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# A METHOD FOR EVALUATING THE MAXIMUM TSUNAMI LOADINGS ON SEAWALLS

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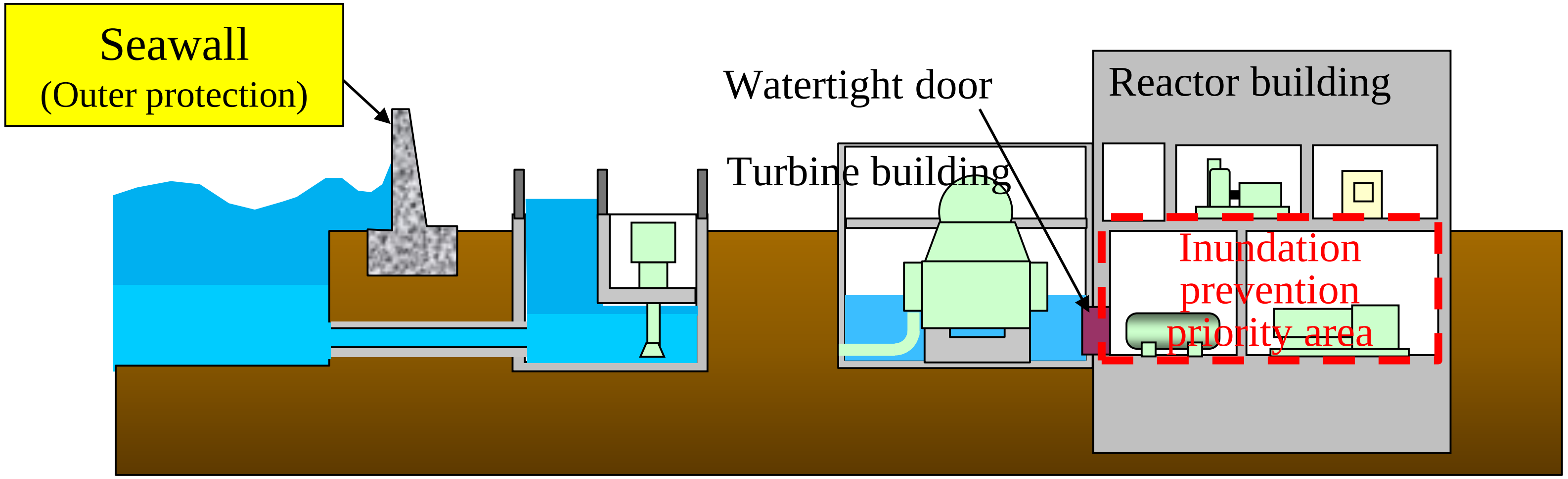
## ■ Requirements for Protection against a Design Basis Tsunami

The regulatory requirements for tsunami-resistant design have been revised after "The 2011 off the Pacific coast of Tohoku Earthquake".

- SSCs* that are important for safety shall be located at adequately high places so that run-up waves caused by the design basis tsunami will not reach them.
- If such SSCs are located at places where run-up waves may reach, <u>the tsunami protection measures shall be taken.</u>
- After evaluating the possibility of tsunami inundation and the possible inflow routes (door, penetration, etc.), measures to prevent inundation and flooding shall be taken.

*SSCs: Structure, Systems and Component



## ■ Background

○ The regulatory requirements and guides (*1) require the tsunami protection facilities, such as seawalls, to maintain protective functions against the tsunami load.

- When deciding tsunami design load, technical basis (*2) and its applicability should be confirmed.

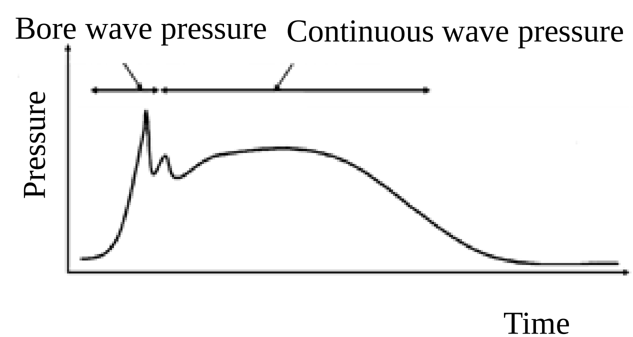
➢ Moreover, the guide requires that the load of bore wave pressure and continuous wave pressure on structure, which changes with time, should be paid attention to.

*1 : Regulatory guide for reviewing tsunami-resistant design on construction plan [in Japanese] and so forth
*2 : The interim guidelines of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) [in Japanese] and so forth

○ The bore wave pressure and the continuous wave pressure is acting on seawalls.

➢ The wave pressure at impact of the leading-edge of tsunami is called bore wave pressure. The bore wave pressure changes largely in a short time.

➢ The wave pressure which exerts on the seawall after bore wave pressure is called continuous wave pressure. The continuous wave pressure acts relatively for a long time.



Time history of the tsunami wave pressure

It is necessary to evaluate the tsunami design load appropriately with consideration of characteristics of such tsunami wave pressures.

○ Evaluation method of the design wave pressure by MLIT (MLIT method)

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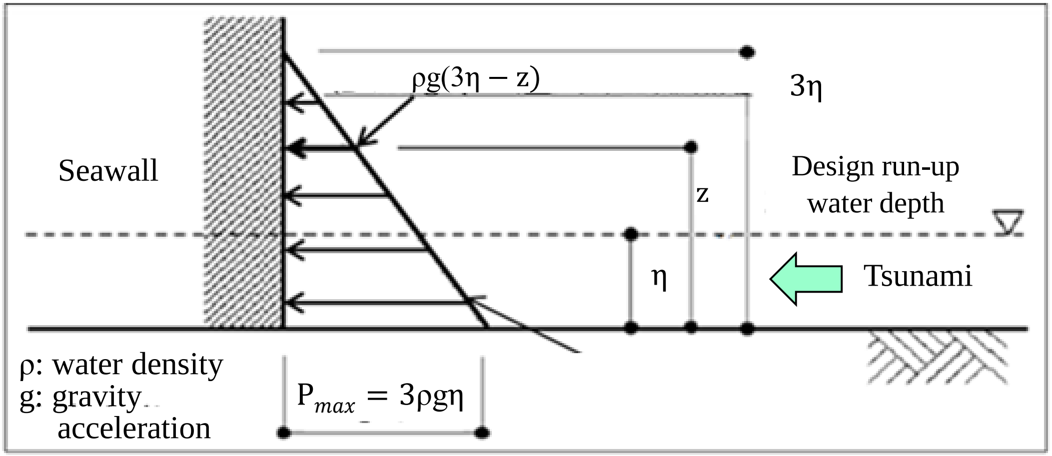
- The MLIT method is commonly used as a simple evaluation method for seawall design.
- The tsunami design pressure acting on seawalls is evaluated from the hydrostatic pressure equivalent to the height of 3 times the design run-up water depth where the seawall stands (water depth coefficient (α) = 3). This value is experimentally obtained.
- The method underestimates wave pressures acting on seawalls which stands far from the shoreline. The water flow is faster and more shallow than the experimental condition.

▪ **Water depth coefficient (α)**

Non-dimensional number indicating the ratio of the maximum continuous wave pressure acting on seawalls to the hydrostatic pressure equivalent to the design run-up water depth.

$$\alpha = \frac{P_{max}}{\rho g \eta}$$

$P_{max}$ : maximum continuous wave pressure
η : design run-up water depth
ρ : water density
g : gravity acceleration




MLIT method

## ■ Objective

- Hydraulic flume tests were carried out in order to find out the characteristics of the tsunami pressures acting on seawalls, and we investigated the following items;
  - The appropriate time parameter representing the characteristics of the tsunami flow
    - ✓ The parameters such as the run-up water depth (η(t)) and the flow velocity (v(t)) where the seawall stands change largely with time because tsunami is non-steady flow.
  - The evaluation method of the wave pressure on seawalls including the effects of (the bore wave pressure and) the continuous wave pressure
    - ✓ The effects of the continuous wave pressure was mainly discussed in this presentation because the bore wave pressure generally has smaller effects on that structural integrity than continuous wave pressure.
  - The evaluation method of the design wave pressure acting on seawalls
    - ✓ We investigated the conservative evaluation method of the design wave pressure which can be applied even when water flow was fast and shallow.

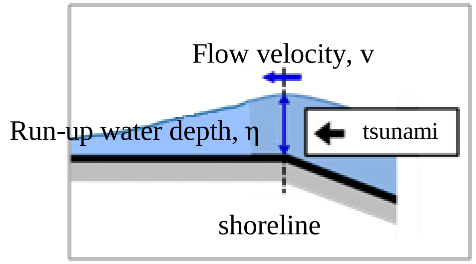
# ■ Overview of Hydraulic Flume Tests

- In order to clarify the appropriate time parameter representing tsunami flow characteristics, the run-up test was conducted, and the specific energy (E(t)) and the Froude number (Fr(t)) were evaluated.
  - The run-up test: the run-up water depth (η(t)) and the flow velocity (v(t)) of the tsunami wave were measured.

✓ Specific energy (E(t))

Kinetic and potential energy per unit weight

The specific energy is based on Bernoulli's theorem for non-viscous, steady, and one-dimensional flow.



Run-up test

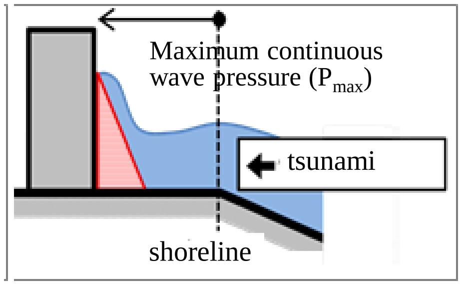
✓ Froude number (Fr (t))

The value of non-dimensional number indicating the ratio of the fluid inertial force and gravity

$$E(t) = \frac{v^2(t)}{2g} + \eta(t), \quad Fr(t) = \frac{v(t)}{\sqrt{g\eta(t)}}$$

v(t) : flow velocity
η(t) : run-up water depth
g: gravity acceleration

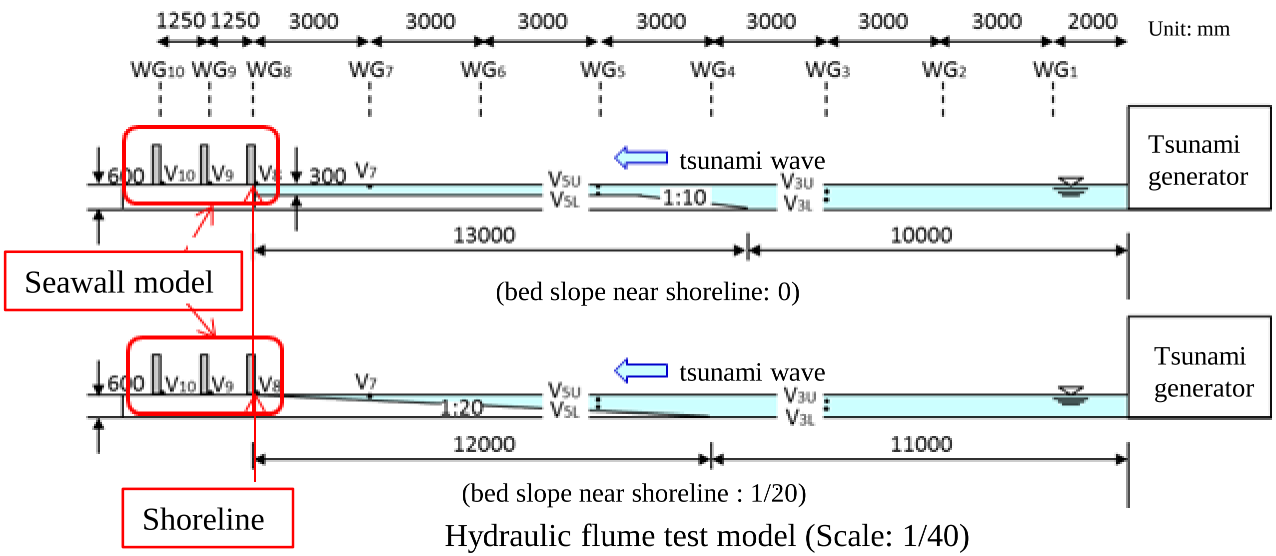
- In order to evaluate the characteristics of the continuous wave pressure, wave pressure tests were carried out, and the water depth coefficient (α) that is equivalent to the maximum continuous wave pressure was evaluated.
  - Wave pressure test: the maximum continuous wave pressure ($P_{max}$) acting on seawalls was measured.



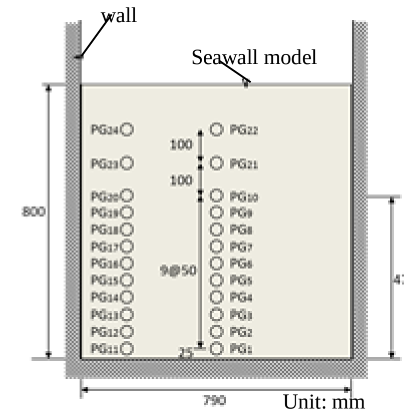
Wave pressure test

# ■ Hydraulic Flume Test Model and Waves

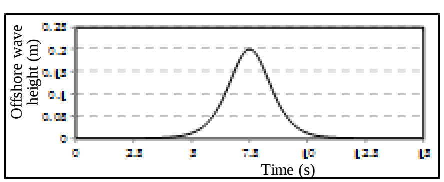
- ➢ The flume measures 23m in length (1/40 scale ratio) and has a width of 0.8m.
- ➢ The wave generator at the end of the flume produced solitary waves, sine waves and long-period waves.
- ➢ Two types of bed slope near the shoreline are considered: a zero slope and a 1/20 slope.



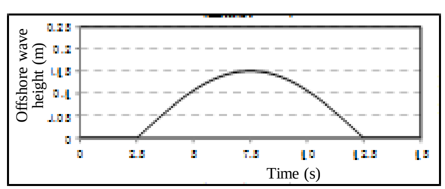

Hydraulic flume test model (Scale: 1/40)



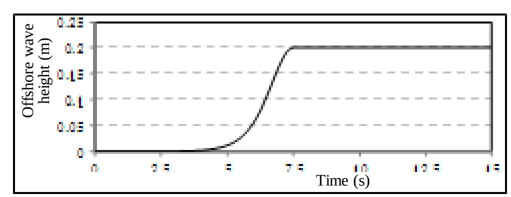

Seawall model (Scale: 1/40)




(Solitary wave)




(Sine wave)



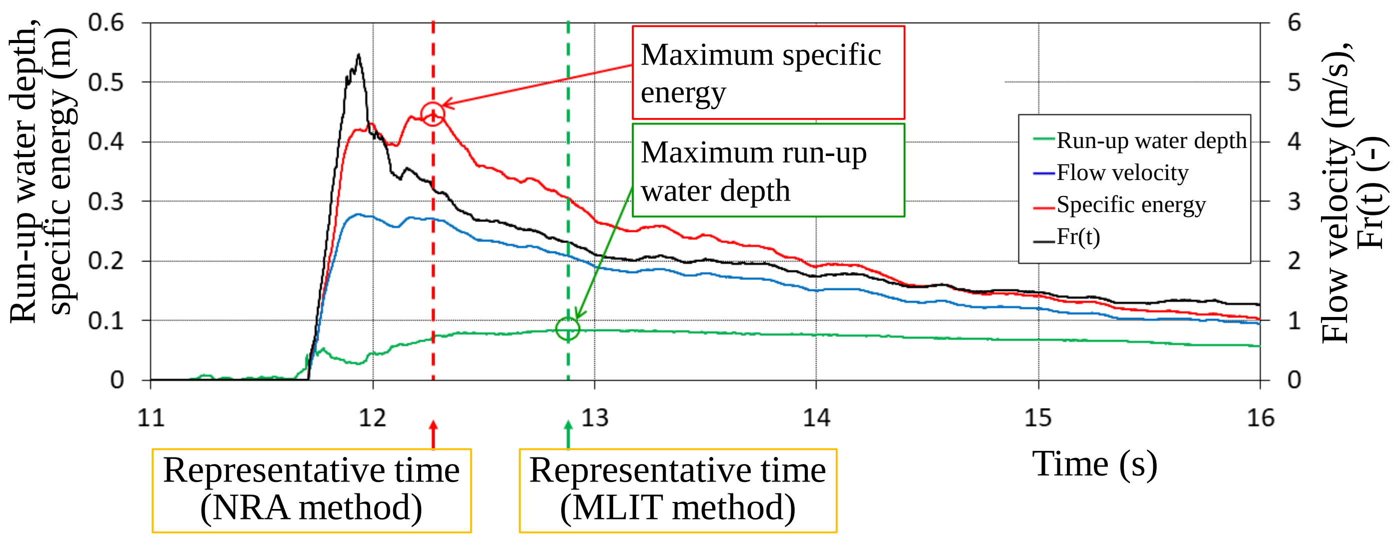

(Long-period wave)

Examples of waves

## Test results – Run-up test -

- The parameter such as the run-up water depth (η(t)) and the flow velocity (v(t)) change largely with time because tsunami is non-steady flow. (the Froude number (Fr(t)) also changes with time)
- It is necessary to decide the representative time with consideration of structural effect on seawalls.
- In the MLIT method, the time when the run-up water depth becomes the maximum was selected as the representative time, however the dynamic effect based on the flow velocity was not considered.

- Considering that the maximum wave pressure acting on seawalls relates to the maximum tsunami energy, it may be reasonable to select the time when the specific energy (E(t)) becomes the maximum as the representative time.




Time history of the run-up water depth, flow velocity, specific energy and Froude number

# ■ Evaluation Method of the Tsunami Wave Pressure

➢ The theoretical formula indicating the relations between the water depth coefficient ($\alpha$) and the Froude number ($Fr$) was derived from Bernoulli's theorem.

1. In the case of the ideal one-dimensional steady flow running through a flat flume, the specific energy ($E$) of each location is preserved (Bernoulli's theorem).
2. If a seawall is set up in the flume, since the horizontal flow velocity ($v$) becomes 0 in front of the seawall, the specific energy ($E$) becomes equal to the water depth in front of the seawall ($h$).

$$E = \frac{v^2}{2g} + \eta$$

$v$ : horizontal flow velocity
$\eta$ : water depth
(at any point)

$$E = 0 + h$$

0 : horizontal flow velocity
$h$ : water depth
(in front of seawall)

3. In this situation, the hydrostatic pressure at the bottom of the seawall ($P$) is calculated from the water depth in front of the seawall ($h$).

$$P = \rho g h \quad \Rightarrow \quad \frac{P}{\rho g} = \frac{v^2}{2g} + \eta \qquad \cdots \text{Eg. (1)}$$

4. Dividing both sides of Eg.(1) by the water depth ($\eta$), we derived the theoretical formula.

$$\frac{P}{\rho g \eta} = \frac{v^2}{2 g \eta} + 1 \quad \Rightarrow \quad \underline{\alpha = 1 + 0.5 Fr^2}$$

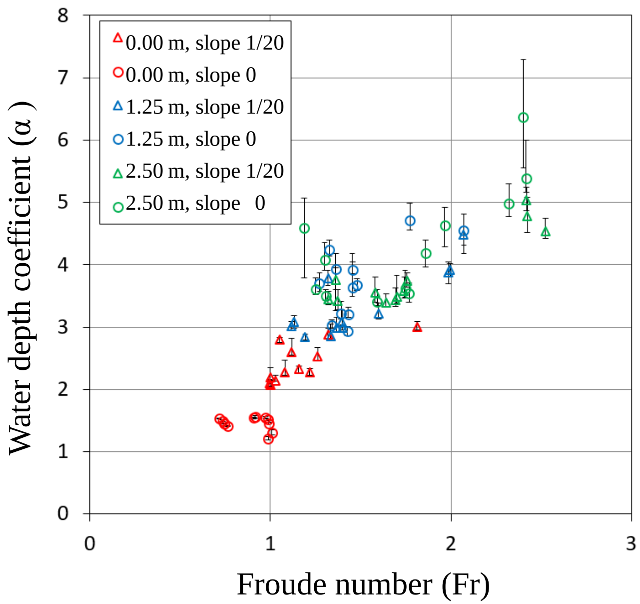
$$\left\{ \begin{aligned} \alpha &= \frac{P}{\rho g \eta} \\ Fr &= \frac{v}{\sqrt{g\eta}} \end{aligned} \right.$$

- We applied the theoretical formula as the evaluation formula of the wave pressure, assuming that the maximum specific energy from run-up test results were correlated with the maximum continuous wave pressure acting on seawalls, although actual flow is in non-steady and multi-dimensional flow.

## ■ Test results –Wave pressure test-

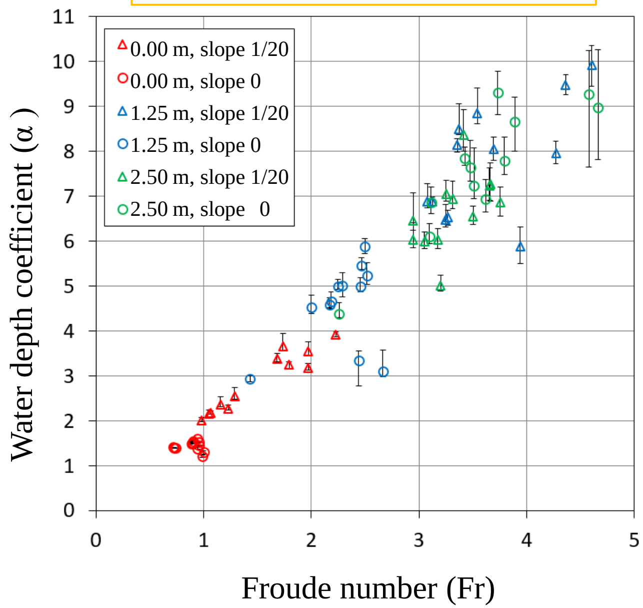
- We evaluated the Froude number (Fr) when the specific energy (E(t)) becomes the maximum, and the relations between the Froude number (Fr) and the water depth coefficient (α).
- The method using the maximum run-up water depth as the representative time included more uncertainty than the proposed method using the maximum specific energy.
- The maximum continuous wave pressure is highly correlated to the maximum specific energy.

Maximum run-up water depth time (MLIT method)




Relations between the water depth coefficient and the Froude number when the run-up water depth becomes the maximum

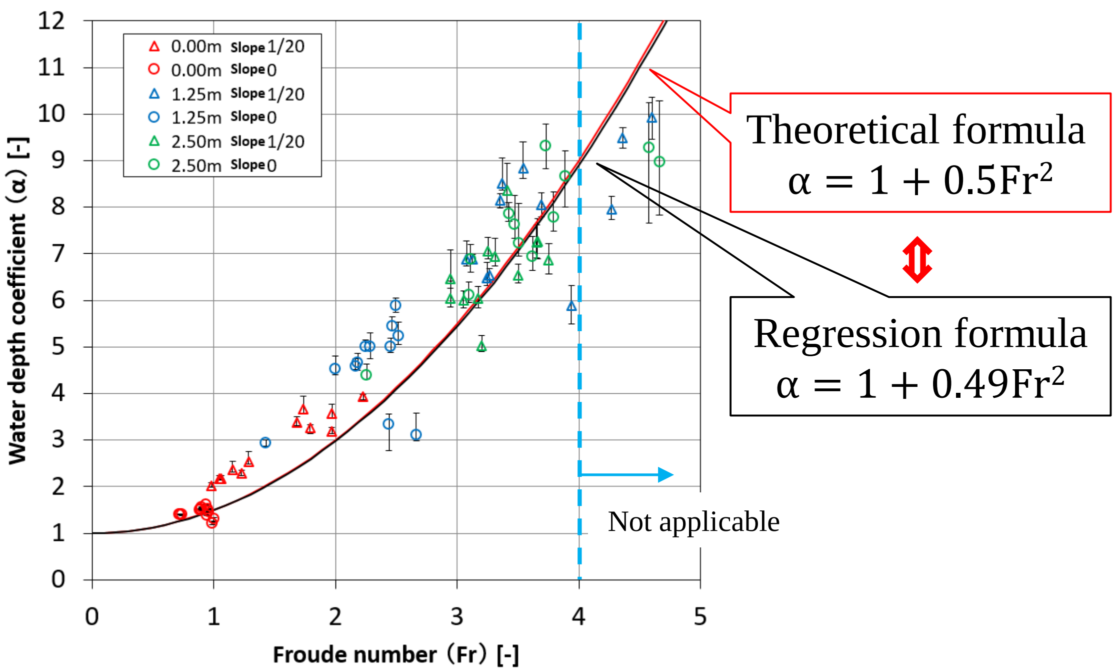
Maximum specific energy time (NRA method)




Relations between the water depth coefficient and the Froude number when the specific energy becomes the maximum

■ **Test results –Wave pressure test-**

- The regression formula was derived from the wave pressure test results by the least-squares method. ($\alpha = c \cdot \mathrm{Fr}^2 + 1$, $c$; constant)
  - The theoretical formula and the regression formula were consistent.
- The evaluation approach using Froude number (Fr) when the specific energy (E(t)) becomes the maximum is appropriate.
- However, the theoretical formula based on Bernoulli's theorem cannot be applied when $\mathrm{Fr} \geq 4$, because of the strong unsteady and multi-dimensional effects.

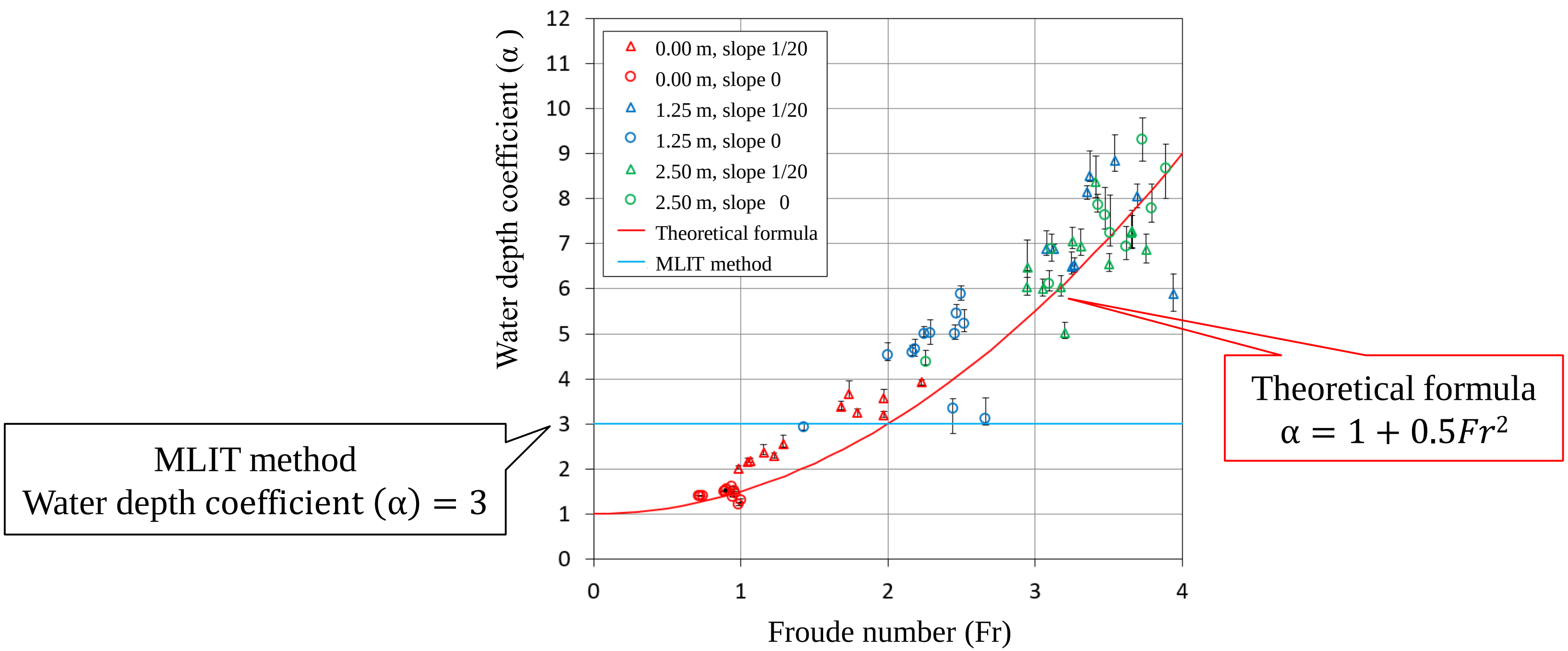



Relations between the water depth coefficient and the Froude number when the specific energy becomes the maximum

## ■ Test results –Wave pressure test-

- ➢ The MLIT method (α=3) can be applied only when the Froude number becomes small.
- ➢ The evaluation method of the wave pressure based on the theoretical formula can be applied when Fr < 4.

- ➢ The evaluation formula of the wave pressure, $\alpha = 1 + 0.5Fr^2$ (Fr < 4), was obtained. By using the evaluation formula, we can predict the wave pressure acting on seawalls from the run-up test.




Relations between the water depth coefficient and the Froude number when the specific energy becomes the maximum

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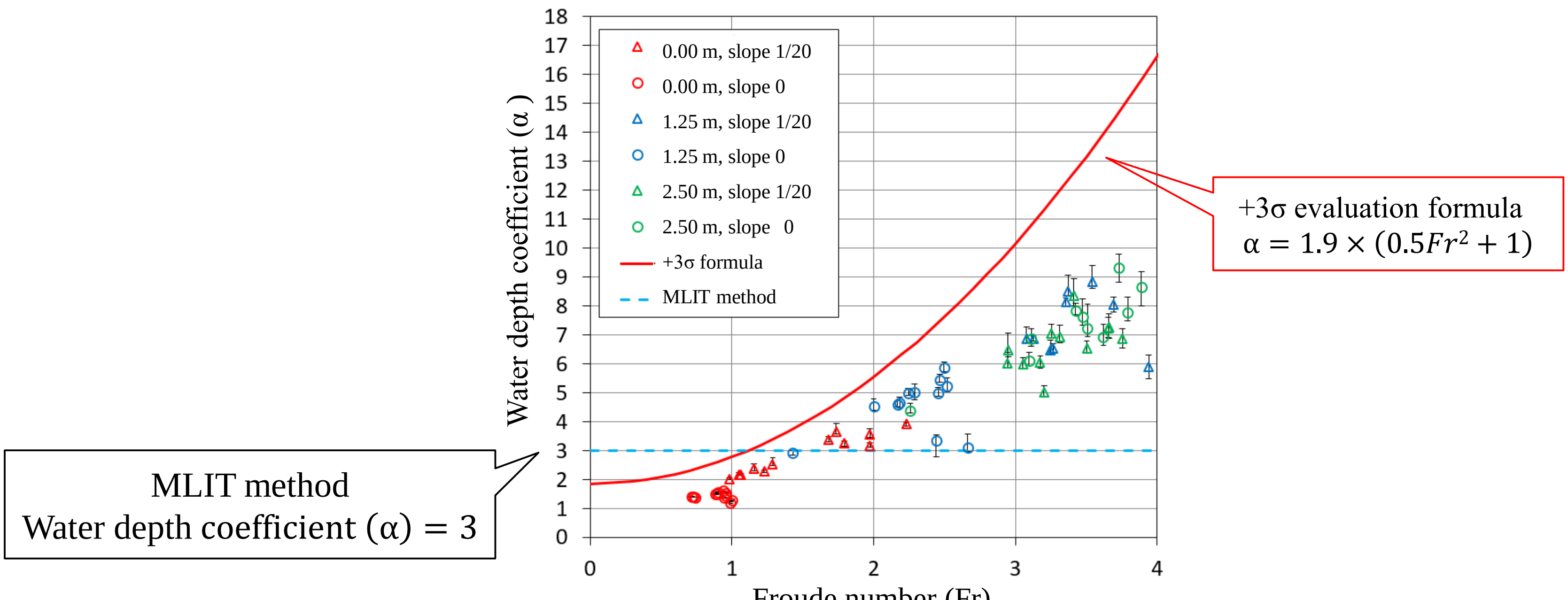
## ■ Evaluation formula of the design wave pressure

- ➢ Including the logarithmic standard deviation +3$\sigma$ of test results in the theoretical formula, we developed the evaluation formula of the design wave pressure.
  - The logarithmic standard deviation +3$\sigma$ is selected to envelop all test results.

- ➢ The conservative evaluation formula of the design wave pressure including the logarithmic standard deviation +3$\sigma$ from the theoretical formula is shown as follows:

$$\alpha = 1.9 \times (1 + 0.5\mathrm{Fr}^2) \quad \mathrm{Fr} < 4$$

- ➢ The MLIT method (water depth coefficient 3) can be applied as a simpler method when Fr≦1.




Evaluation formula of the design wave pressure

# 4. Summary

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## ■ Evaluation of the tsunami wave pressure acting on seawalls*

- ➢ Considering that the maximum wave pressure acting on seawalls relates to the maximum tsunami energy, it may be reasonable to select the time when the specific energy (E(t)) becomes the maximum as the representative time.
- ➢ The evaluation formula of the wave pressure, $\alpha = 1 + 0.5Fr^2\ (Fr < 4)$, was obtained. By using the evaluation formula, we can predict the wave pressure acting on seawalls from the run-up test.

## ■ Evaluation method of the design wave pressure*

- ➢ The conservative evaluation formula of the design wave pressure including the logarithmic standard deviation $+3\sigma$ from the theoretical formula is shown as follows:

$$\alpha = 1.9 \times (1 + 0.5Fr^2) \quad Fr < 4$$

- ➢ The MLIT method (water depth coefficient 3) can be applied as a simpler method when $Fr \leqq 1$.

*The results has been disclosed in the NRA Technical Reports
"Applicability of Water Depth Coefficient in Evaluation for Tsunami Wave Force Acting on Seawall (NTEC-2014-4001, in Dec., 2014)",
"Effects of Bore Pressure of Tsunami on Seawall (NTEC-2015-4001, in Dec., 2015)" and
"Water Depth Coefficients for Evaluating Tsunami Pressure on Seawall (NTEC-2016-4001, in Dec., 2016)".