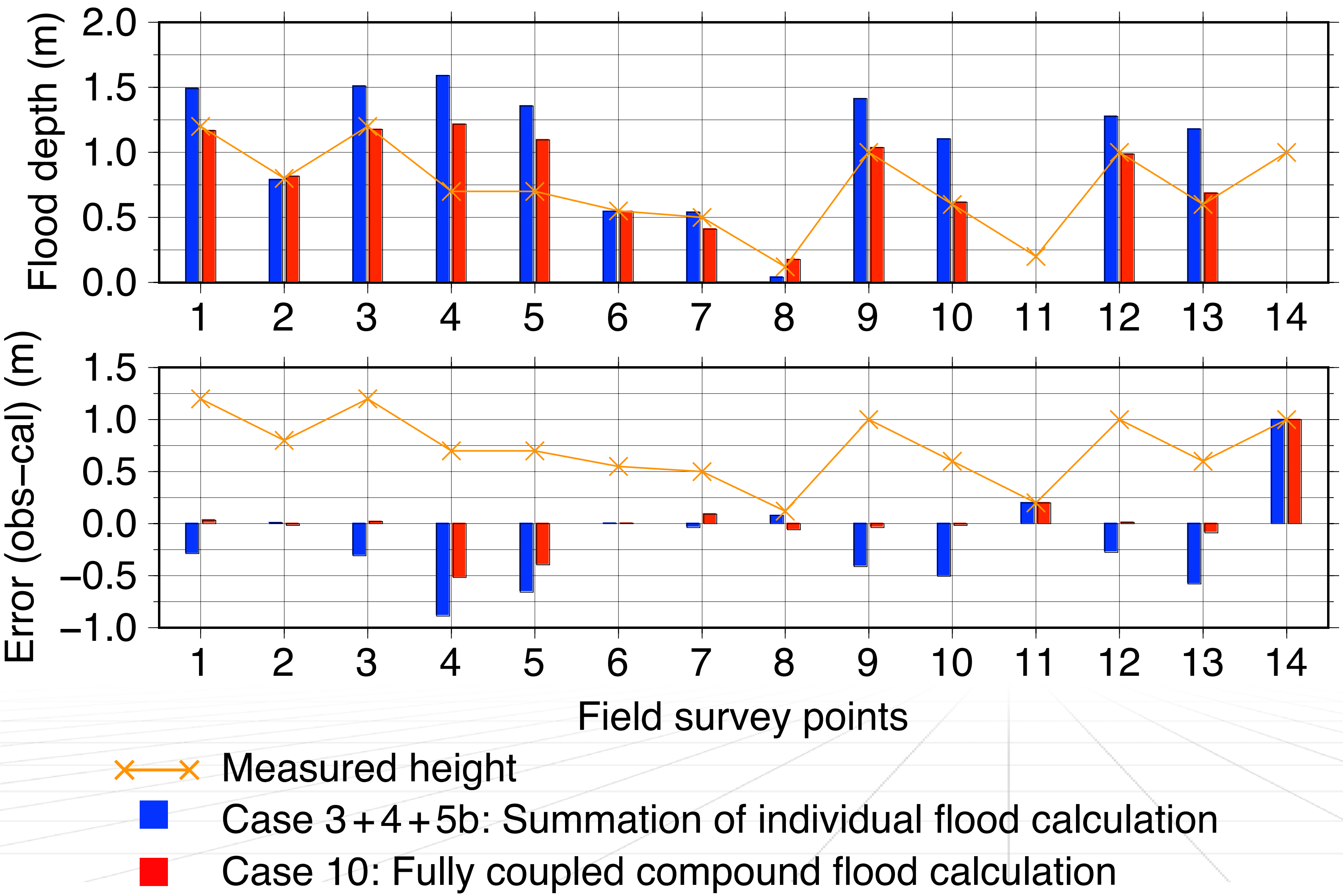
< Location of field survey points (total 14 points) >





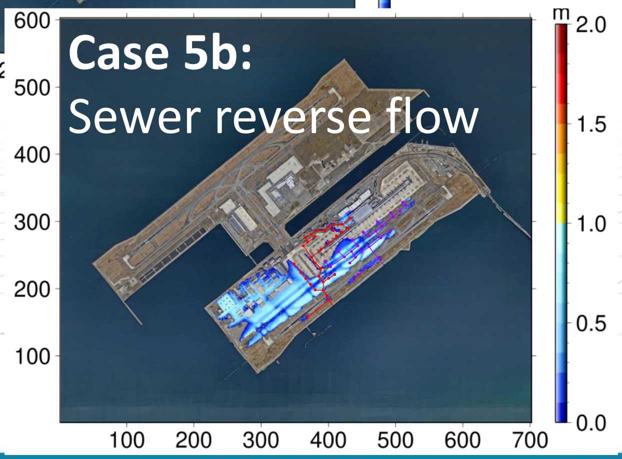
< Field survey overview >

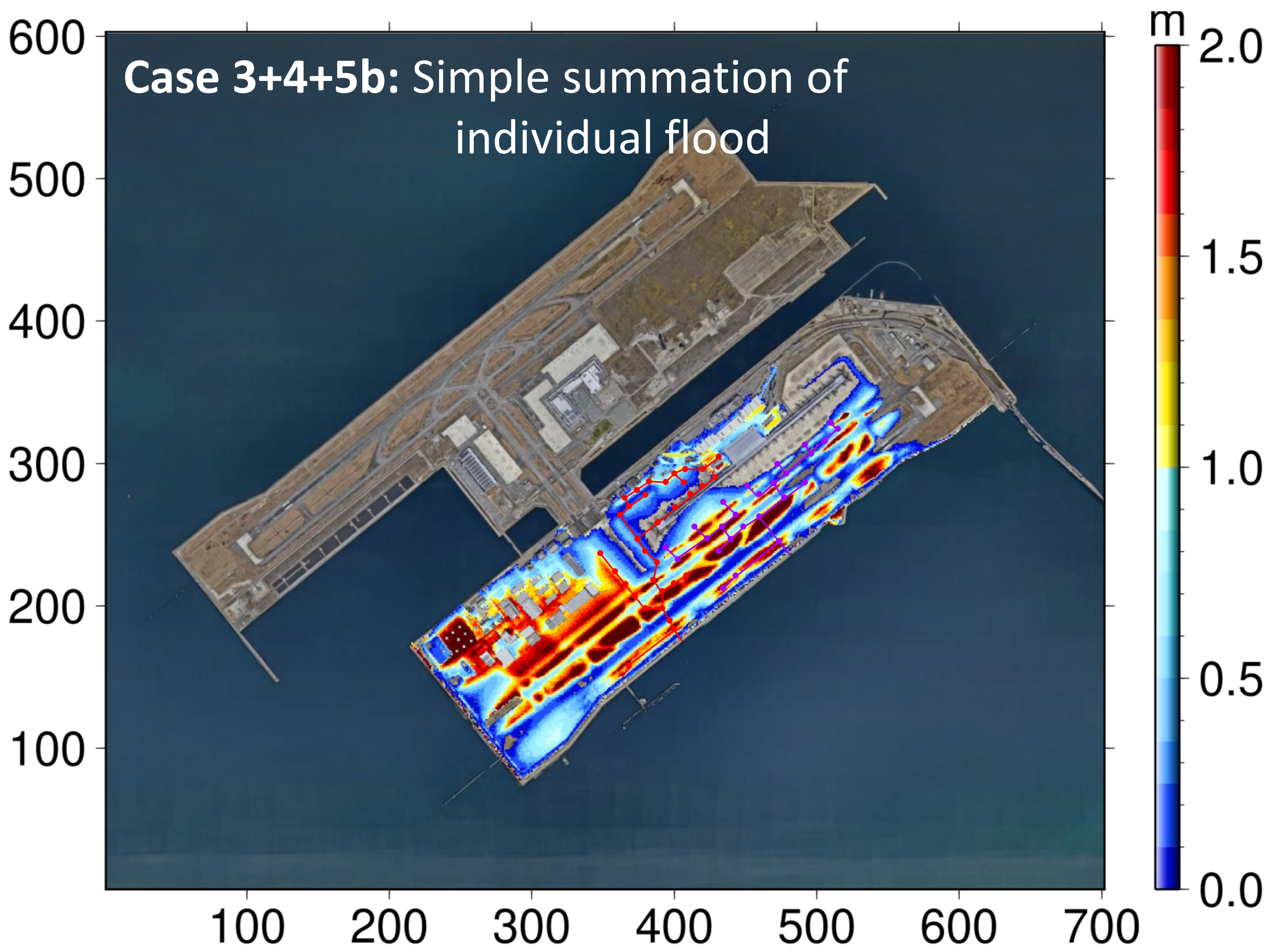
Comparison of peak flood depth by individual VS compound flood



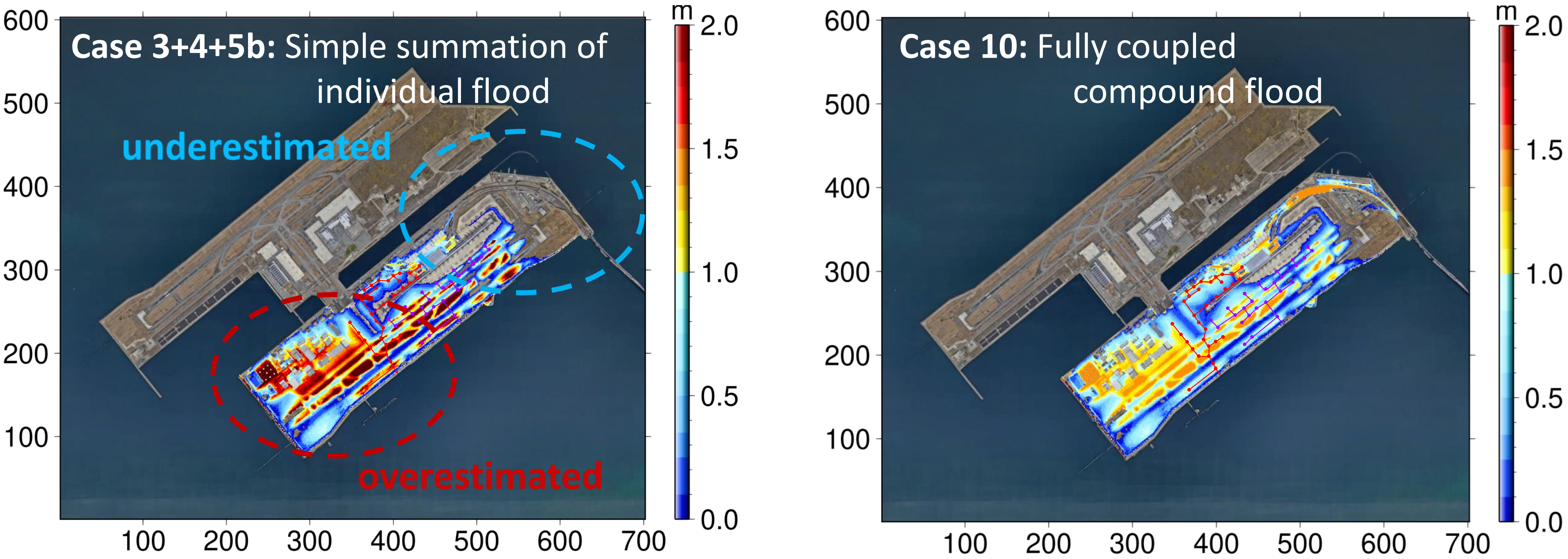
- **Summation of individual flood calculation cases:**
  Case 3 (wave overtopping)
  \+
  Case 4 (seawall collapse)
  \+
  Case 5b (sewer reverse flow)
- **Fully coupled compound flood calculation case:**
  Case 10
- **Simple summation of ■ overestimated flood depth.**

Comparison of peak flood depth by individual VS compound flood



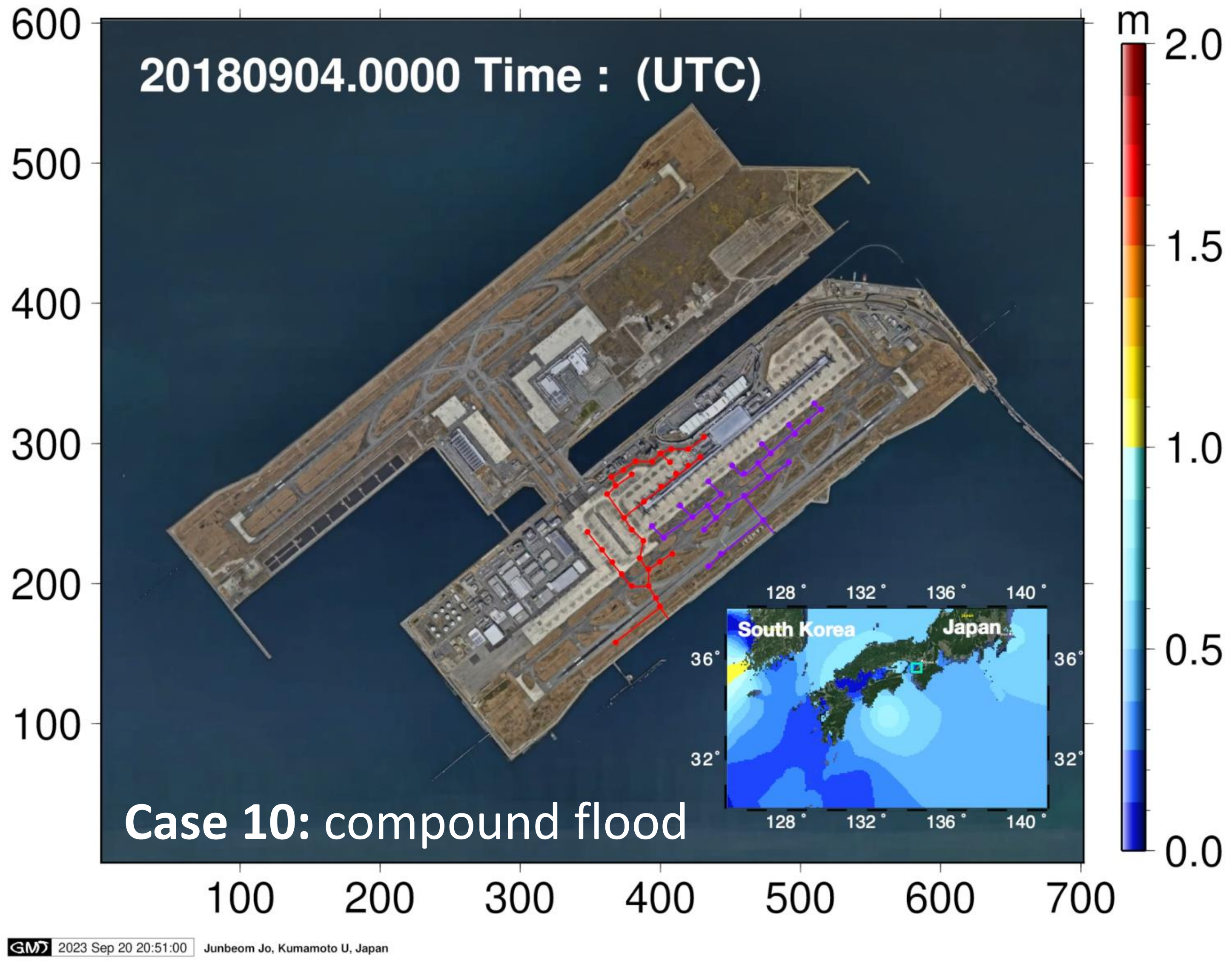


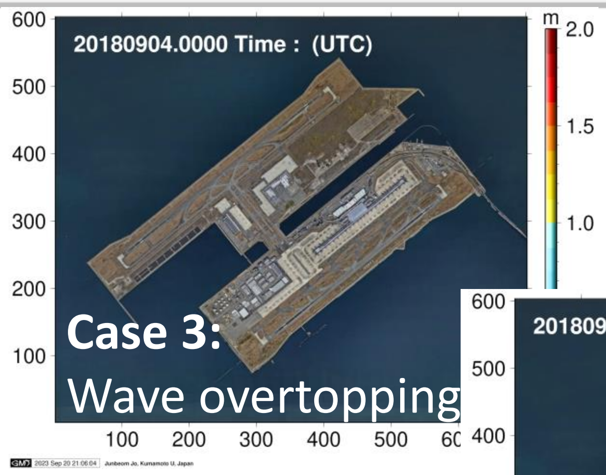
Comparison of peak flood depth by individual VS compound flood

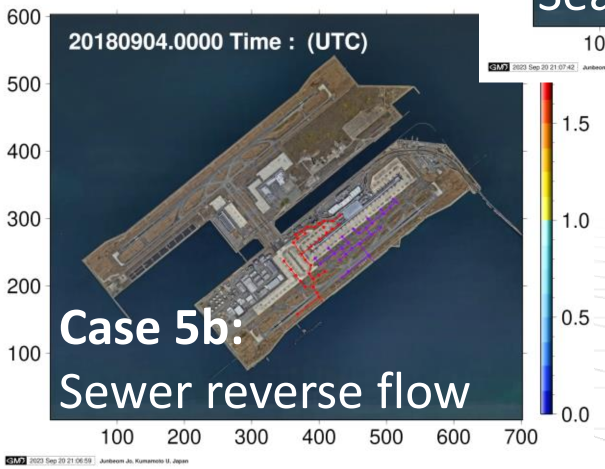


- **The simple summation of individual floods** resulted in an **overestimation** of flood depth in the **low-lying areas** while **underestimating** it in **higher area**.
- This might be because **the non-linear impact of 2D flood spreading on the surface** has been disregarded.

Flood pattern by cases (compound flood, wave overtopping, and reverse flow)



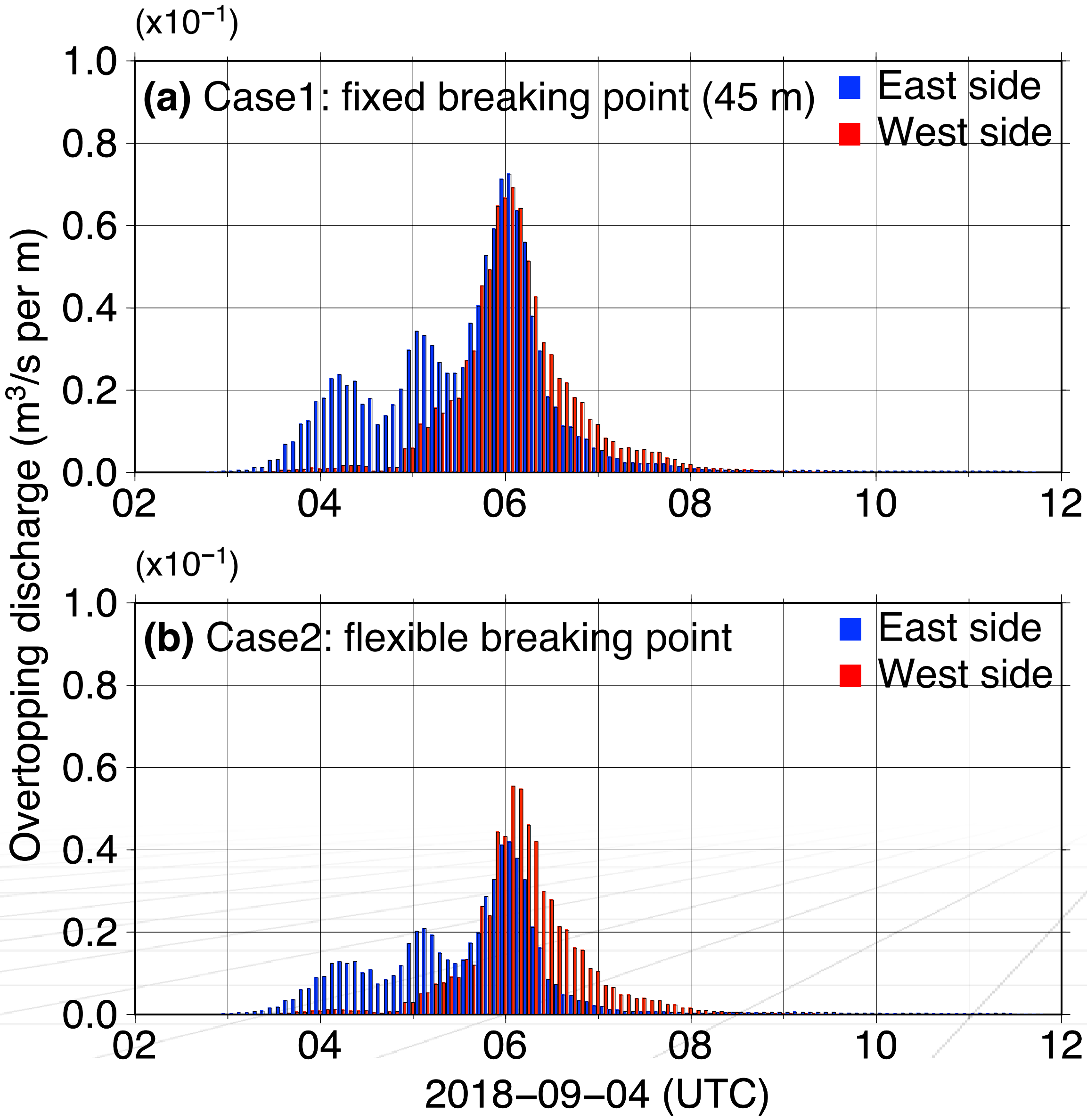


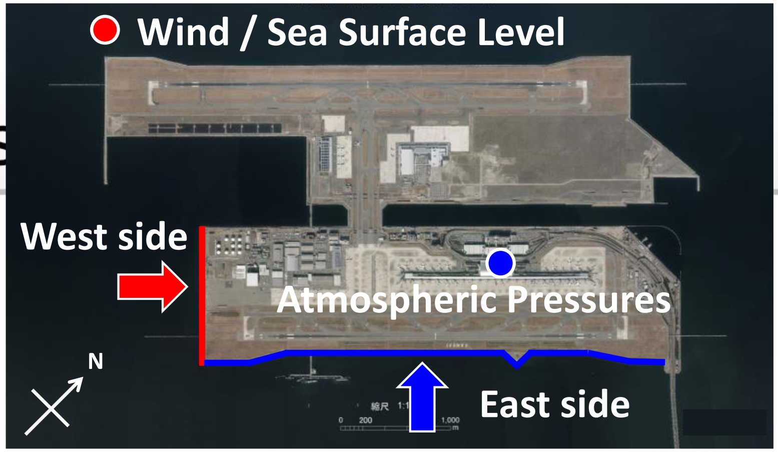


Thank you!

- Results: individual components
- Cases 1 to 5

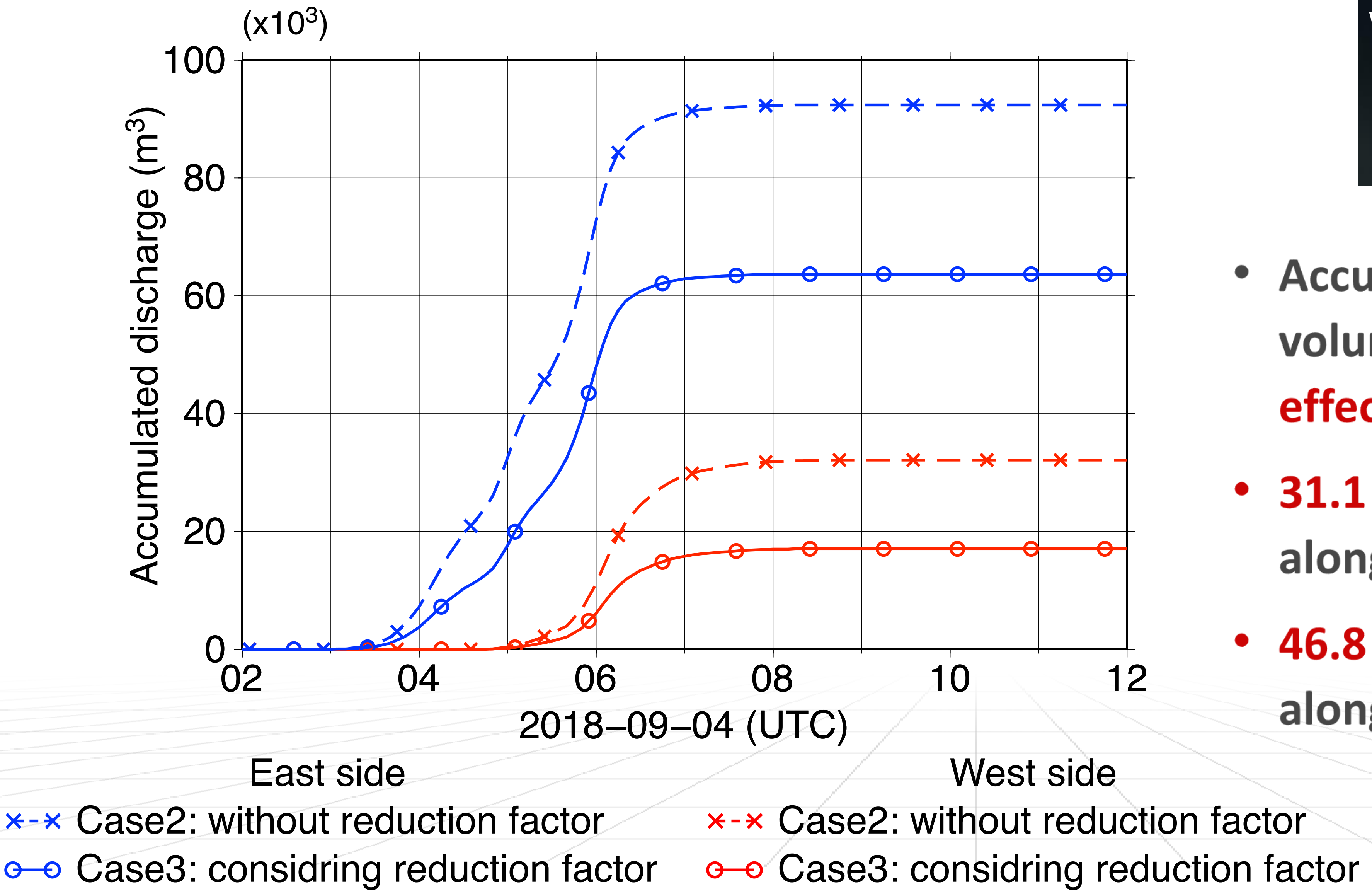
Overtopping discharge: fixed VS flexible point methods

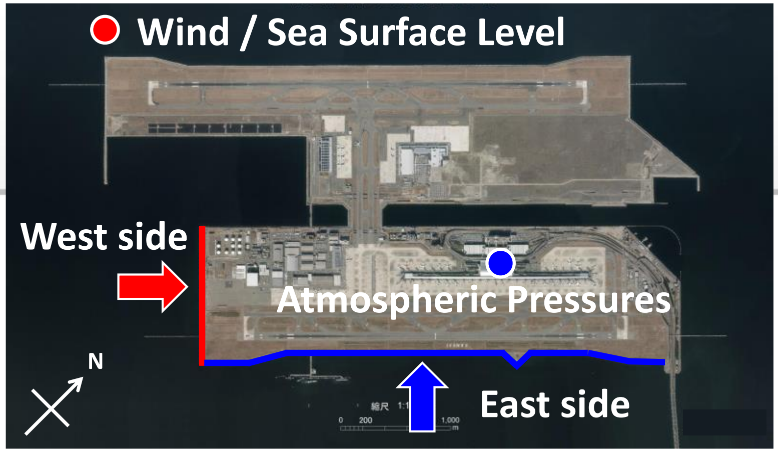




- **The breaking point**, in **case (a)**, was **fixed** as **45 m from the seawall**.
- In **case (b)**, **the breaking point** was **estimated flexibly** by **the wave transformation model**.
- **The estimated breaking point (flexible case)** was **closer** than 45 m (fixed case).
- **Lower wave** by flexible breaking point **affects the decrease of wave overtopping amount**.

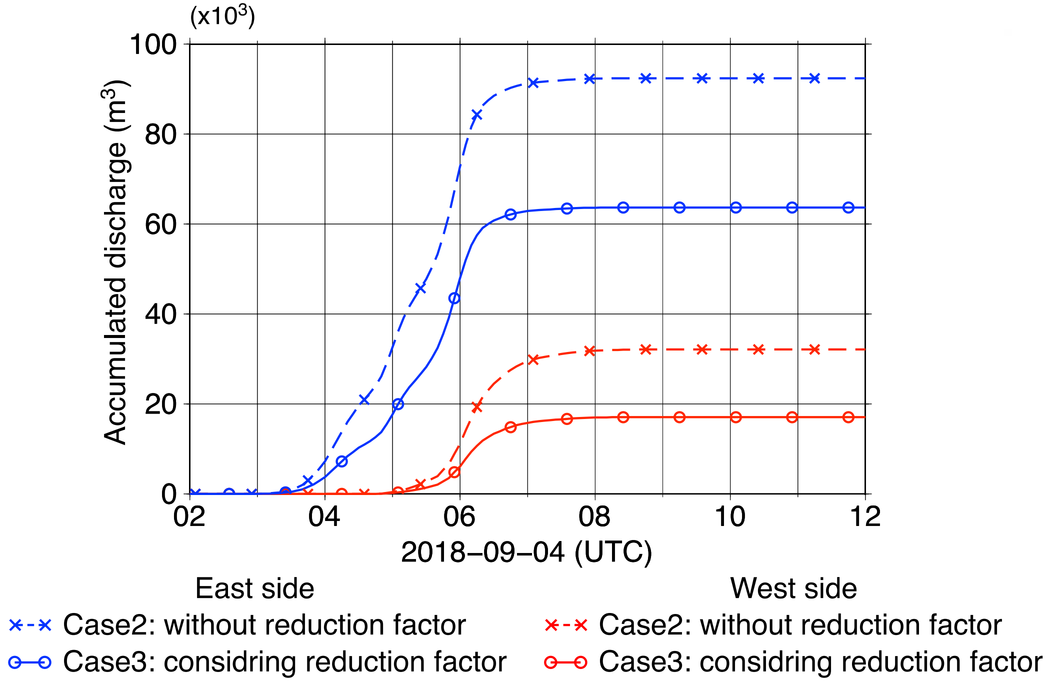
Accumulated volume considering reduction factor

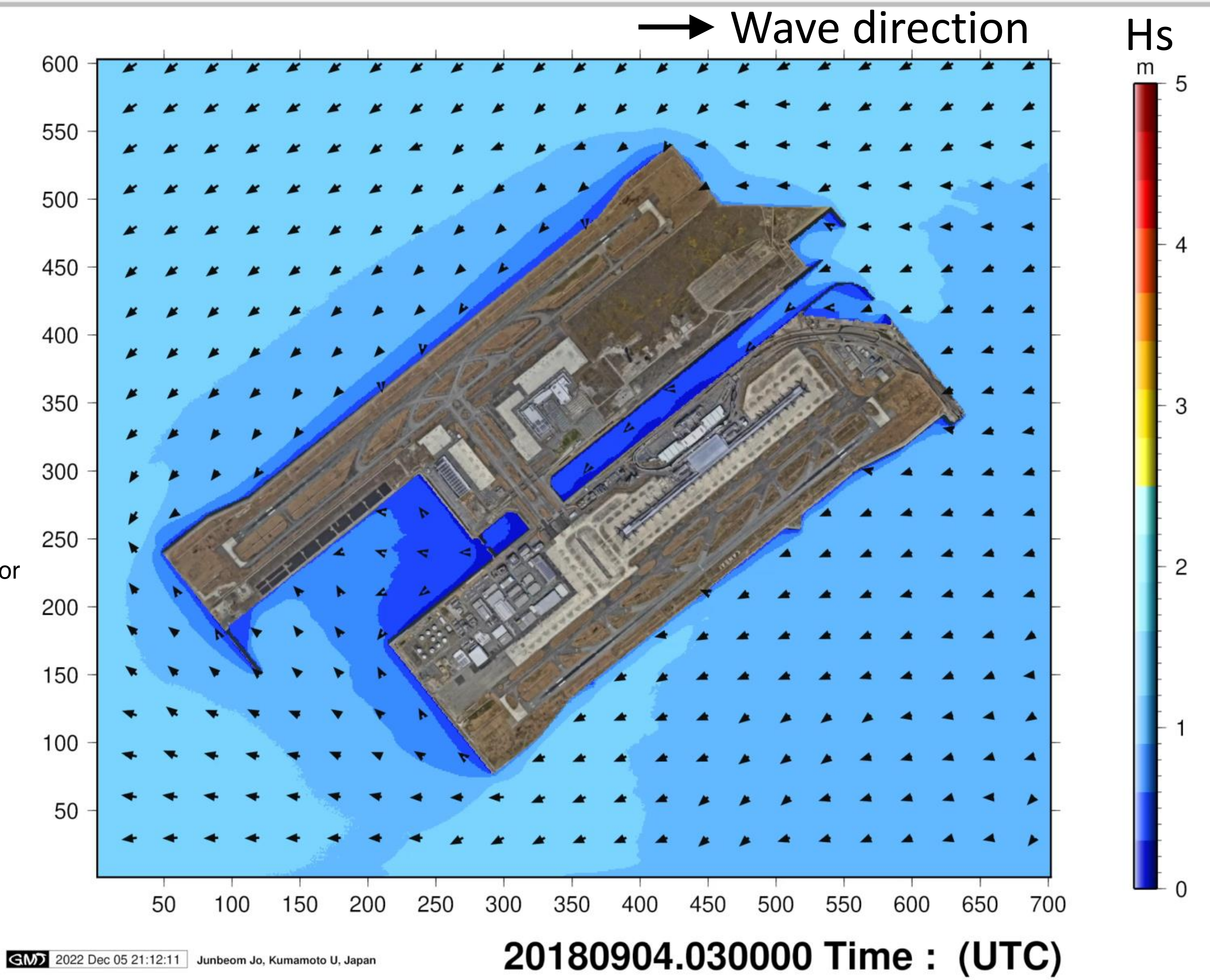




- **Accumulated overtopping volume** was reduced by **the effect of oblique waves**.
- **31.1 %** of reduction occurred **along the east side**.
- **46.8 %** of reduction occurred **along the west side**.

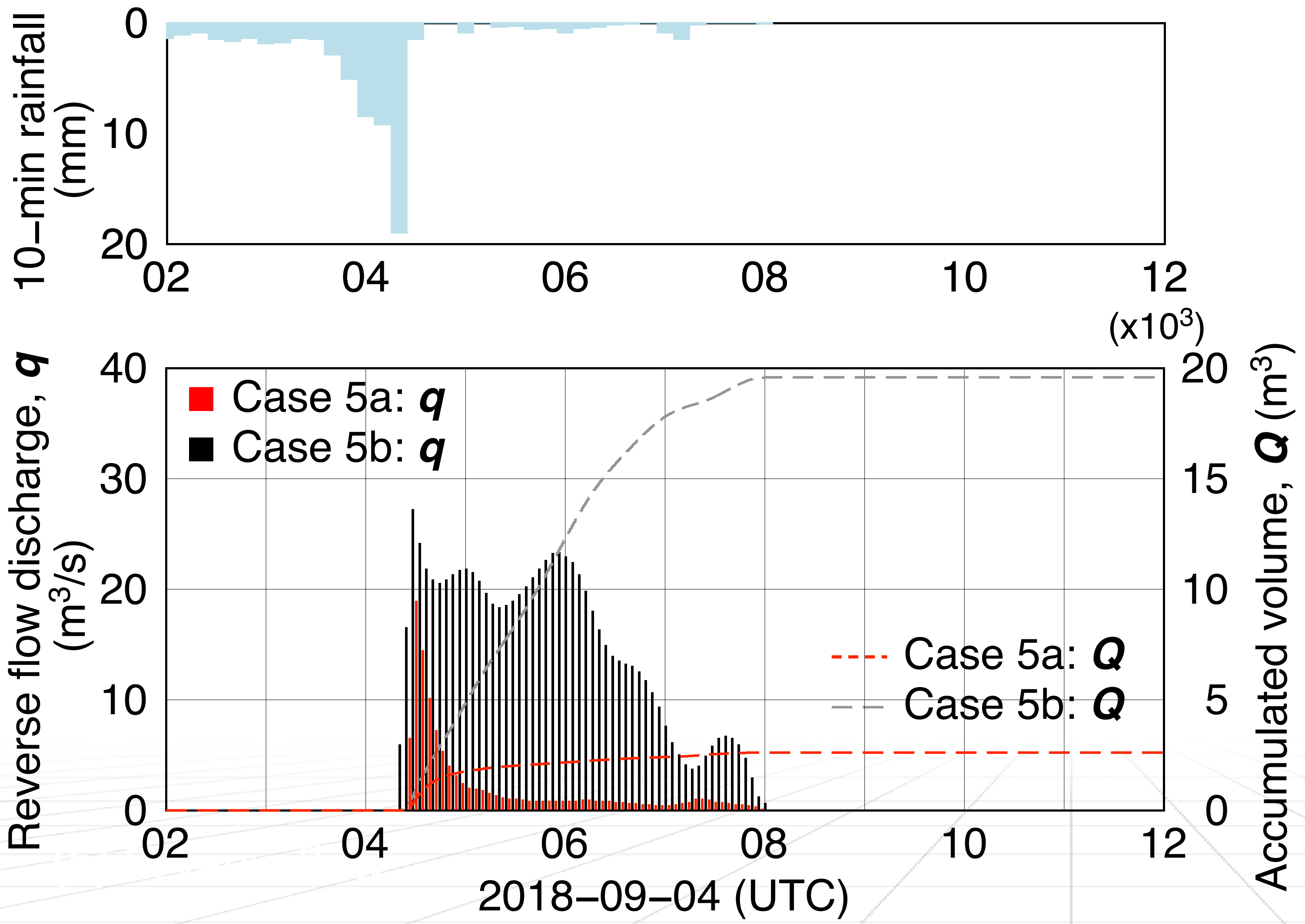
Accumulated volume considering reduction factor





- **The reduction** in wave overtopping discharge **due to the reduction factor** is attributed to **the broad directional distribution of waves** at the seawall front.

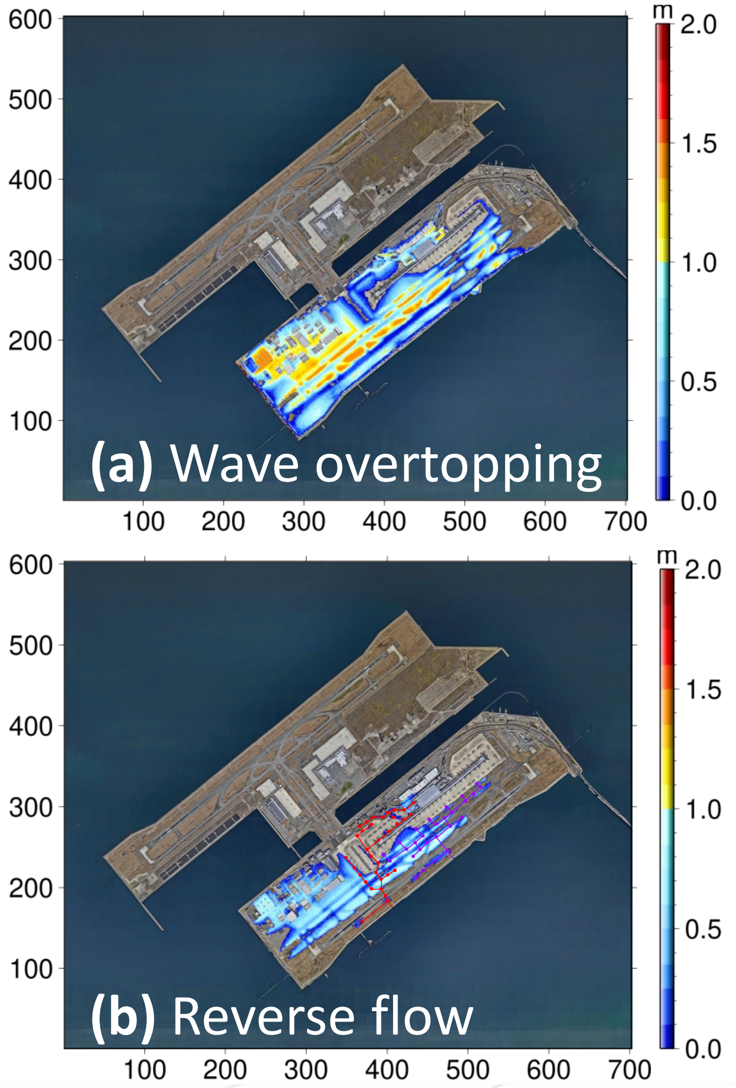
Reverse flow through manholes depending on the installation of flap gates



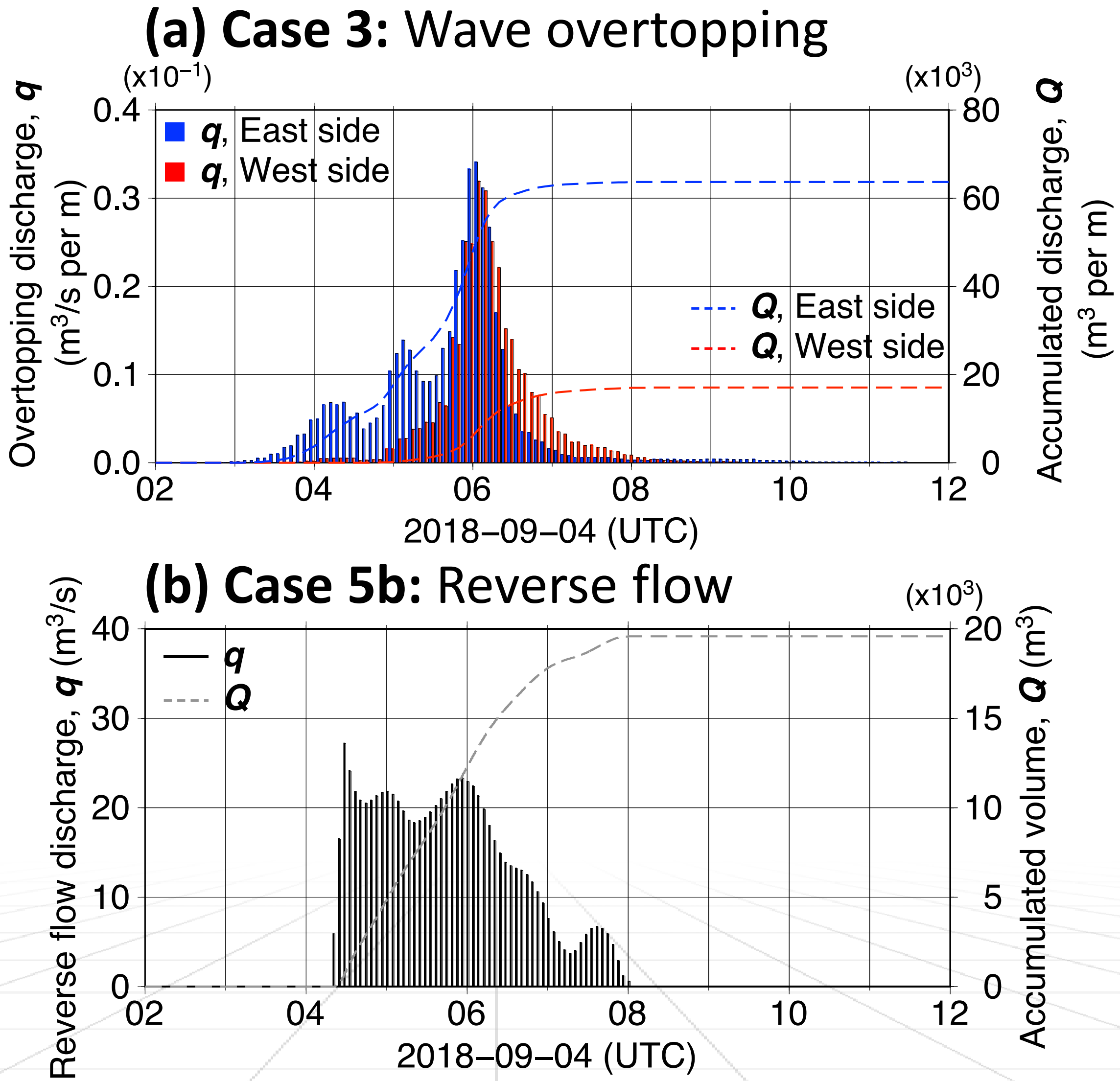
< Time series of flood discharge through manholes >

- **Case 5a:** Flap gates prevent seawater backflow, allowing only rainfall-induced reverse flow.
- **Case 5b:** Rising sea levels result in seawater backflow through the sewer system.
- **Rainfall-induced flood (Case 5a)** : 2.6×10^3 m^3
- **Seawater-induced flood** : 17.0×10^3 m^3
- **Both-induced flood (Case 5b)** : 19.6×10^3 m^3

Flood discharge by individual factor (wave overtopping and reverse flow)



< Peak flood depth >



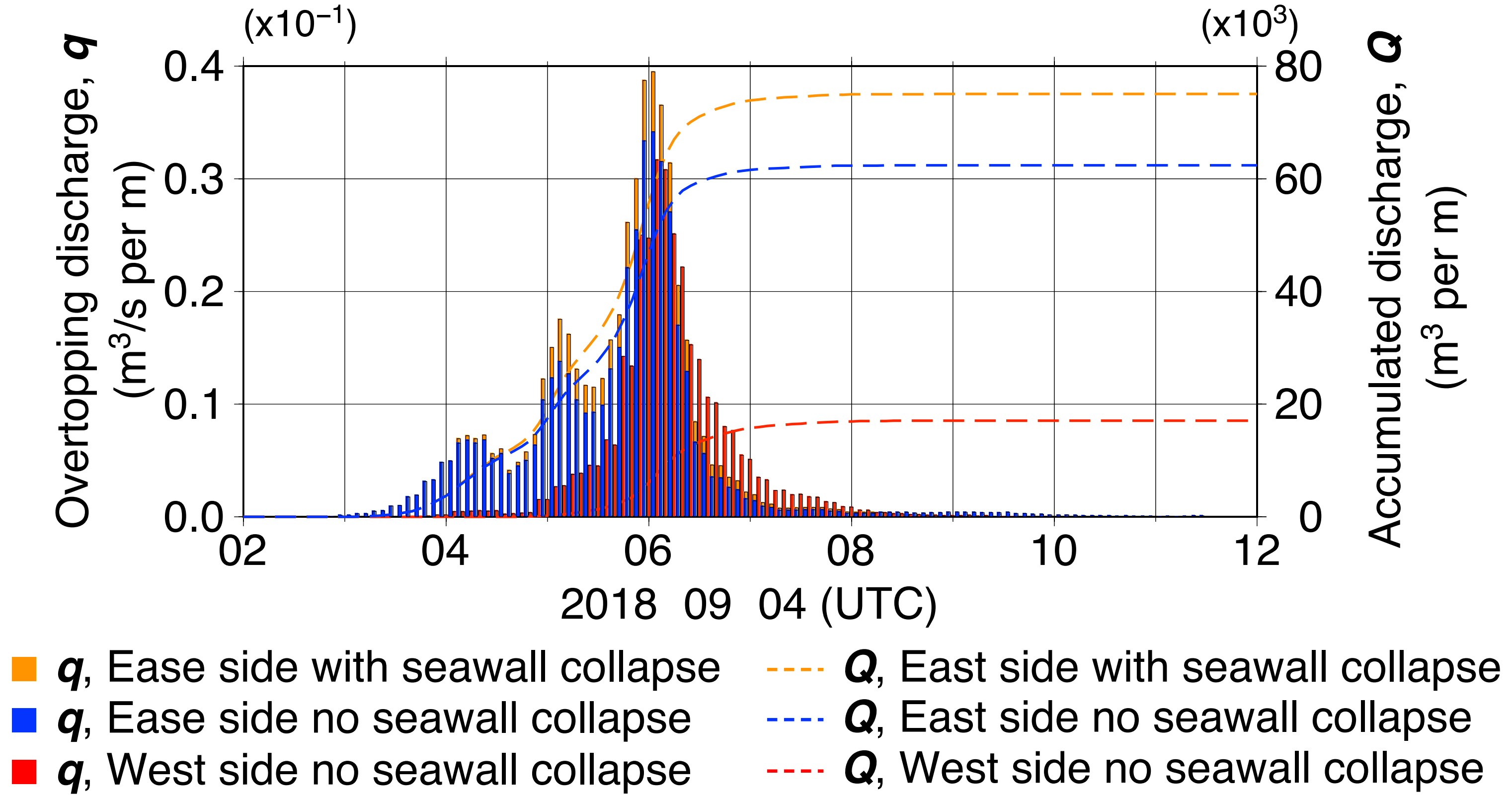
< Time series of flood discharge >

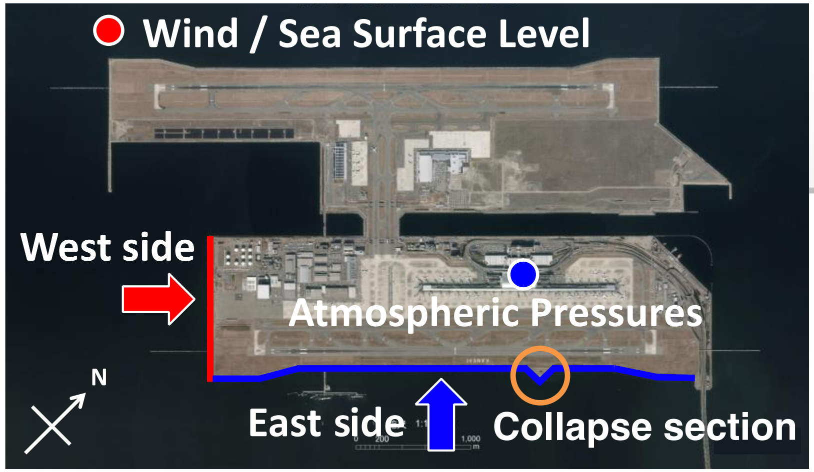
- **Flood duration**
  - wave overtopping
    - 03:00 – 10:00
  - reverse flow
    - 04:20 – 08:00
- **Peak discharge**
  - wave overtopping
    - 06:00
  - reverse flow
    - 04:30
- **Flood timing** might be **faster** by **the flood factor.**

- **Results:**
  partial compound flood
- **Cases 6 and 7**

- **Results:**
  partial compound flood

Flood discharge by failure & Overtopping (Case 6)

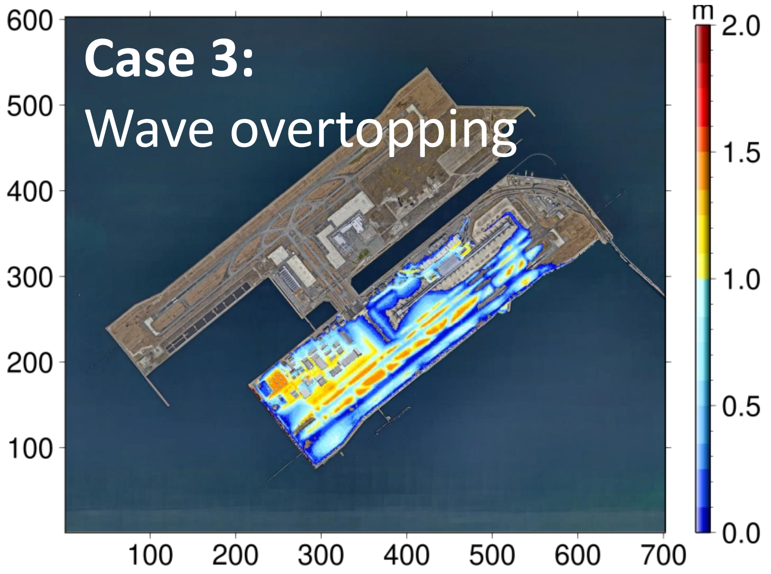


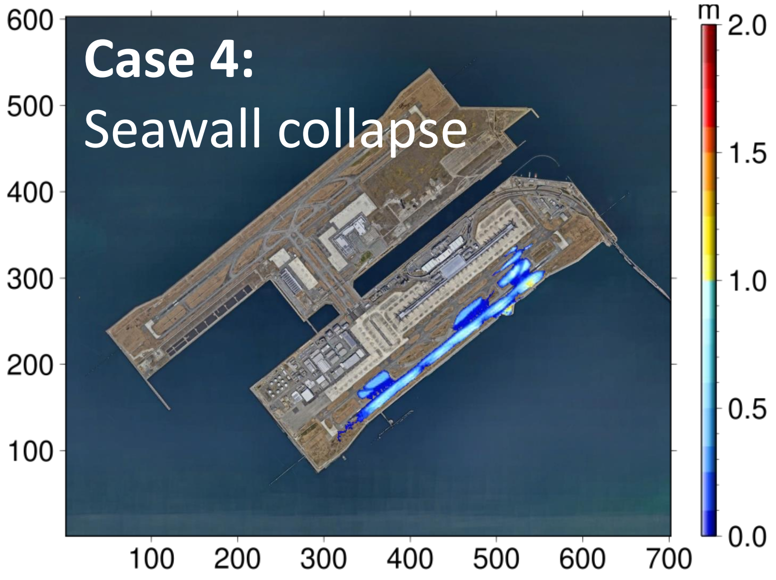


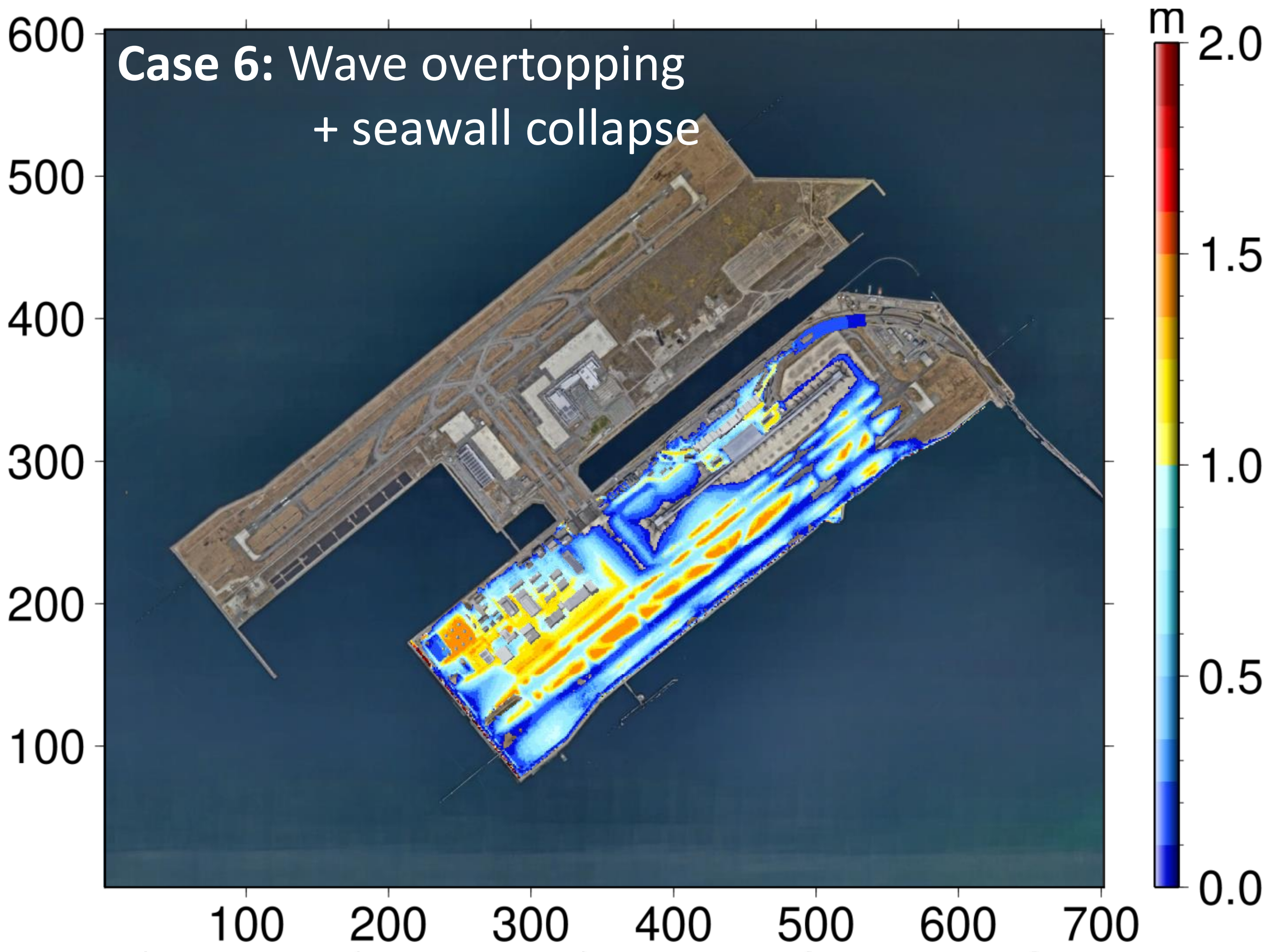
- **Seawall collapse** occurred at the Ease side.
- **In Case 6,** the flood discharge was calculated taking into account **the seawall collapse.**

- **Peak discharge** has increased by 15.66%.
  - ■ (orange) ***q*** : 0.39×10^{-1} m³/s per m
  - ■ (blue) ***q*** : 0.34×10^{-1} m³/s per m
  - ■ (red) ***q*** : 0.31×10^{-1} m³/s per m
- **Accumulated discharge** has increased by 20.29%.
  - ---- (orange) ***Q*** : 75.05×10^{3} m³ per m
  - ---- (blue) ***Q*** : 62.39×10^{3} m³ per m
  - ---- (red) ***Q*** : 17.05×10^{3} m³ per m

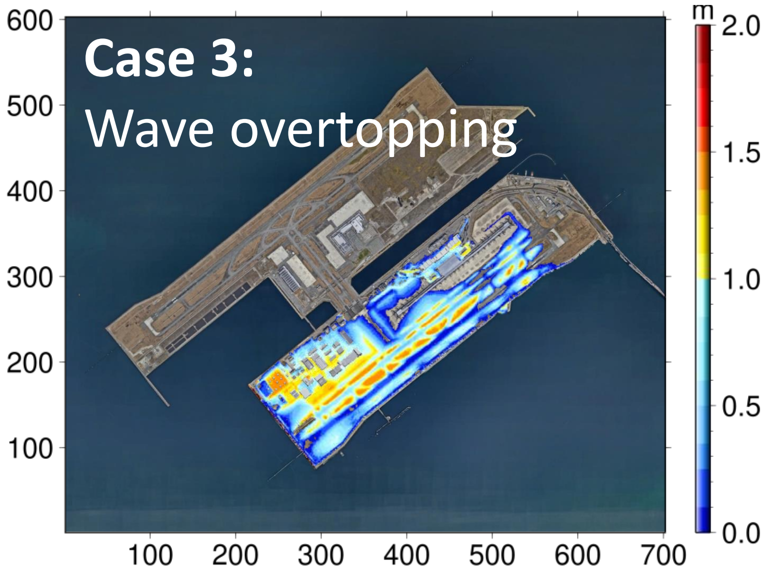
Flood discharge by failure & Overtopping (Case 6)

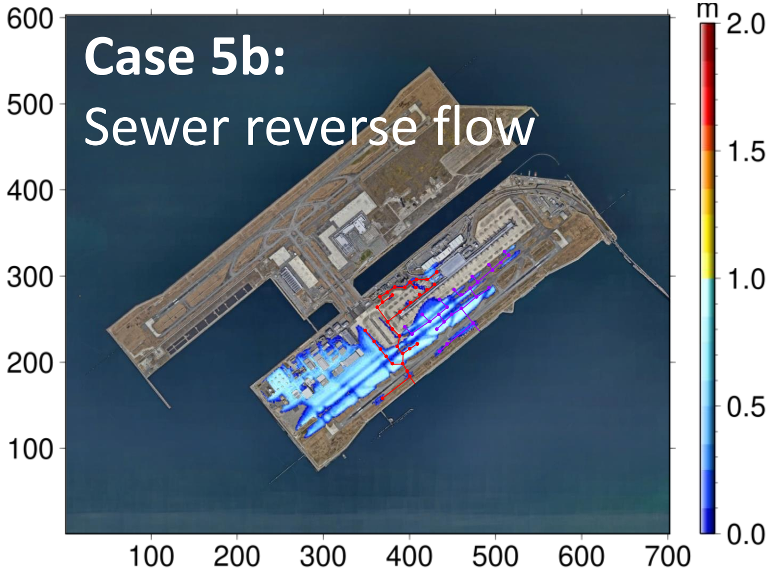


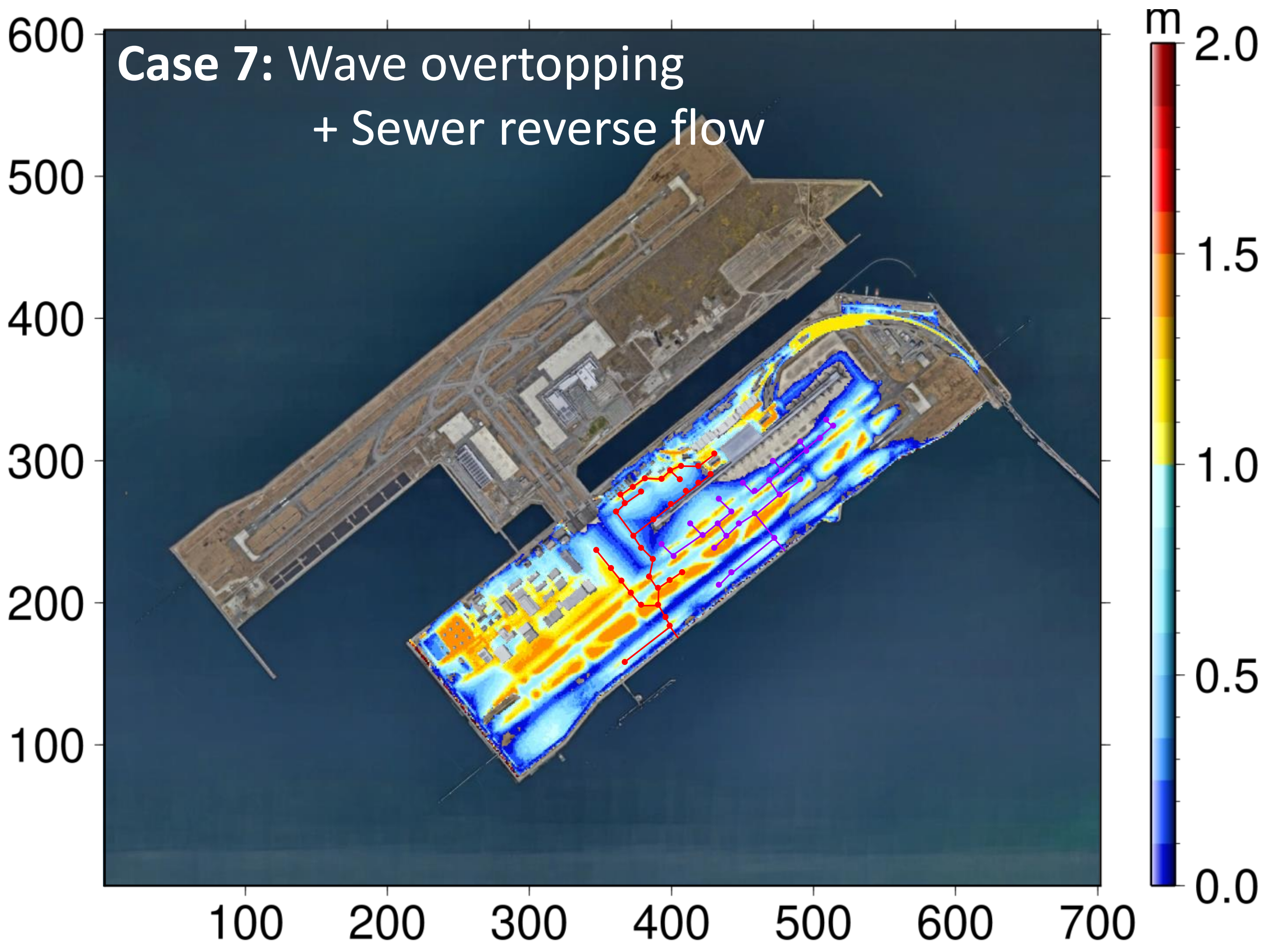




Flood discharge by Flood discharge by Reverse flow & Overtopping (Case 7)

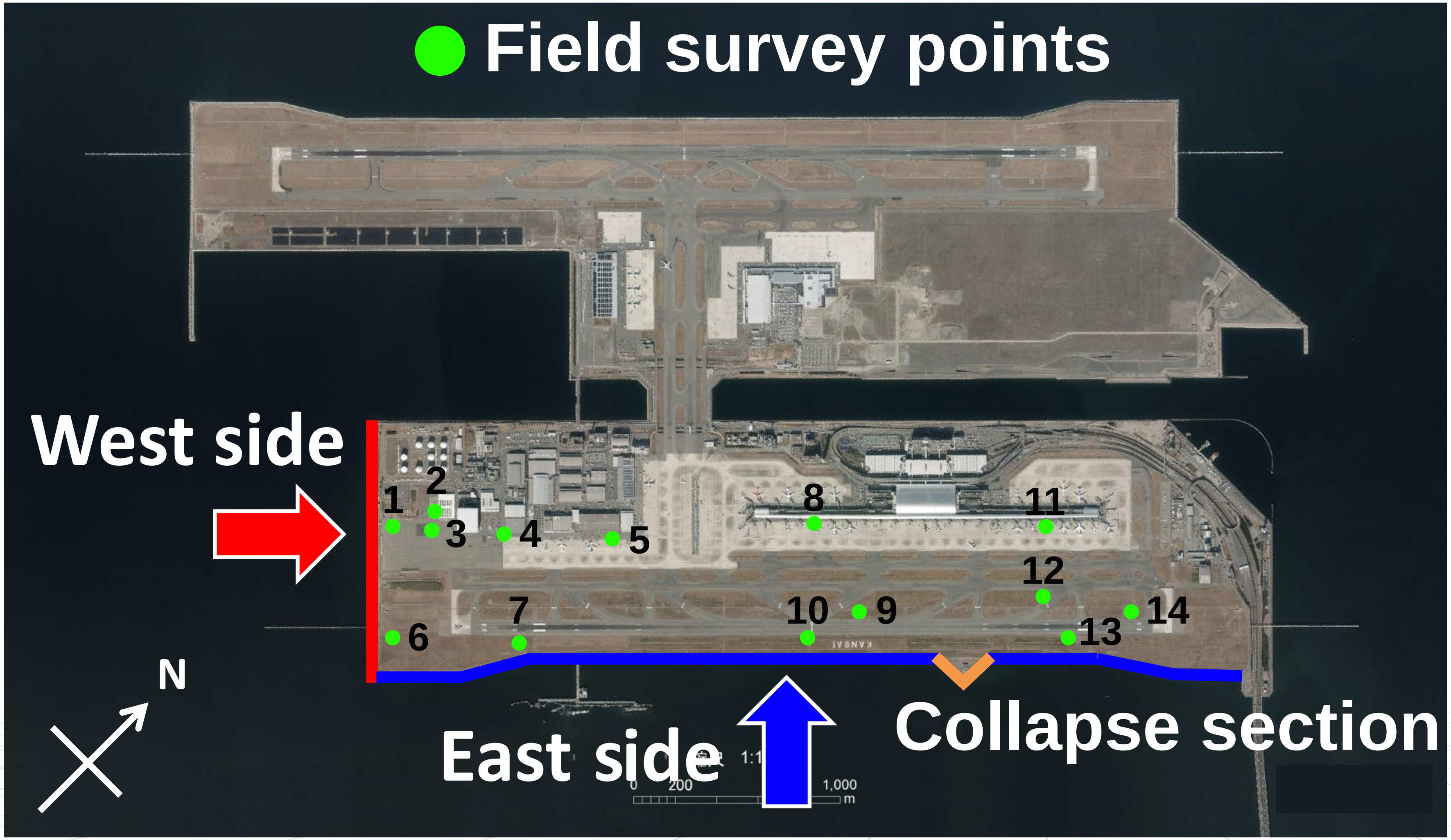




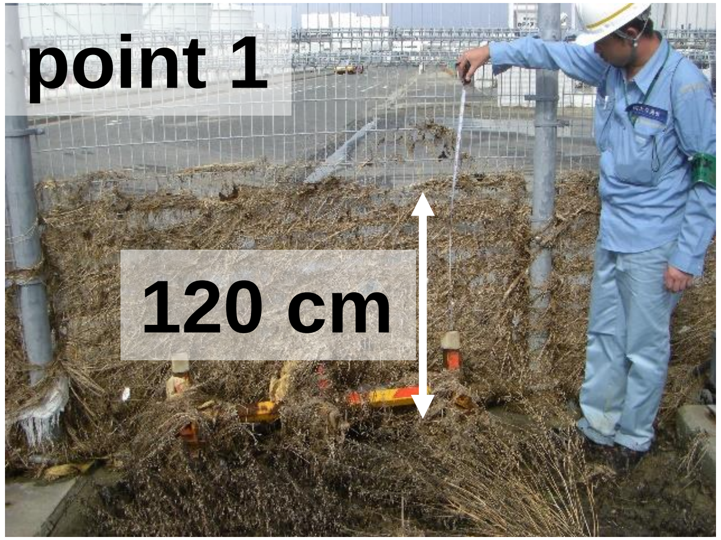


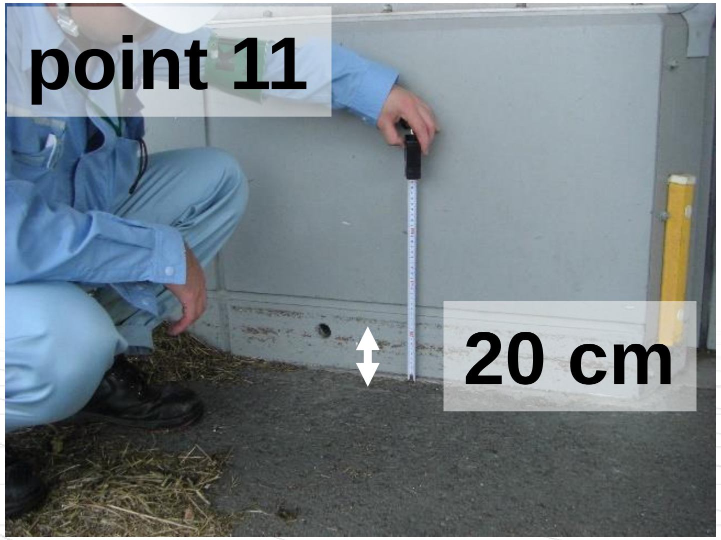
- Comparisons to survey

Comparison of peak flood depth with field survey



< Location of field survey points (total 14 points) >

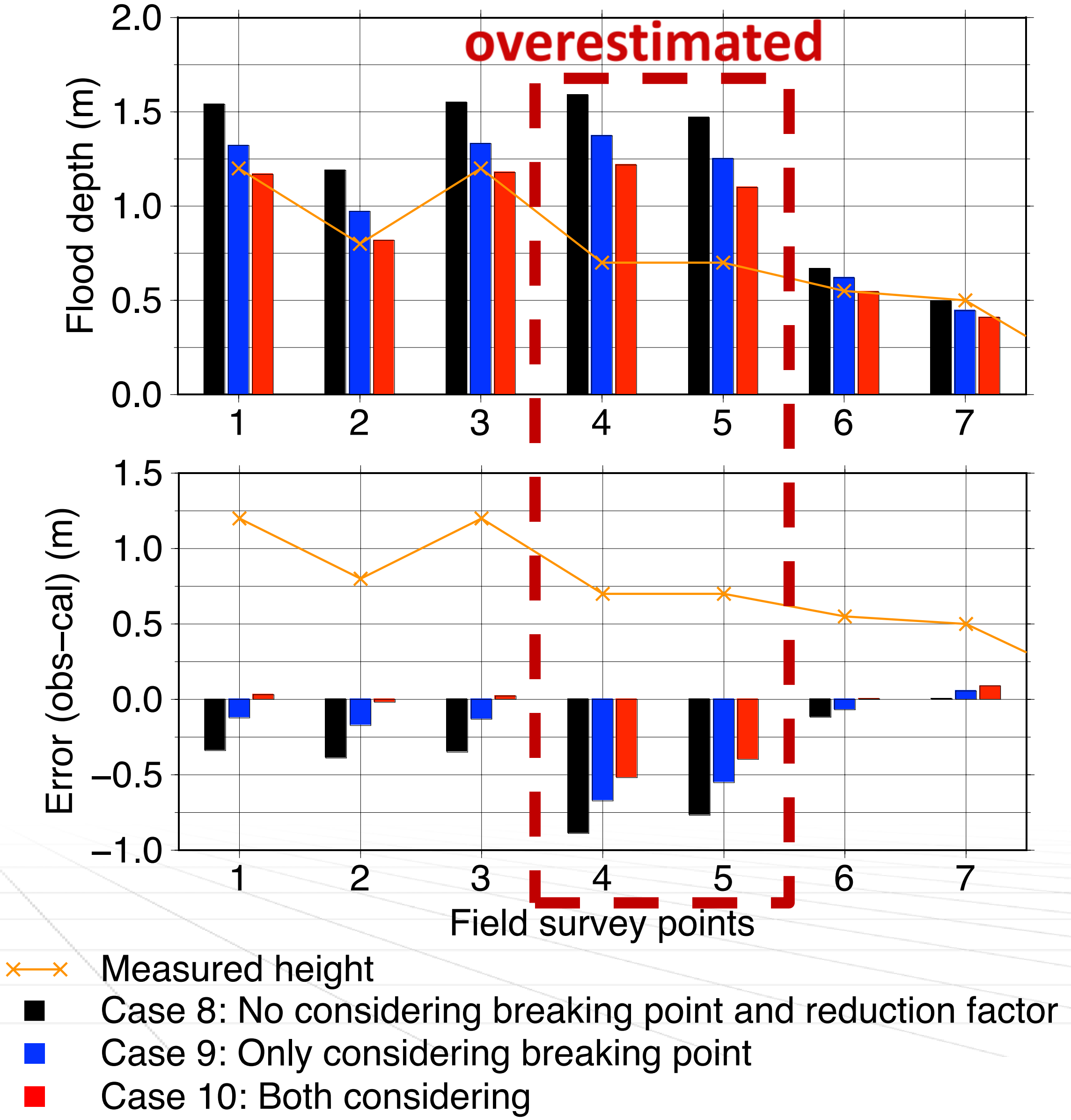




< Field survey overview >

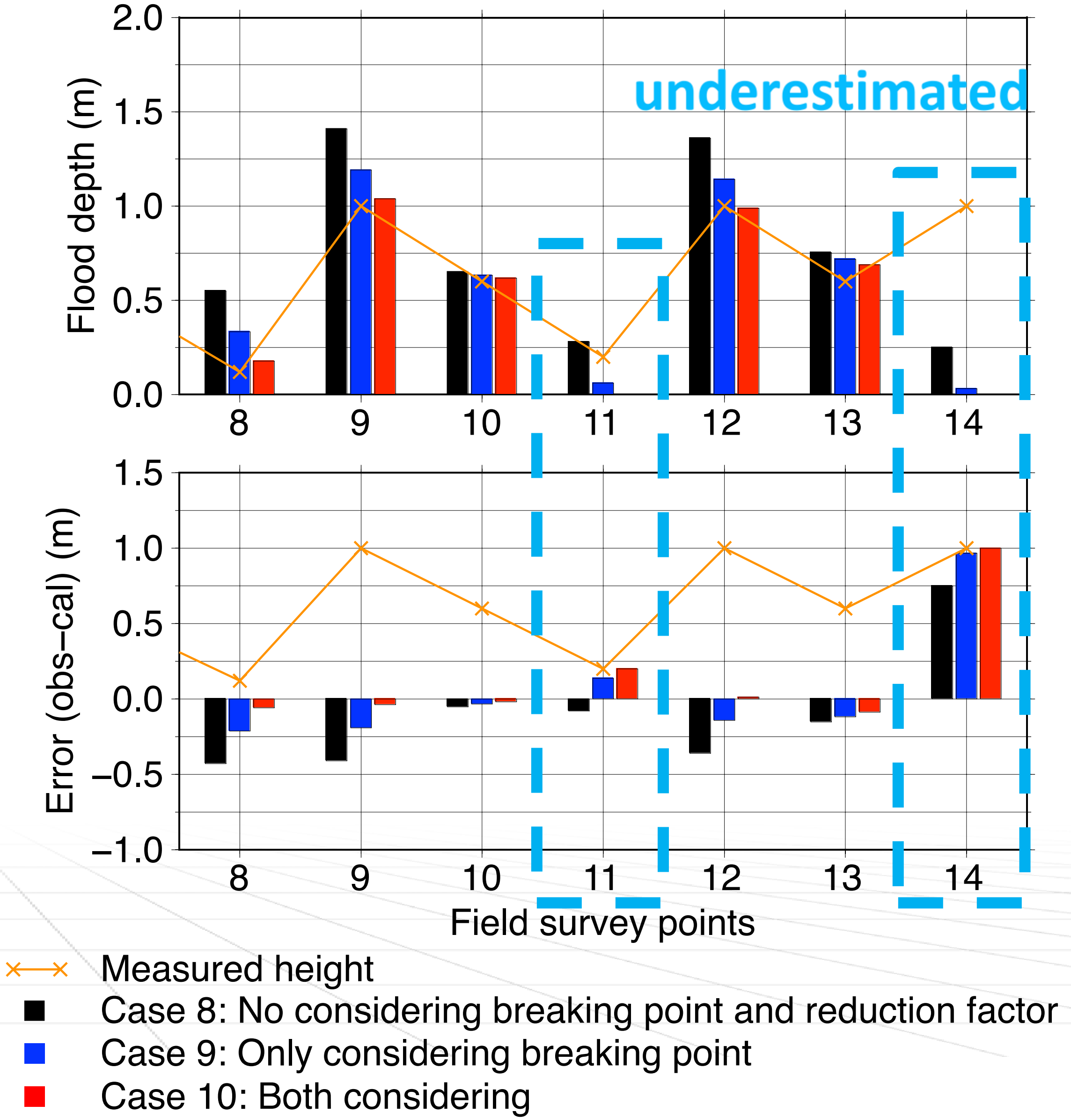
Comparison of peak flood depth by full compound flood (cases 8 to 10)

< Field survey points 1-7 >

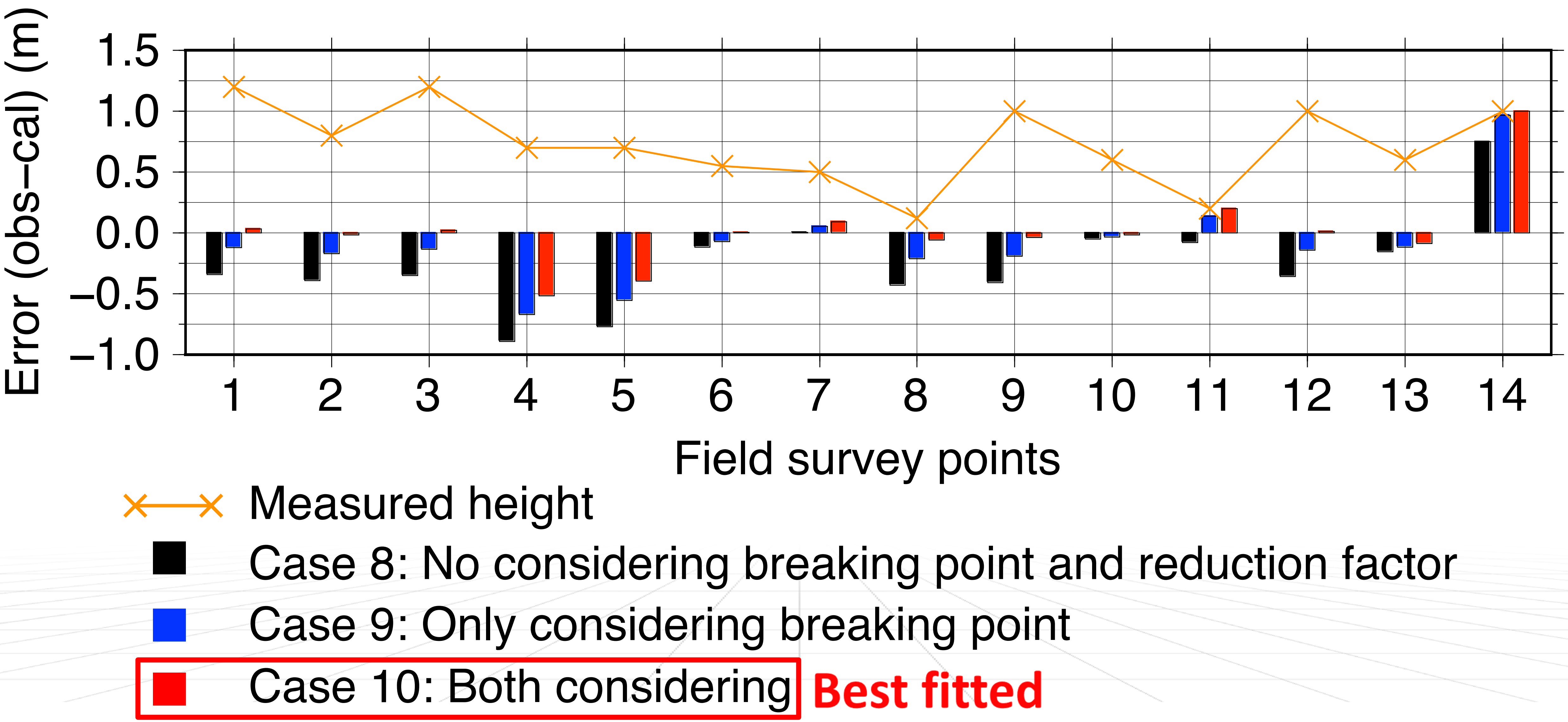


Comparison of peak flood depth by full compound flood (cases 8 to 10)

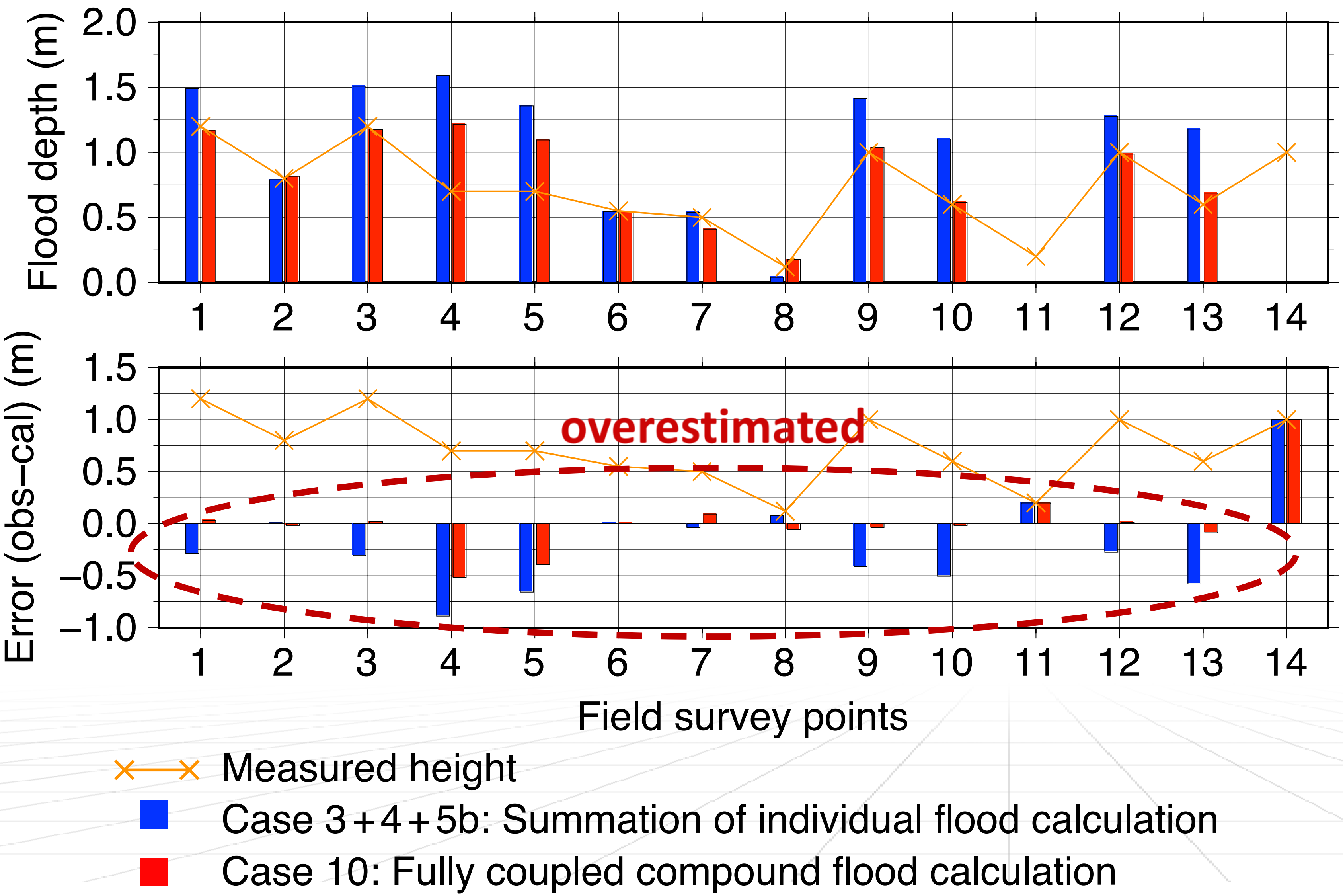
< Field survey points 8-14 >



Comparison of peak flood depth by full compound flood (cases 8 to 10)



Comparison of peak flood depth by individual VS compound flood



- **Summation of individual flood calculation cases:**
  Case 3 (wave overtopping)
  +
  Case 4 (seawall collapse)
  +
  Case 5b (sewer reverse flow)

- **Fully coupled compound flood calculation case:**
  Case 10

- **Simple summation of ■ overestimated flood depth.**