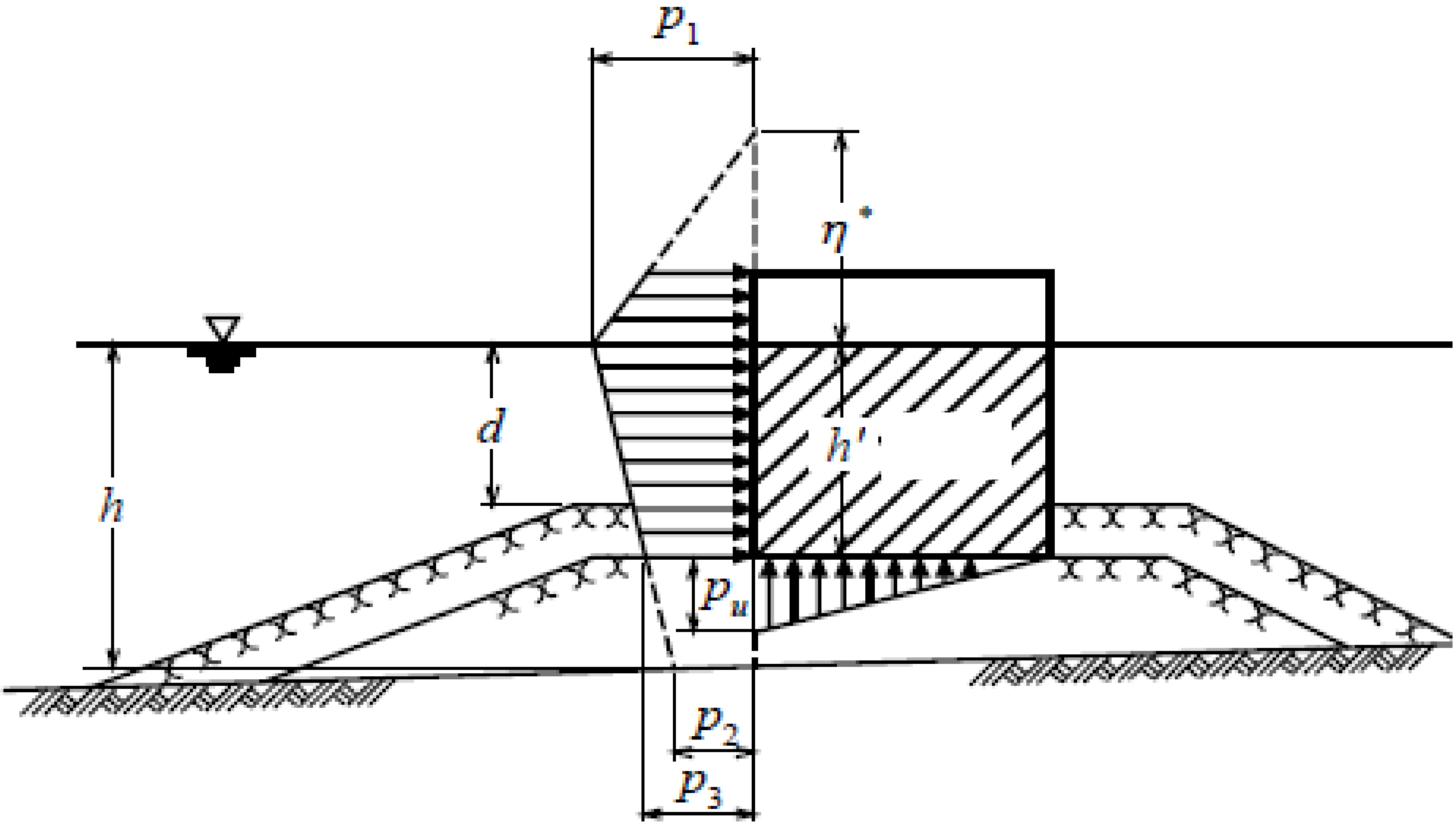
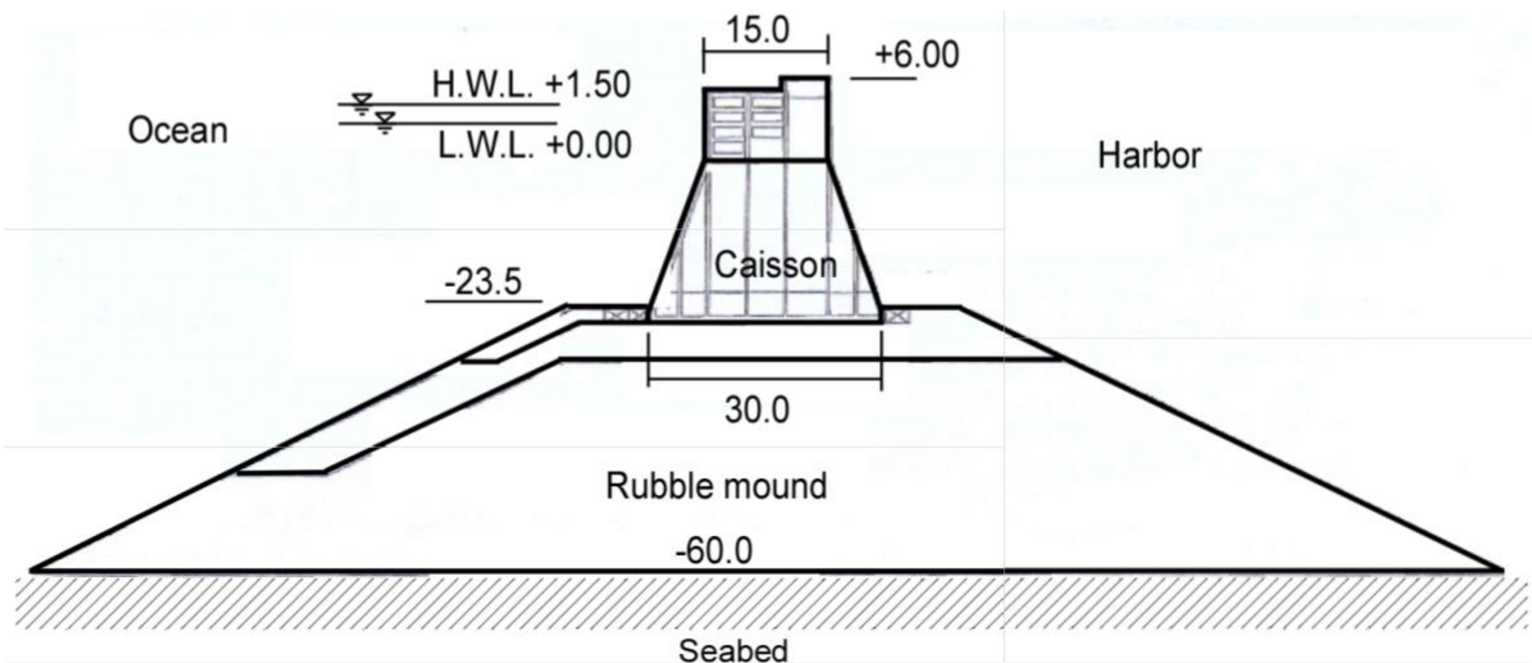
Combined Failure Mechanism of a Breakwater subject to Tsunami during 2011 East Japan Earthquake

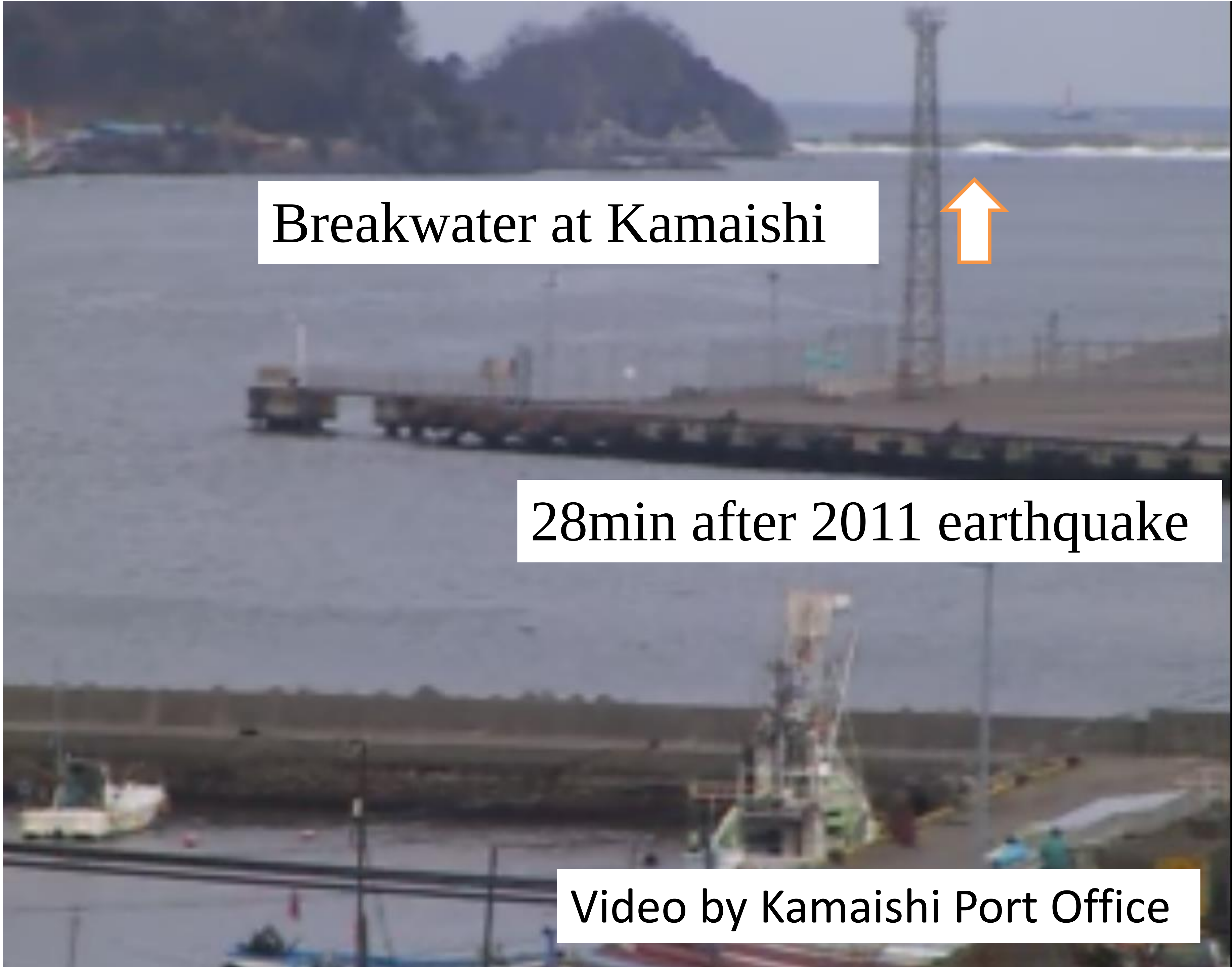
Susumu Iai
Kyoto University

Existing Design Procedure of a Breakwater



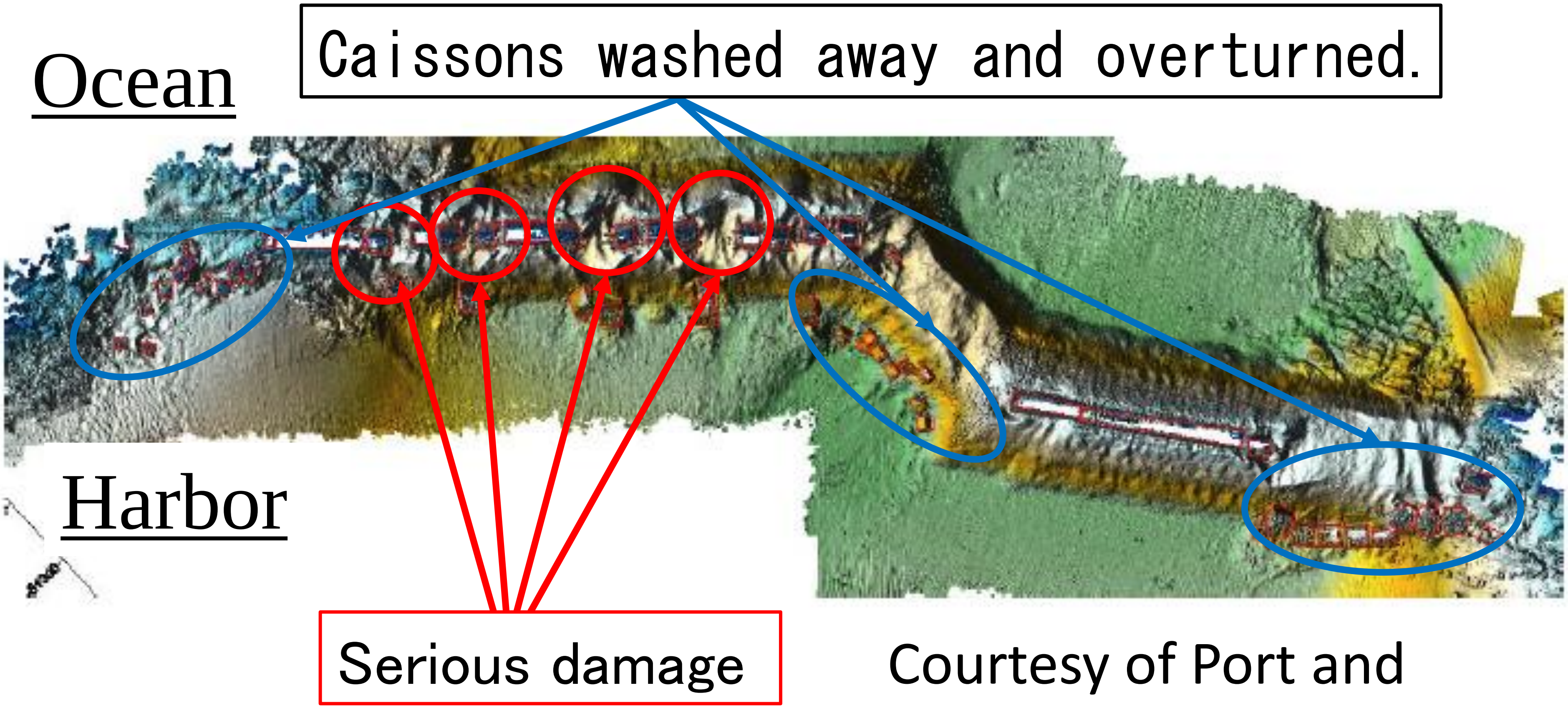
Breakwaters at Kamaishi Harbor




Breakwater at Kamaishi
28min after 2011 earthquake
Video by Kamaishi Port Office

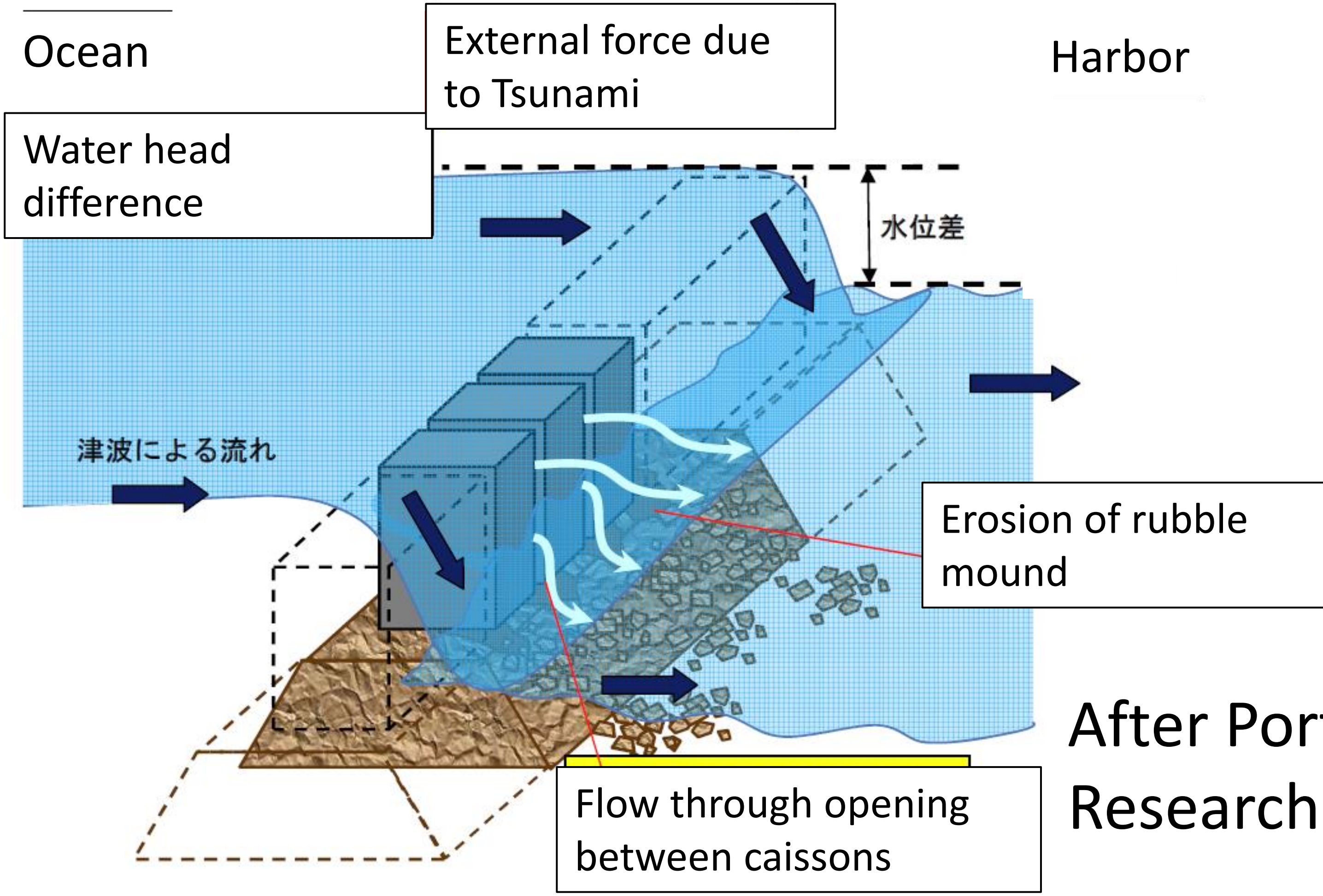

Breakwater at Kamaishi
48min after 2011 earthquake
Video by Kamaishi Port Office

Damage to Breakwaters at Kamaishi Port



Courtesy of Port and Airport Research Institute

Objective

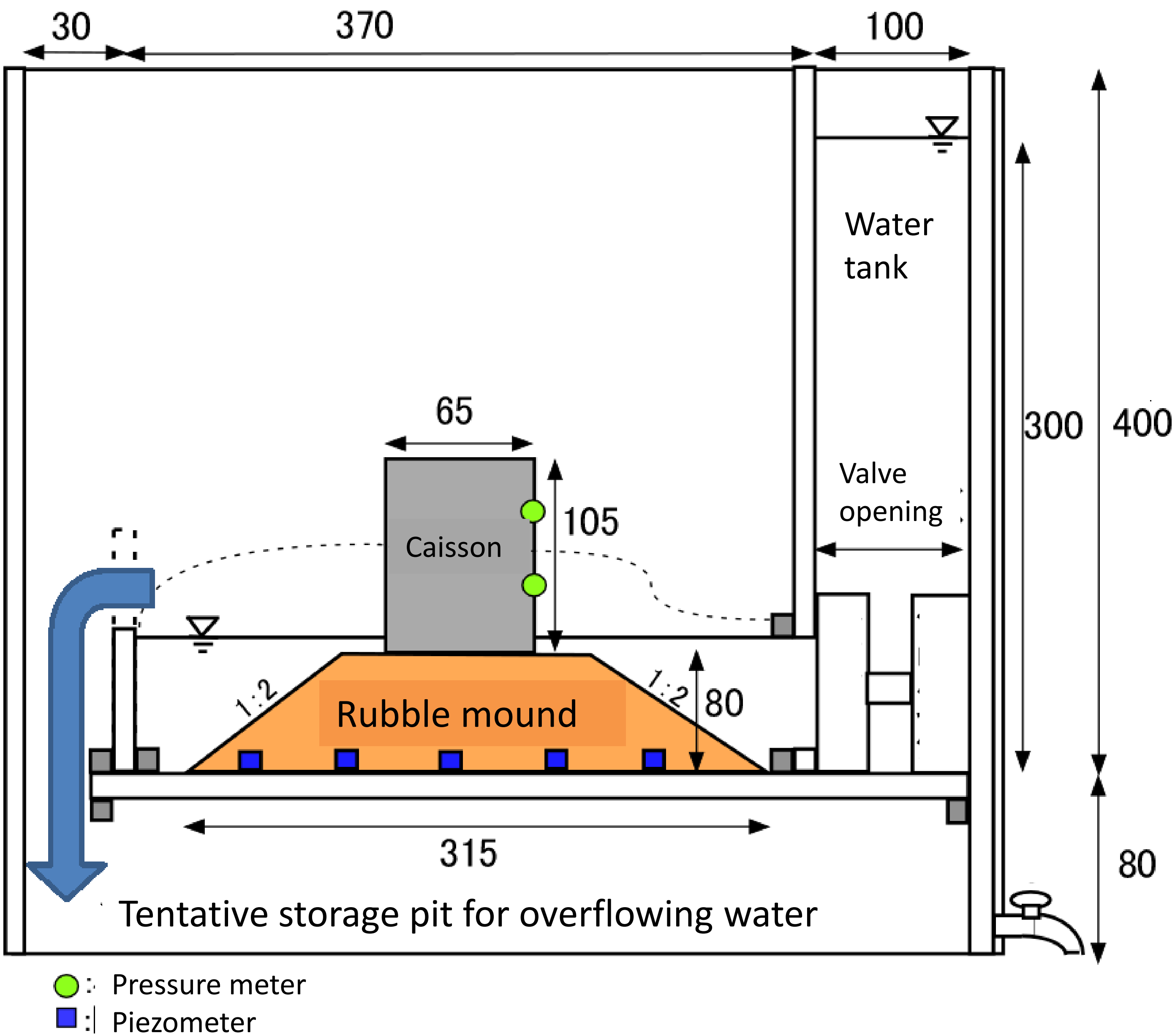


After Port and Airport Research Institute

Combined effects of
water flow in the rubble mound and
Tsunami wave force

Centrifuge model tests

Container for centrifuge model tests

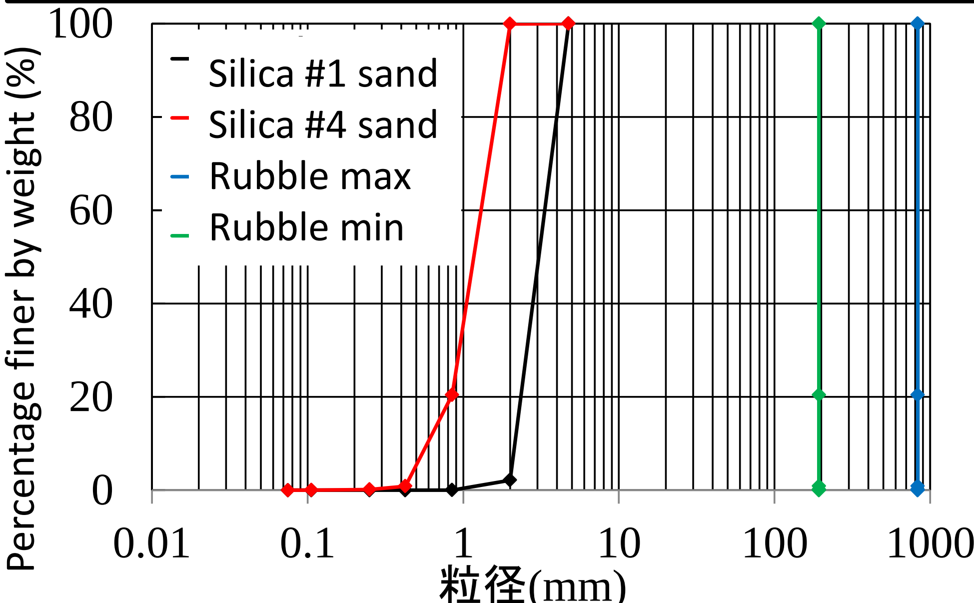


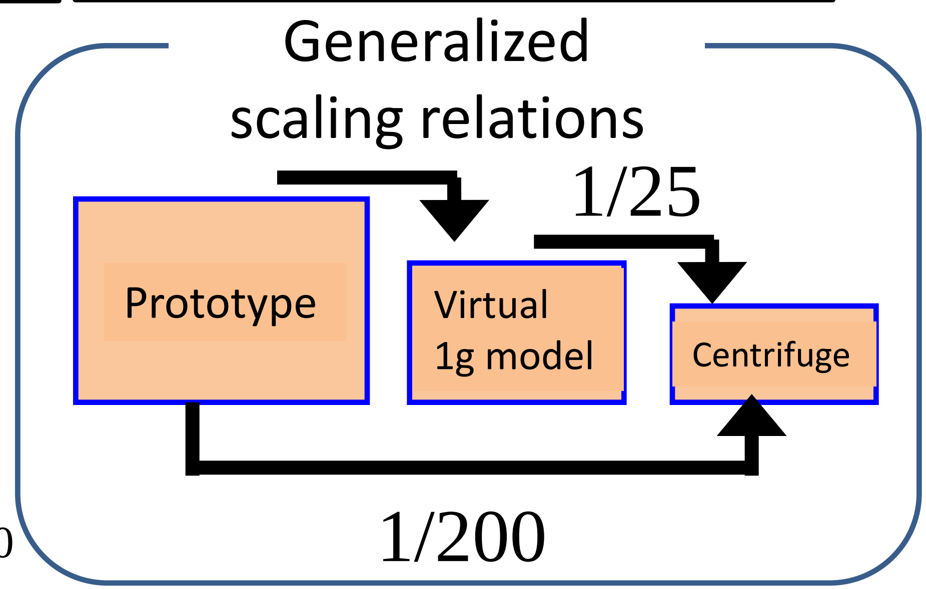
Model test cases

Case	Mound	Relative density	Sea water level	Water level difference
Case 1	Silica #1 sand	55.5%	6.23m	14.4m
Case 2	Silica #1 sand	60.3%	12.6m	10.3m
Case 3	Silica #4 sand	58.0%	8.15m	15.2m
Case 4	Silica #4 sand	65.8%	13.0m	10.9m

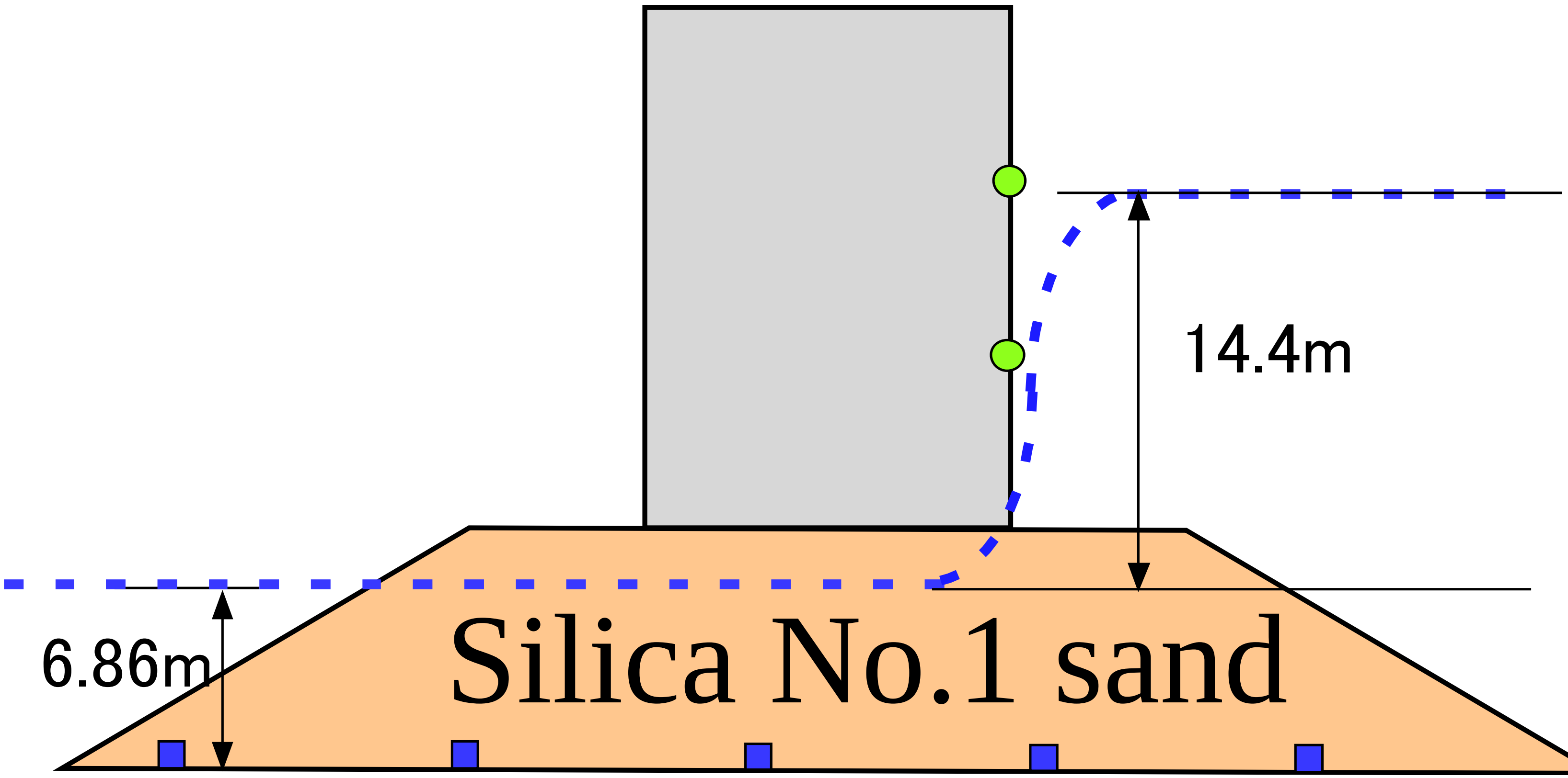
Use smaller particle size to scale permeability of mound

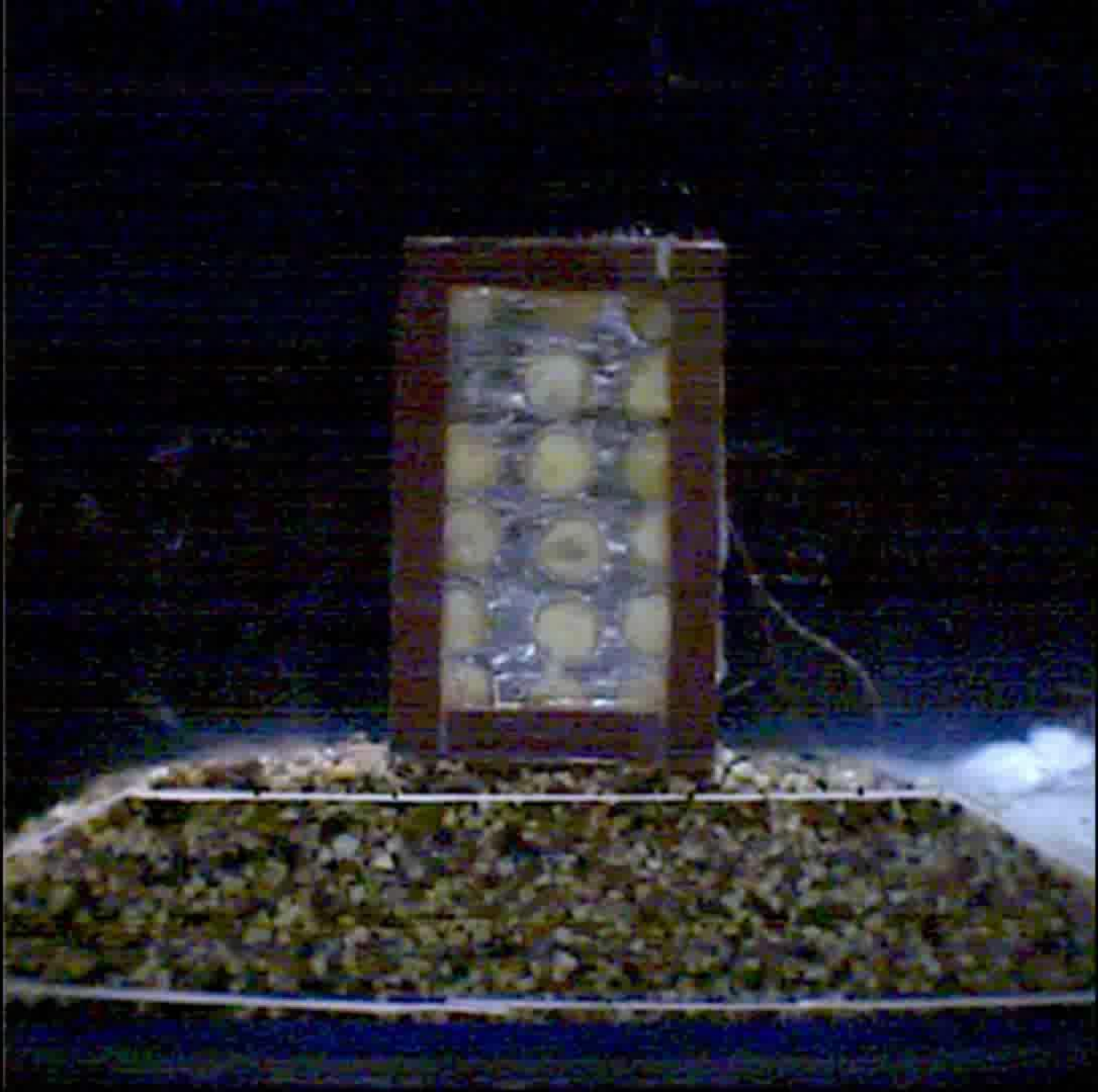
Parameter study on the effect of sea water level



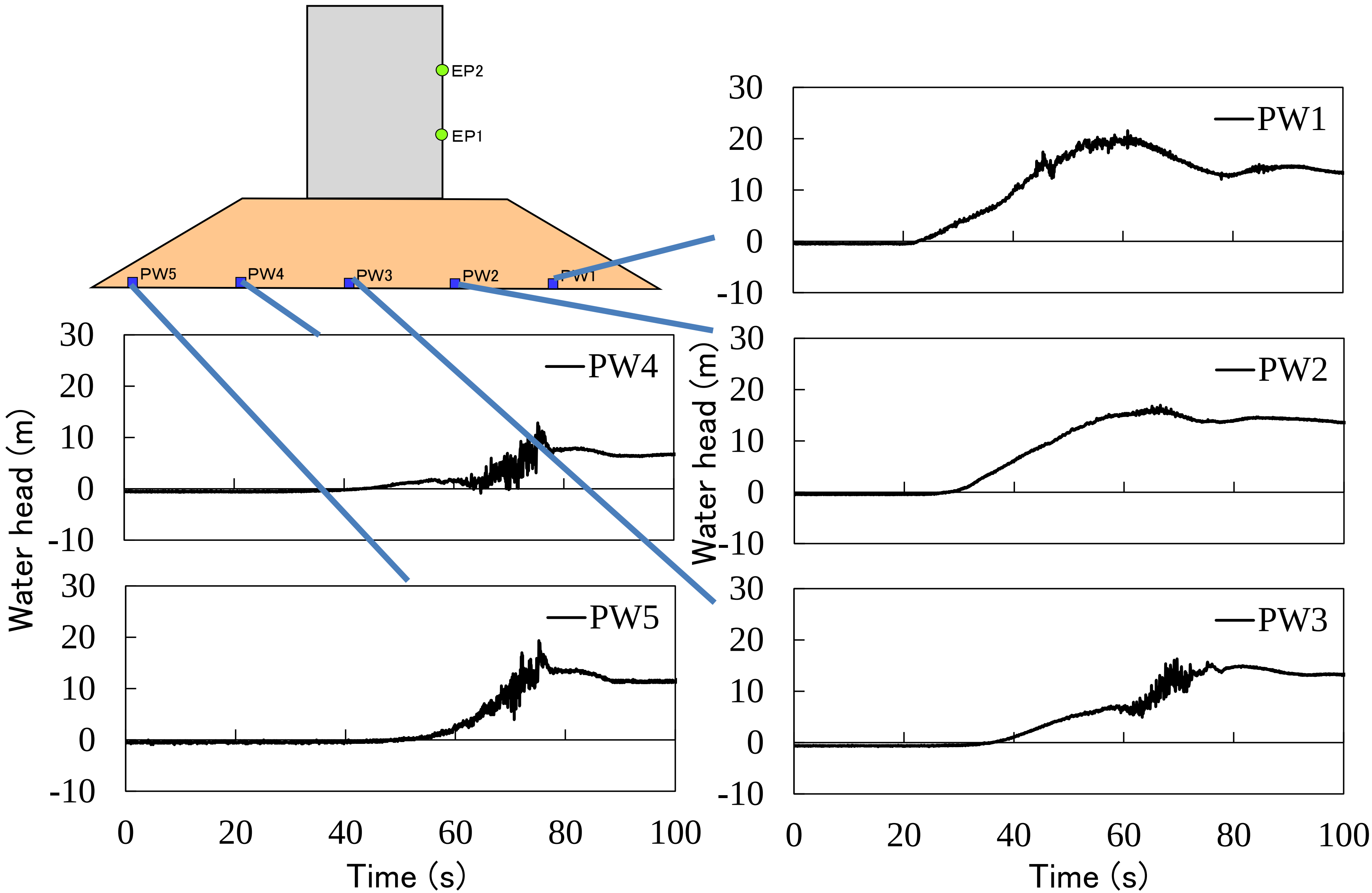


Case 1

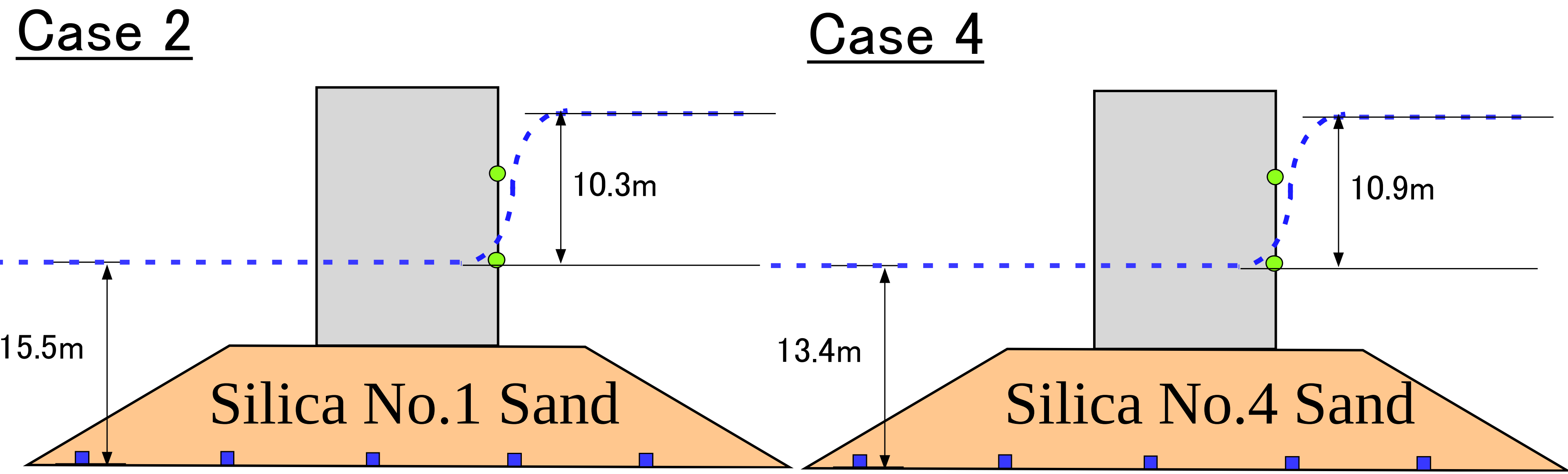




Water head in the mound(Case 1)



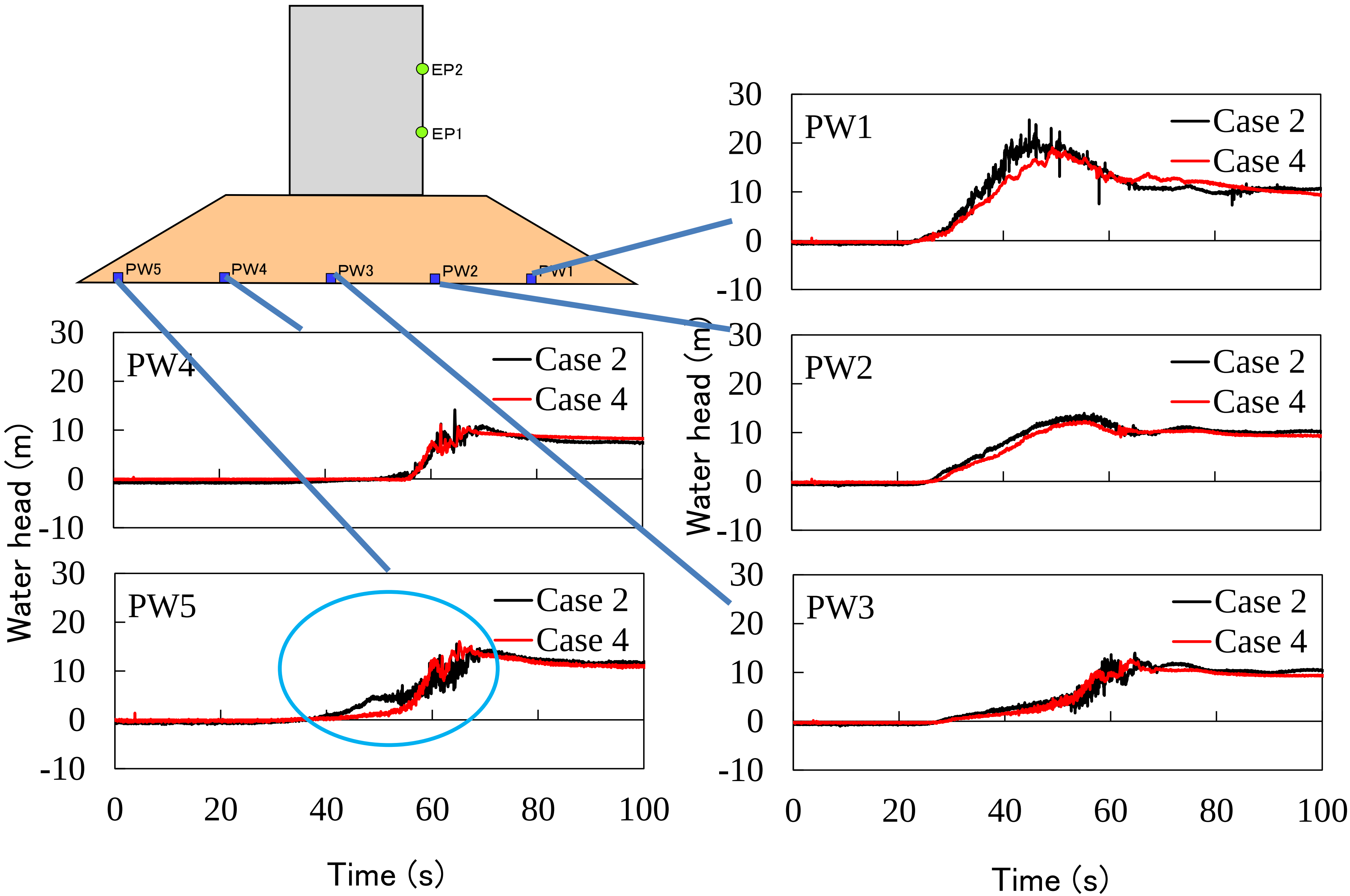
Effects of permeability of the mound (Case 2−Case 4)



Case 2(Silica No.1 Sand)

Case 4(Silica No.4 Sand)

Water head (Case 2-Case 4)

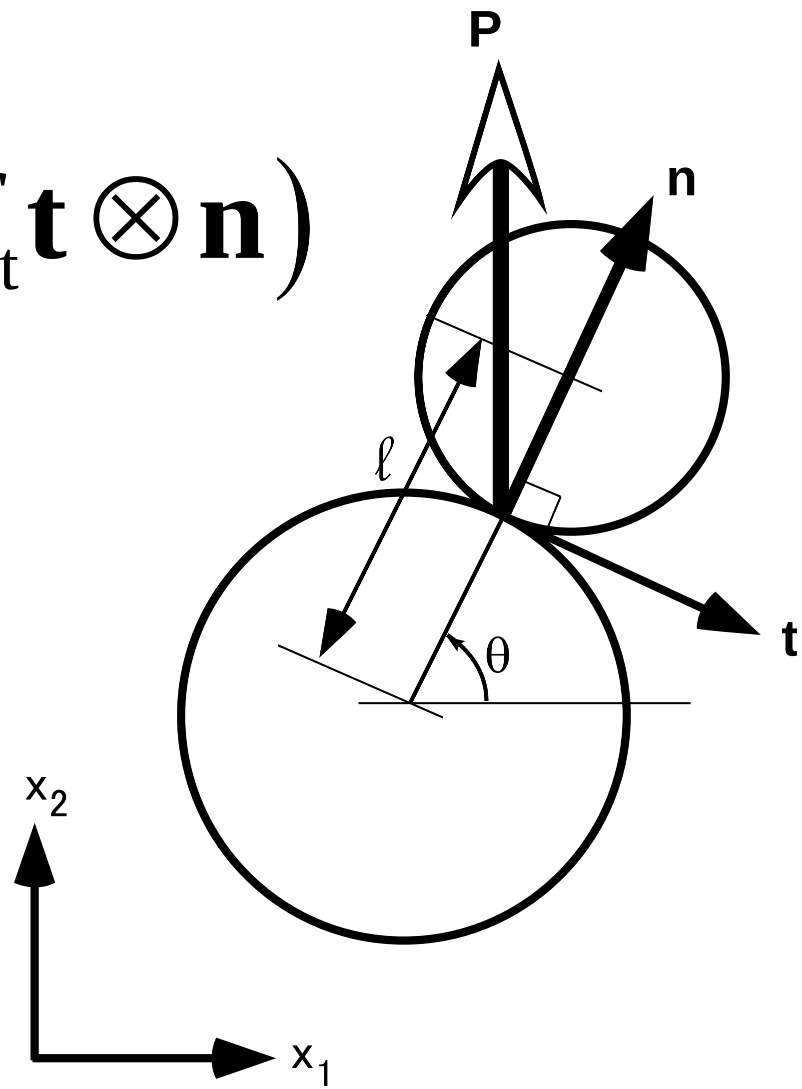


Effective stress analysis

$$\boldsymbol{\sigma}' = \frac{1}{V}\sum l\mathbf{P}\otimes\mathbf{n}$$

$$= \frac{1}{V}\sum l\left(f_{\mathrm{n}}\mathbf{n}\otimes\mathbf{n} + f_{\mathrm{t}}\mathbf{t}\otimes\mathbf{n}\right)$$

$$\mathbf{P} = f_{\mathrm{n}}\mathbf{n} + f_{\mathrm{t}}\mathbf{t}$$

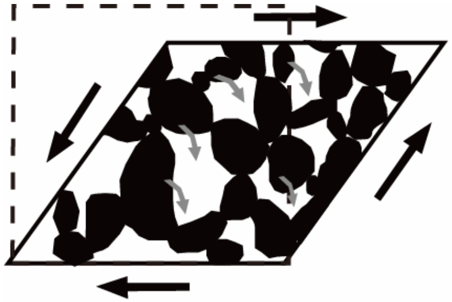


Christoffersen et al (1981)

Strain space multiple mechanism model

$$\boldsymbol{\sigma}' = -p'\mathbf{I} + \int_0^{\pi} q \langle \mathbf{t} \otimes \mathbf{n} \rangle \, \mathrm{d}\omega$$

$$\langle \mathbf{t} \otimes \mathbf{n} \rangle = \begin{bmatrix} \cos\omega & \sin\omega \\ \sin\omega & -\cos\omega \end{bmatrix}$$

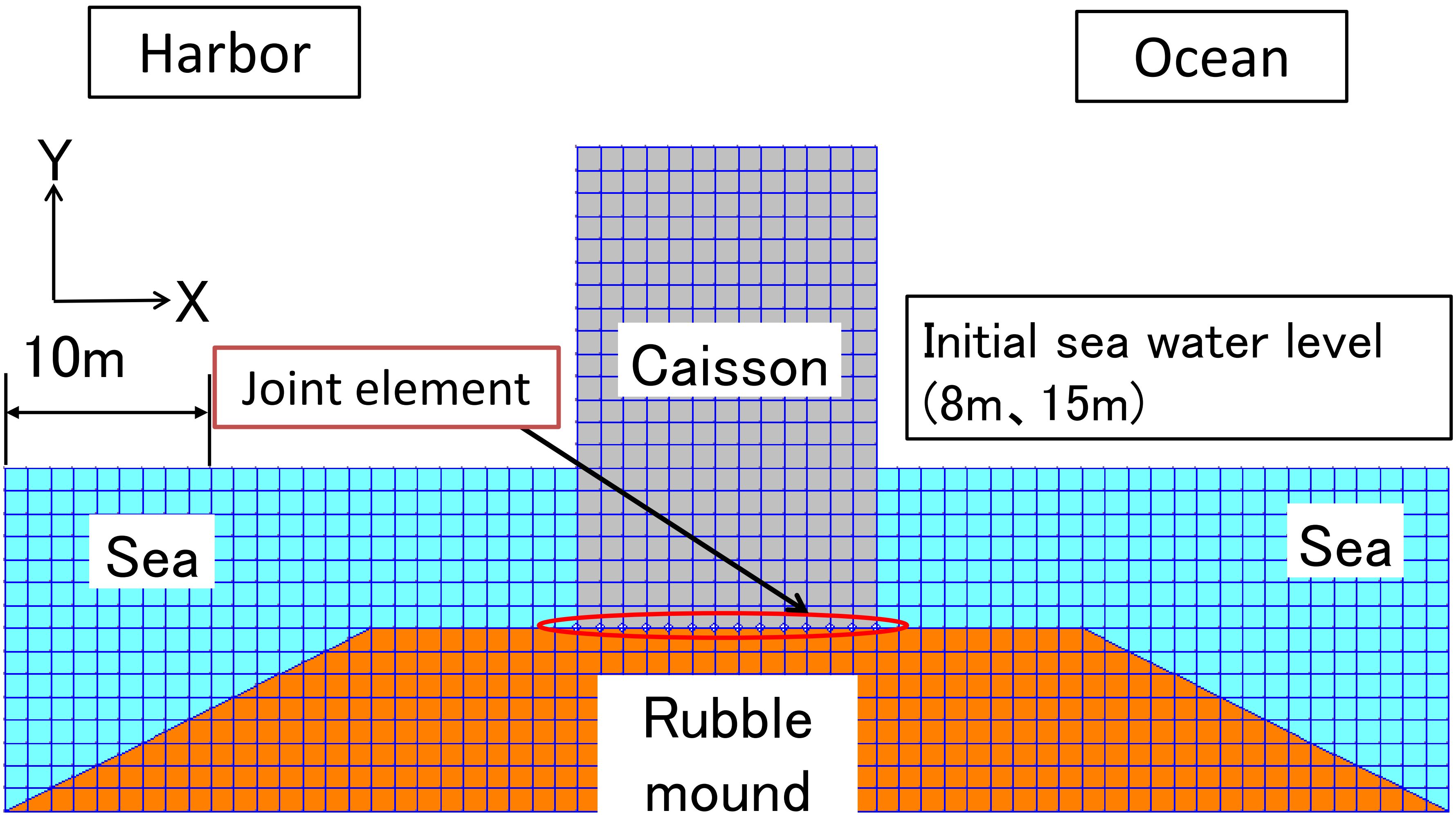


$$\omega = 2\theta$$

$$p = p(\varepsilon') \qquad \varepsilon = \mathbf{I} : \boldsymbol{\varepsilon} \qquad \varepsilon' = \varepsilon - \varepsilon_{\mathrm{d}}$$

$$q = q(\gamma) \qquad \gamma(\omega) = \langle \mathbf{t} \otimes \mathbf{n} \rangle : \boldsymbol{\varepsilon}$$

Finite element mesh for analysis



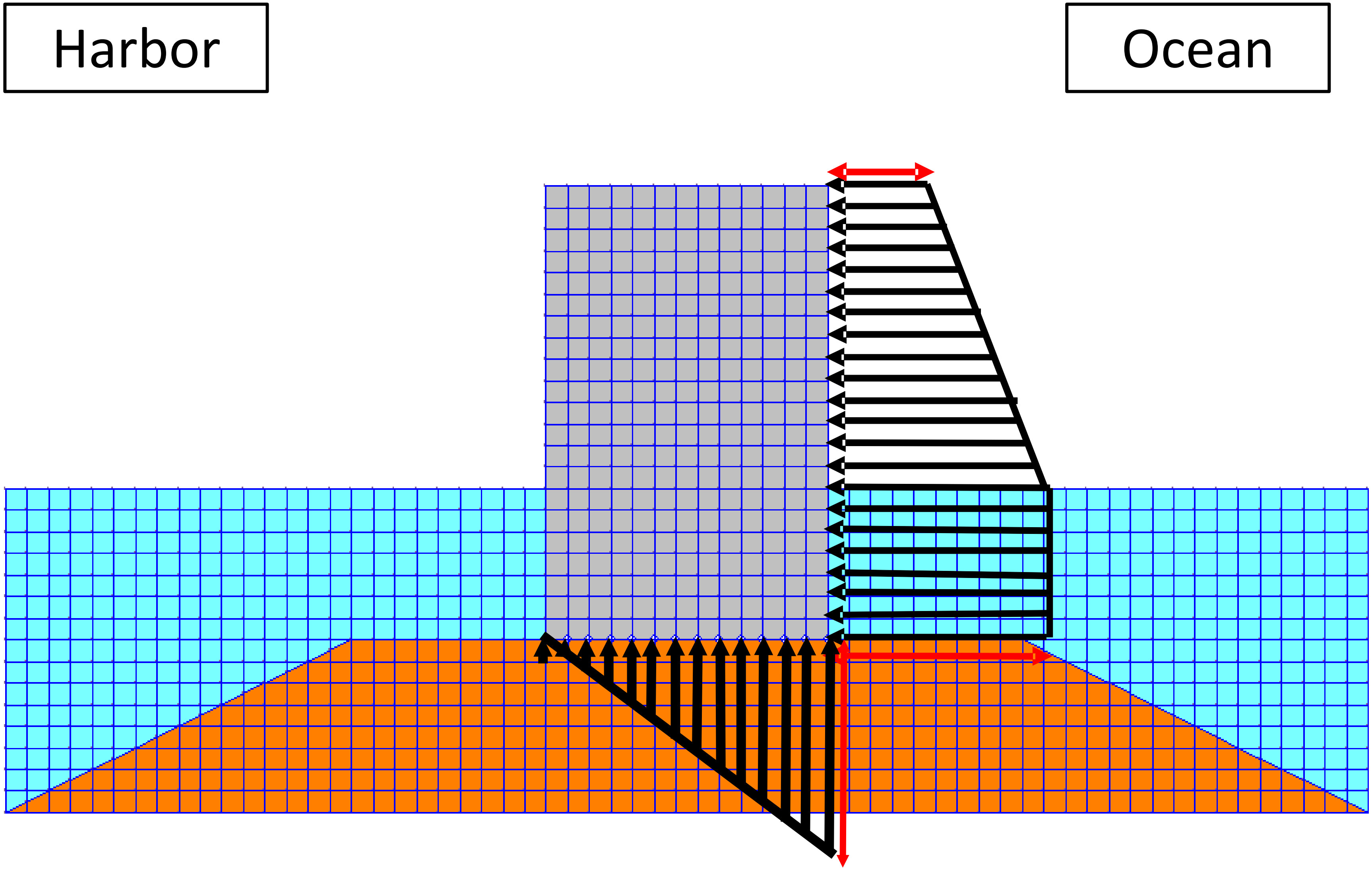
Analysis cases

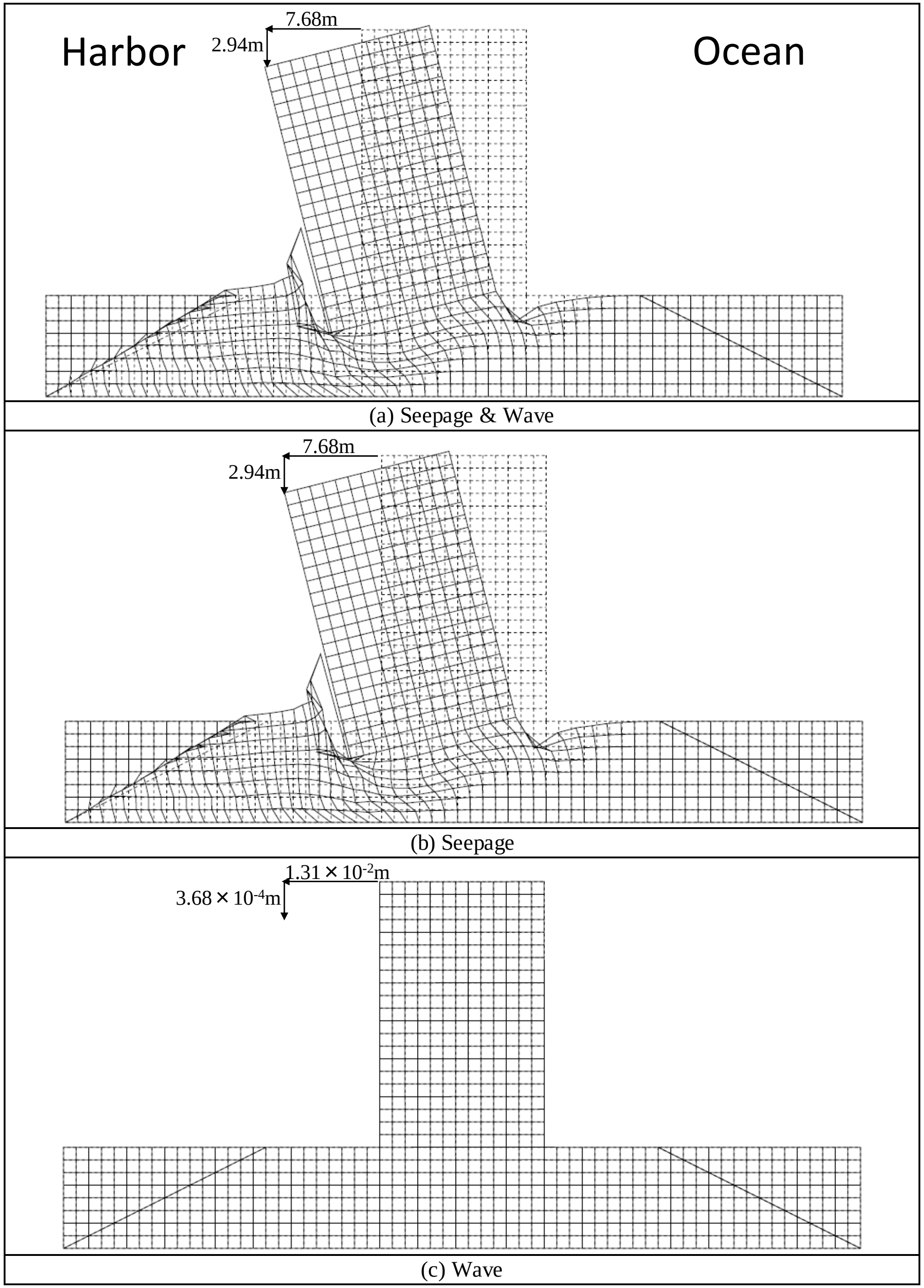
Case	mound	Sea water level	Water level difference
Case 1	Silica #1 sand	8m	15m
Case 2	Silica #1 sand	15m	11m
Case 3	Silica #4 sand	8m	15m
Case 4	Silica #4 sand	15m	11m

Model parameters

mound	density	permeability	shear modulus	ϕf	cohesion
Silica #1	1.91(t/m3)	7.06×10^{-2}(m/s)	6.15×10^{4}(kPa)	40.8°	0(kPa)
Silica #4	1.90(t/m3)	1.56×10^{-3}(m/s)	7.67×10^{4}(kPa)	38.7°	0(kPa)

Tsunami wave force





(a) Seepage & Wave

(b) Seepage

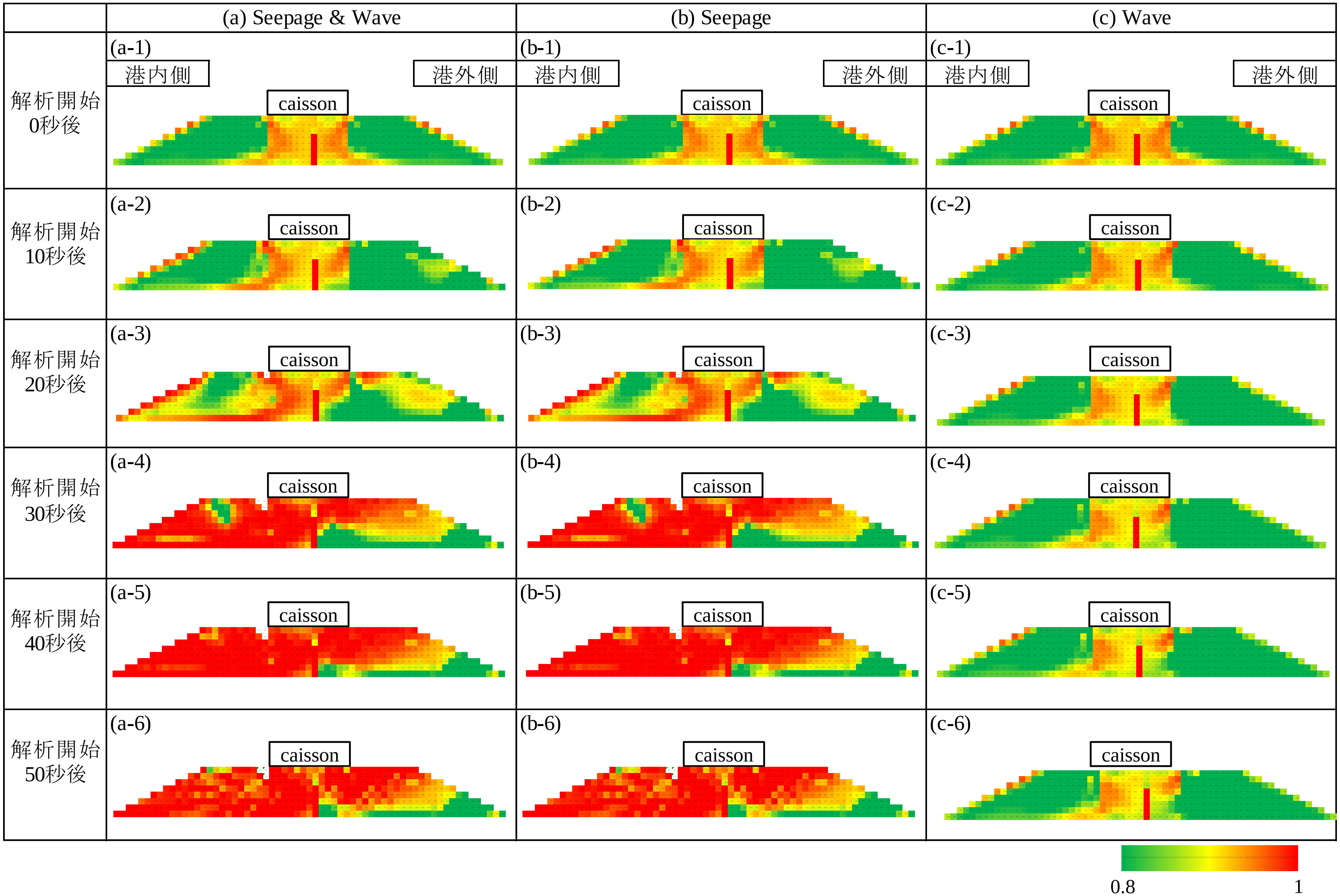
(c) Wave

Seepage & Wave

Seepage

Wave

1/FS (FS=Factor of safety)



Conclusions

- Existing design procedure for a composite breakwater is based on the limit equilibrium of external wave force and resistance against sliding, overturning and bearing capacity failure.
- The centrifuge model tests and effective stress analyses suggests that combined failure mechanism due to seepage flow in the mound and external wave force due to Tsunami should be considered in design.