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The State of the Art and Science of Coastal Engineering

Study on Estimation of Scouring Behind the Breakwater

○ Kohei Suzuki
Chuo University

Katsumi Seki
Chuo University

Taro Arikawa
Chuo University




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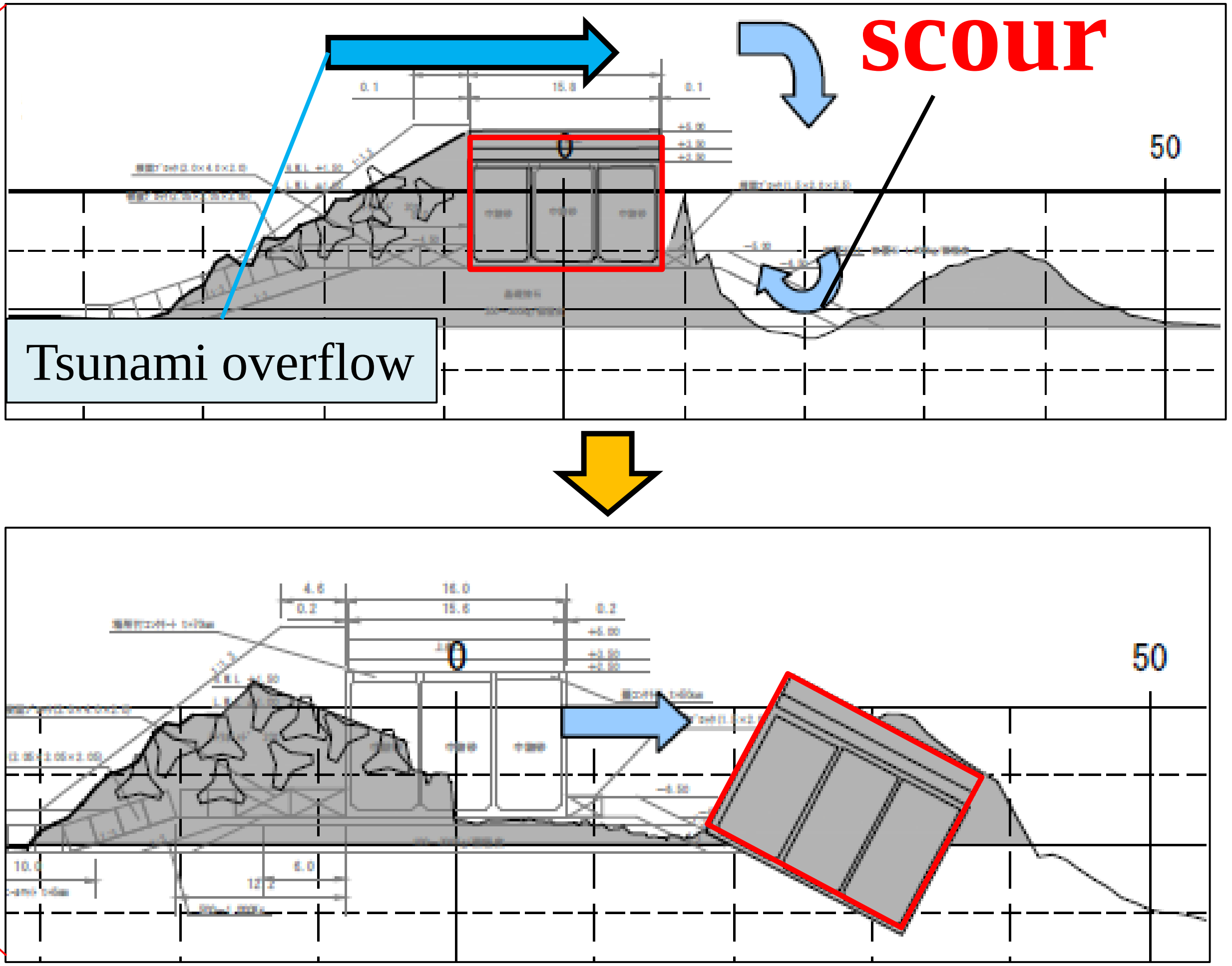
1. Introduction

BACKGROUND

Hachinohe Port in Aomori Prefecture

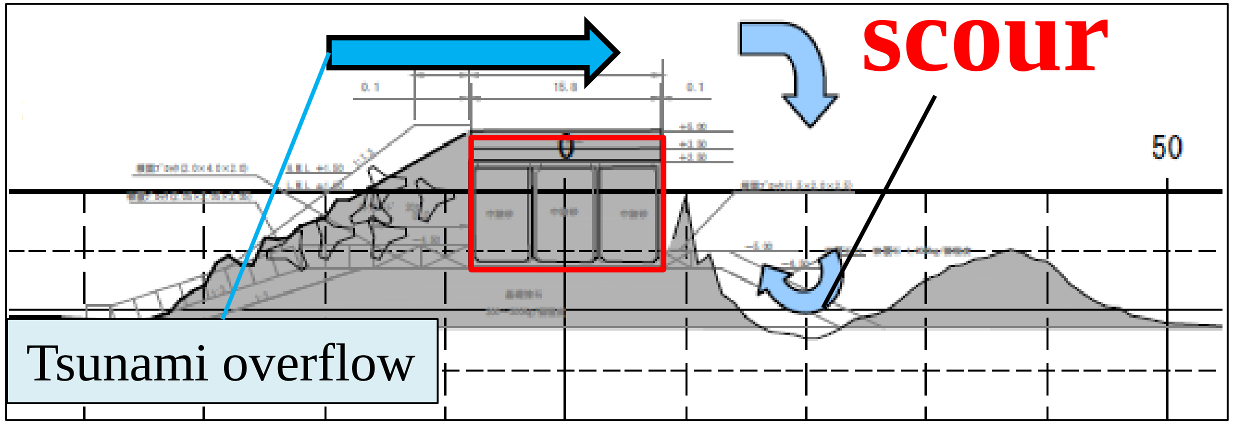
*Refer to Ministry of Land, Infrastructure and Transport

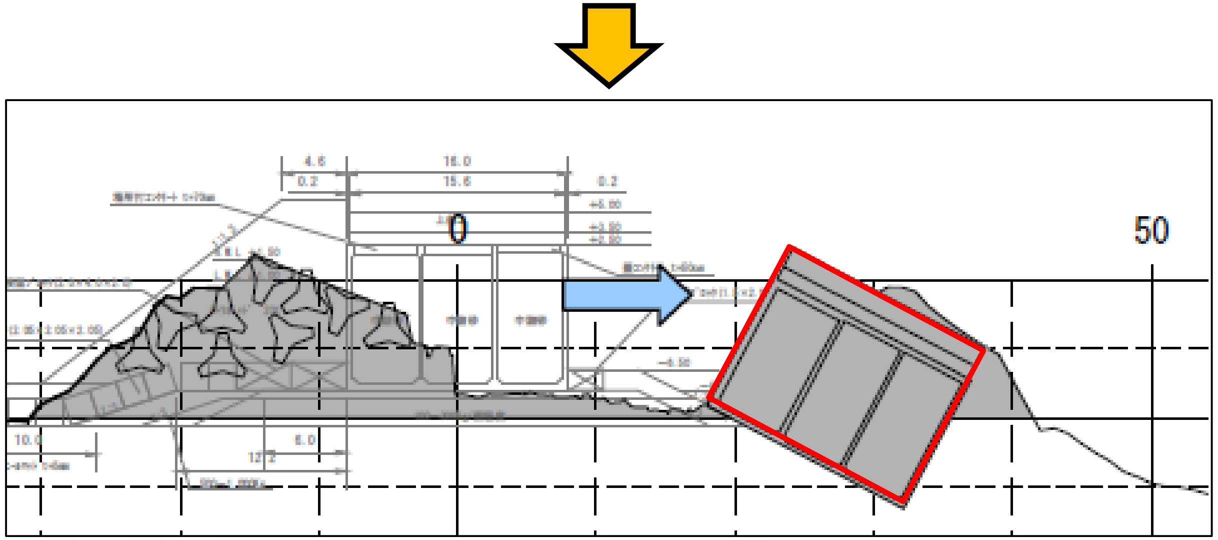
Cross Section of the damage



1. Introduction

BACKGROUND





Mechanism of collapse

1. Tsunami overflow the breakwater and the ground behind the breakwater will be scoured.
2. The bearing capacity of the ground was reduced due to scour.
3. Although the water level did not exceed the sliding limit water level of the caisson, some caissons were moved and some of them collapsed.

1. Introduction

Previous Research on Scour Depth behind the Breakwater

$D_{max} = 2.1R_N$ Noguchi *et al.*(1997)
$D_{max} = 5.83R_N$ Arikawa *et al.*(2014)

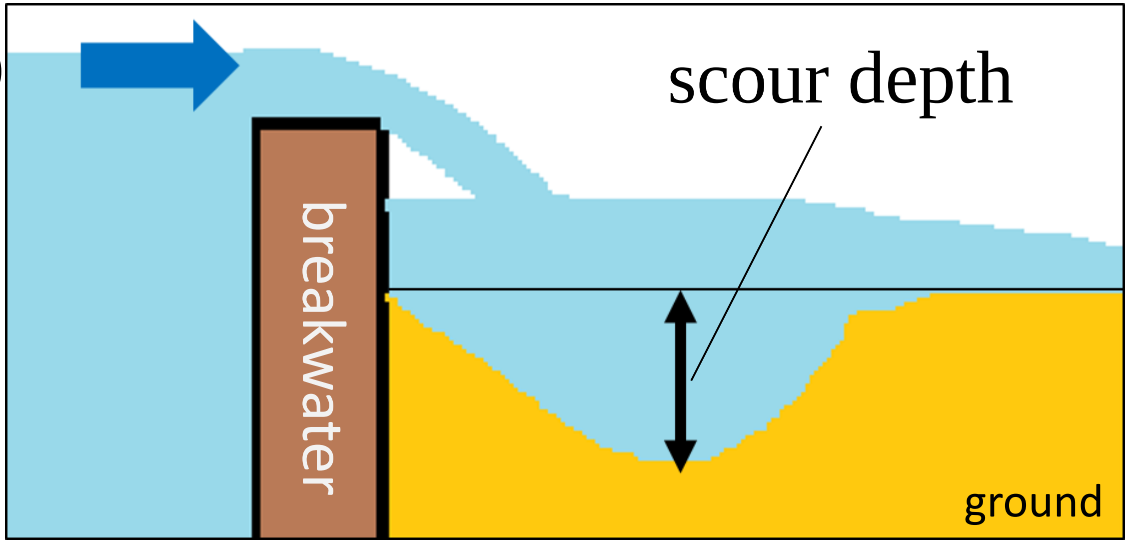
→ They designed the prediction formula for maximum scour depth

D_{max} : maximum scour depth

The R_N is obtained below （Noguchi *et al.*(1997))

$$R_N = g^{-\frac{1}{4}} q^{\frac{1}{2}} Z_f^{\frac{1}{4}}$$

g : gravitational acceleration [m/s^2]
q : flow rate per unit width [m^2/s]
Zf : overflow height [m]



1. Introduction

Previous Research on Scour Depth behind the Breakwater

$D_{max} = 2.1R_N$ **Noguchi *et al.*(1997)**

$D_{max} = 5.83R_N$ **Arikawa *et al.*(2014)**

→ They designed the prediction formula for maximum scour depth

However…

Little is known about the coefficients of these formula are different.

The purpose of this study...

To clarify the difference of the coefficients...

Scour experiments are conducted, and the experiment and past experiment are analyzed.

And we tried to design an estimation formula for scour depth.

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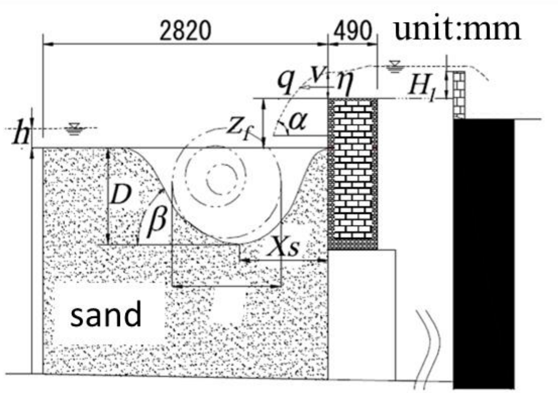
2. Experiment

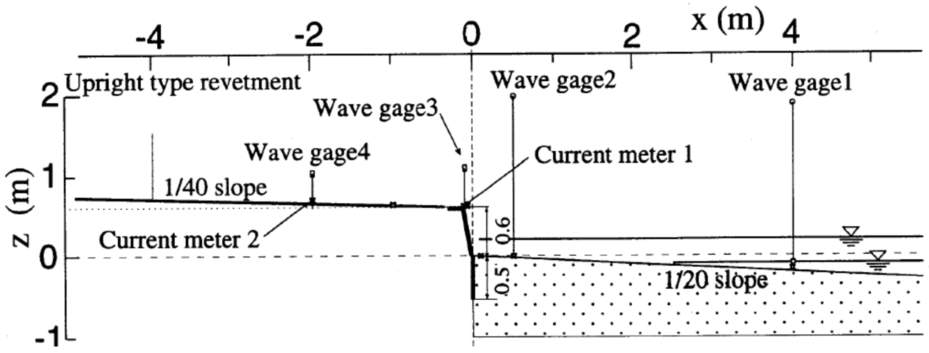
Previous experimental cross section

Small scale experiment Arikawa *et al.*(2014)



case	z_f (cm)	H_1 (cm)	η (cm)	h (cm)	v (m/s)	q (m²/s)
1		-13.2	1.0	0	0.17	0.002
2		-8	3.3	2.5	0.80	0.026
3	24	0	4.7	5.5	1.09	0.051
4		5	6.0	8.6	1.31	0.078
5		16	6.8	13.9	1.37	0.093
6	34	0	4.2	5.1	1.06	0.045
7	48	0	4.0	5.4	1.07	0.043
8		0	4.2	5.5	1.09	0.046

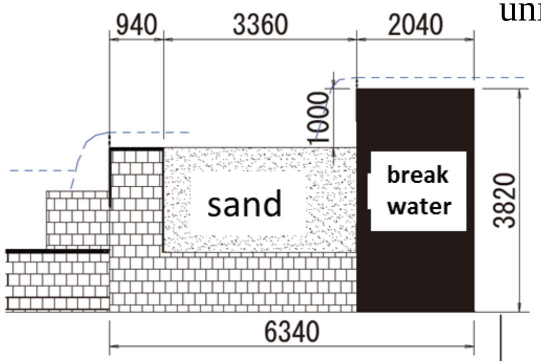
Noguchi *et al.*(1997)



*Refer to Experimental study on the seawall overtopping and scour behind seawall due to Tsunami upstream Noguchi *et.al*(1997)

Large scale experiment Arikawa *et al.*(2014)

unit:mm



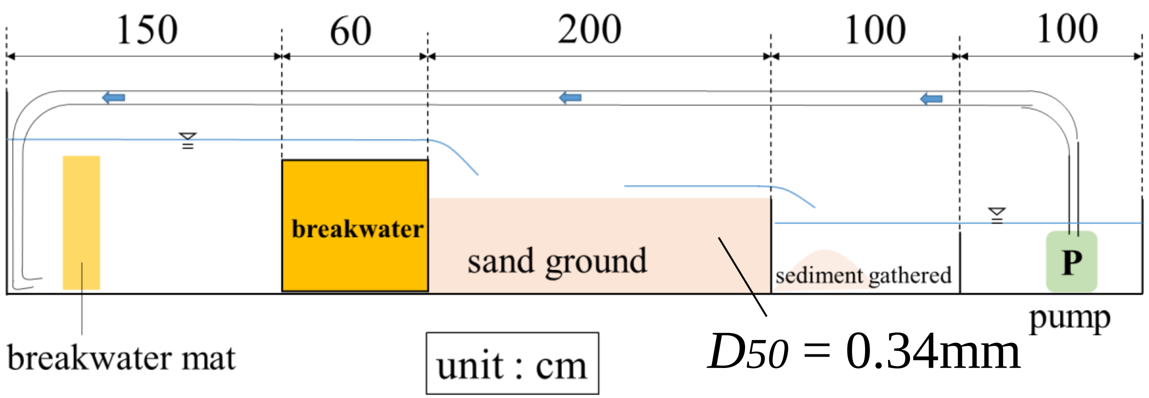
case	z_f (cm)	η (cm)	h (cm)	v (m/s)	q (m²/s)
1		9.1	7.5	1.36	0.124
2	100	10.0	12.2	1.70	0.170
3		14.8	15.0	1.95	0.288

Arikawa *et al.*(2014) conducted scour experiments on two different scale.

*Refer to Experimental Study on Scour behind Seawall due to Tsunami Overflow Arikawa *et.al*(2014)

2. Experiment

Experimental cross section

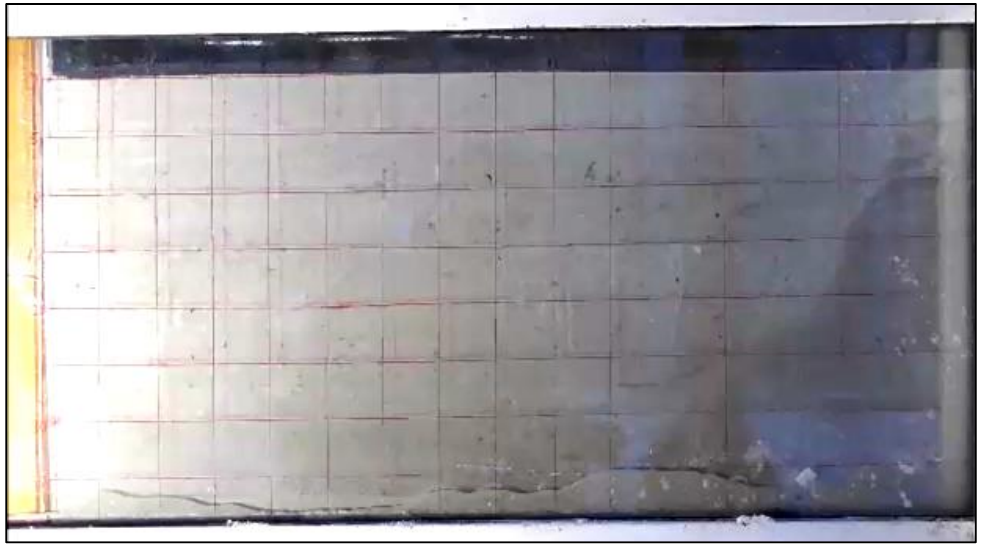


The wave flume in Chuo University :
0.30 m in width, 0.50 m in height.
Particle diameter : 0.34 mm

Experimental video

case No.4

16 times speed



Experimental condition

case No.	Zf [cm]	$q\ [m^2/s]$	case No.	Zf [cm]	$q\ [m^2/s]$	case No.	Zf [cm]	$q\ [m^2/s]$
1	5	0.0043	6	15	0.0024	9	15	0.0055
2	10		7	20		10	20	
3	15		8	25		11	25	
4	20					12	25	0.0087
5	25							

Zf : height of waterfall

q : flow rate per unit width

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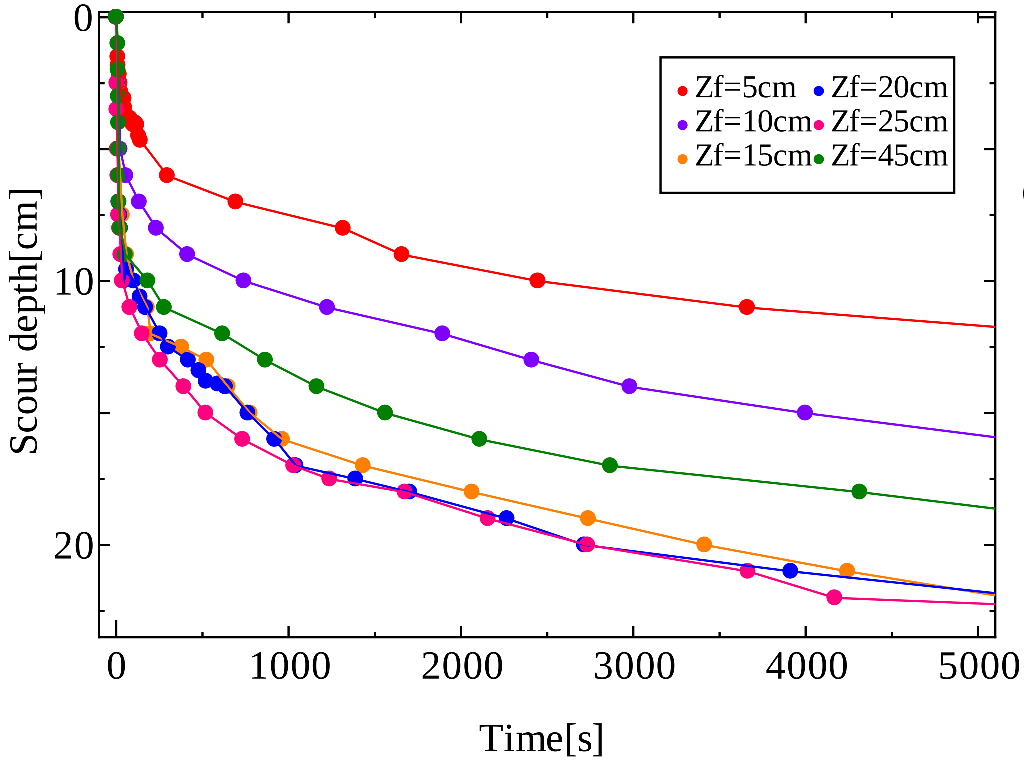
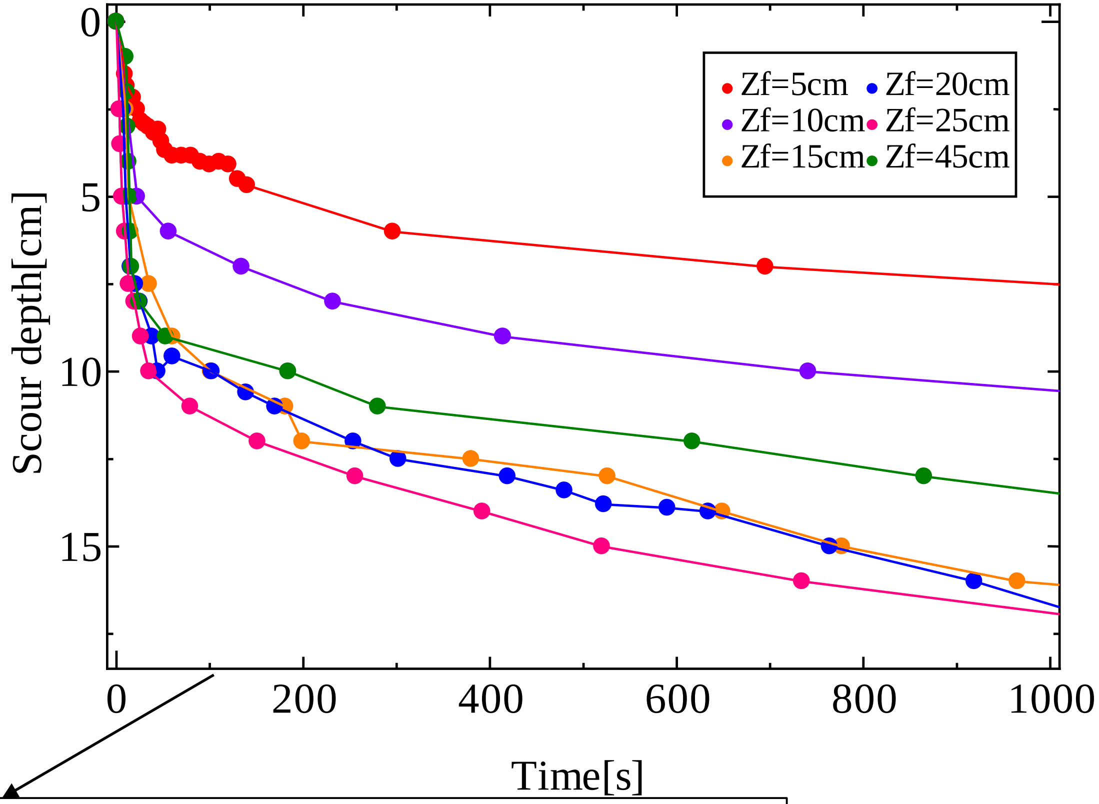
2. Experiment
3. Result of the experiments
4. The estimation formula on scour
5. Conclusion

3. Result of the experiments

case No.1~5



enlarged time



The ground was scoured at a stretch in early phase.
And after, the ground was scoured slowly.

3. Result of the experiments

Investigation of the past experiments conducted by Arikawa *et al*.(2014)

	Arikawa *et al*. (2014)		middle experiment (this experiment)
	small scale	large scale	
grain diameter[cm]	0.021	0.043	0.034

Because the grain diameter are different, we considered a law of similarity.

We applied a law of similarity using sedimentation velocity as shown in Eq. (1), refer to Yamano *et al*.(2013)

$$w_{0m}/w_{0p} = \left(l_m/l_p\right)^{\frac{1}{2}} \cdots (1)$$

w : sedimentation velocity
l : representative length

m: model
p : prototype

Field observation and reproduction experiment of local scour around the pile   Yamano *et al*. (2013)

3. Result of the experiments

Considering a law of similarity

1st. We calculate the sedimentation velocity w_0 in each experiment using Eq.(2) and Eq.(3)

$$w_0 = \sqrt{sgd_N}\left(0.954 + \frac{5.12}{S_*}\right)^{-1} \quad \cdots(2)$$

$$S_* = \frac{d_n}{4\nu}\sqrt{sgd_N} \quad \cdots(3)$$

s : specific gravity of water (= 1.65)
g : gravitation acceleration
d_N : considered grain diameter (d/0.9, d : grain diameter)
ν : coefficient of kinematic velocity

⇩ The following table is the sedimentation velocity in each experiment.

	Arikawa *et al.* (2014)		middle experiment (this experiment)
	small scale	large scale	
grain diameter[cm]	0.021	0.043	0.034
Wo (sedimentation velocity) [cm/s]	2.38	5.92	4.58

2nd. The scale of the small scale experiments is 1/42

The sedimentation velocity in local scale is 15~16 cm/s

$$w_{0m}/w_{0p} = \left(l_m/l_p\right)^{\frac{1}{2}}$$

$$w_{0p} = (42)^{\frac{1}{2}} \times 2.38$$

$$= 15.4 \text{ cm/s} \approx 15\sim16 \text{ cm/s}$$

m: model
p : prototype

w : sedimentation velocity
l : representative length

Continued on the following page

3. Result of the experiments

Considering a law of similarity

3rd. We set the sedimentation velocity in local scale to 16cm/s.

The others model scale that satisfies this sedimentation velocity are calculated below.

Large scale

$$W_{0m}/W_{0p} = \left(l_m/l_p\right)^{\frac{1}{2}}$$

$$5.92/16 = \left(l_m/1.0\right)^{\frac{1}{2}}$$

$$l_m = \frac{0.14}{1} \approx \frac{1}{7}$$

Middle scale

$$W_{0m}/W_{0p} = \left(l_m/l_p\right)^{\frac{1}{2}}$$

$$4.58/16 = \left(l_m/1.0\right)^{\frac{1}{2}}$$

$$l_m = \frac{0.08}{1} \approx \frac{1}{12}$$

As a result of applying a law of similarity using sedimentation velocity, the experiment scale are as follows.

- small experiments ⇒ 1/42
- large scale ⇒ 1/7
- middle experiment ⇒1/12

3. Result of the experiments

Investigation of each experiments

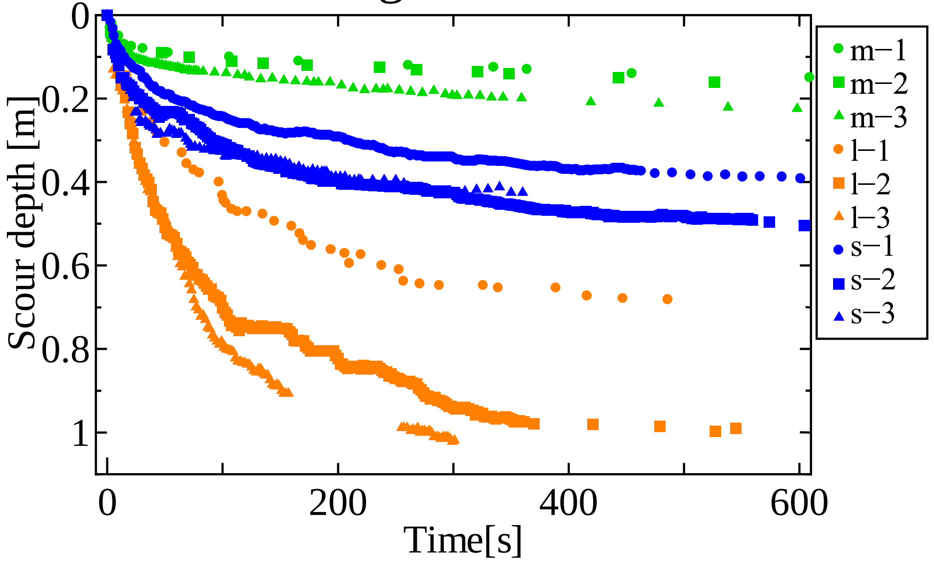
Original scale

middle scale		
case No.	Zf [m]	q $[m^2/s]$
m-1	0.20	0.0055
m-2	0.25	0.0055
m-3	0.25	0.0086
small scale		
case No.	Zf [m]	q $[m^2/s]$
s-1	0.24	0.026
s-2	0.34	0.045
s-3	0.48	0.043
large scale		
case No.	Zf [m]	q $[m^2/s]$
l-1	1.0	0.124
l-2	1.0	0.170
l-3	1.0	0.288

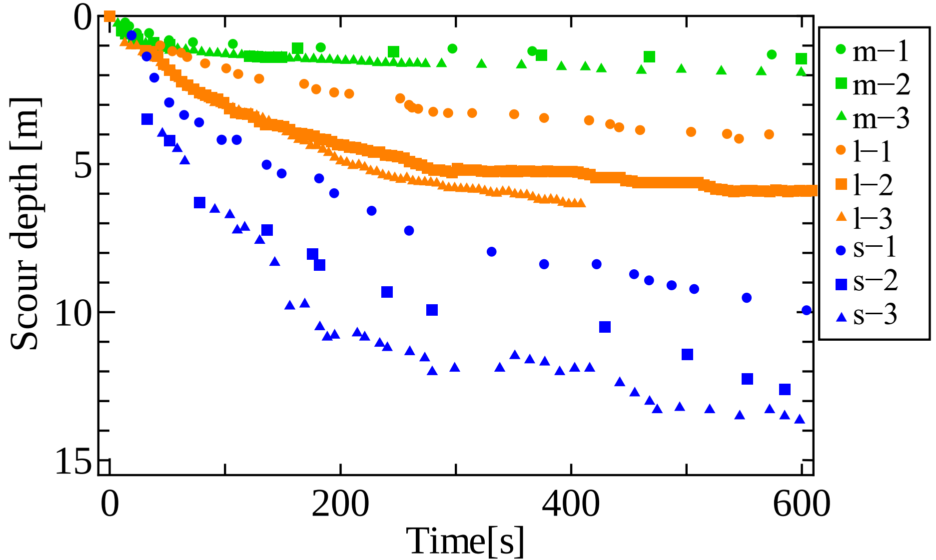
The scale applying a law of similarity

middle scale		
case No.	Zf [m]	q $[m^2/s]$
m-1	2.4	0.229
m-2	3.0	0.229
m-3	3.0	0.357
large scale		
case No.	Zf [m]	q $[m^2/s]$
l-1	7.0	2.23
l-2	7.0	3.15
l-3	7.0	5.33
small scale		
case No.	Zf [m]	q $[m^2/s]$
s-1	10.1	7.1
s-2	14.3	12.2
s-3	20.2	11.7

Original scale



The scale applying a law of similarity



3. Result of the experiments

Investigation of each experiments

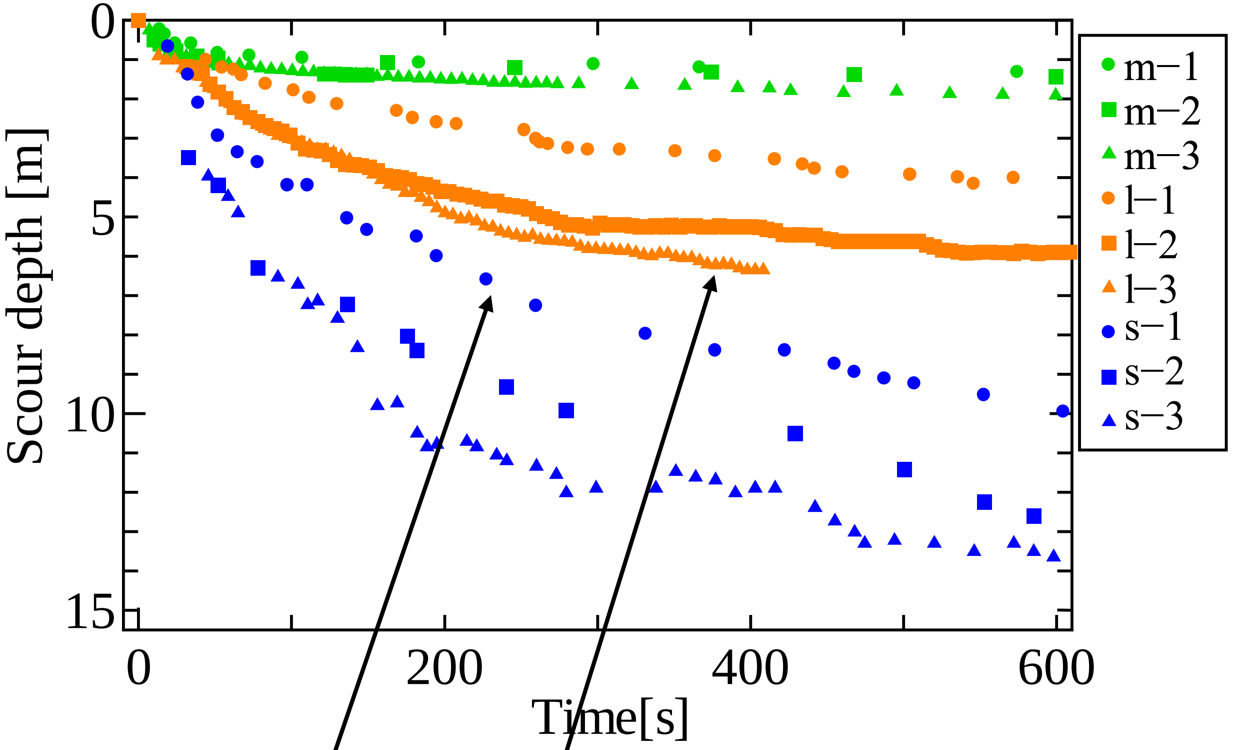
The scale applying a law of similarity

case No.	Zf [m]	q $[m^2/s]$
middle scale		
m-1	2.4	0.229
m-2	3.0	0.229
m-3	3.0	0.357
large scale		
l-1	7.0	2.23
l-2	7.0	3.15
l-3	7.0	5.33
small scale		
s-1	10.1	7.1
s-2	14.3	12.2
s-3	20.2	11.7

l-3

s-1

The scale applying a law of similarity

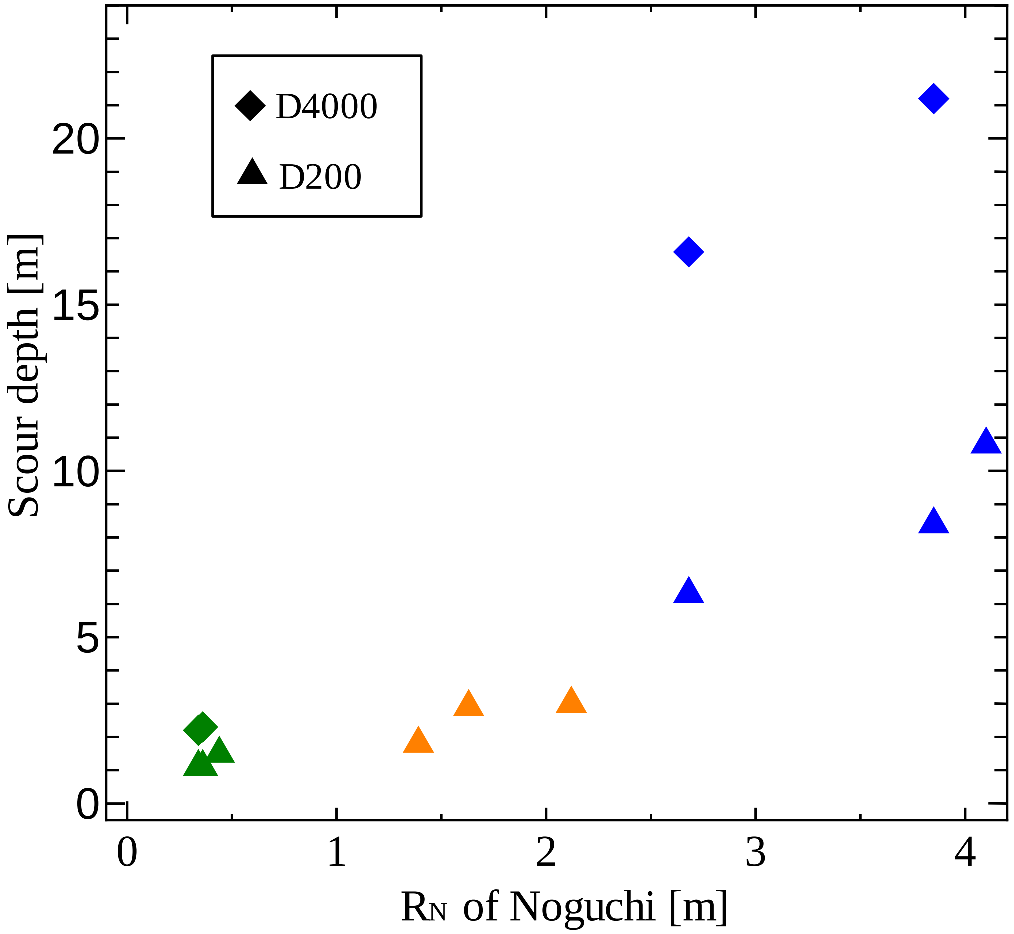


「s-1」 and 「l-3」 are similar conditions and the results are similar.

The law of similarity probably consists

3. Result of the experiments

Investigation for a relation between scour depth and R_N designed by Noguchi *et al*.



The left figure shows the relation between scour depth and the R_N designed by Noguchi *et al*.
(The result is applied to the law of similarity.)

D200 : the scour depth in 200 seconds after start of overflow
D4000 : the scour depth in 4000 seconds after start of overflow

▲ : Scour Depth in 200s after the start of overflow

◆ : Scour Depth in 4000s after the start of overflow

● Small scale ● Large scale ● Middle scale

$$R_N = g^{-\frac{1}{4}} q^{\frac{1}{2}} Z_f^{\frac{1}{4}}$$

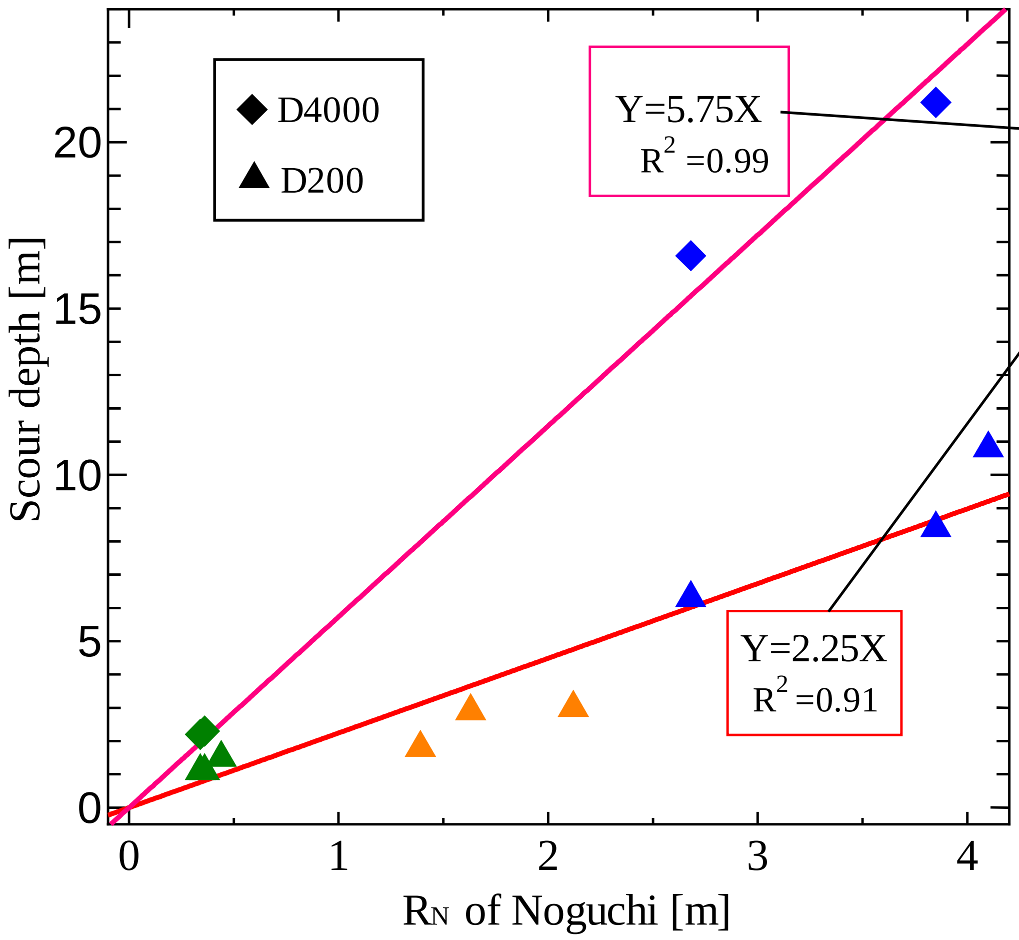
(Noguchi *et al*.(1997))

g : gravitational acceleration $[m/s^2]$
q : per unit width flow rate$[m^2/s]$
Zf : drop height [m]

We draw approximate curves in each experiment…

3. Result of the experiments

Investigation for a relation between scour depth and R_N designed by Noguchi *et al*.



$D_{max} = 2.1R_N$ Noguchi *et al*.(1997)

$D_{max} = 5.83R_N$ Arikawa *et al*.(2014)

The approximate curves are similar to the previous formula for scour depth.

As a result…

$D=2.1R_N$ (Noguchi's formula) : the scour depth in 200 seconds after overflow in local scale

$D=5.83R_N$ (Arikawa's formula) : the scour depth in about 4000 seconds after overflow in local scale

$$R_N = g^{-\frac{1}{4}} q^{\frac{1}{2}} Z_f^{\frac{1}{4}}$$

(Noguchi *et al*.(1997))

g : gravitational acceleration $[m/s^2]$
q : per unit width flow rate$[m^2/s]$
Zf : drop height [m]

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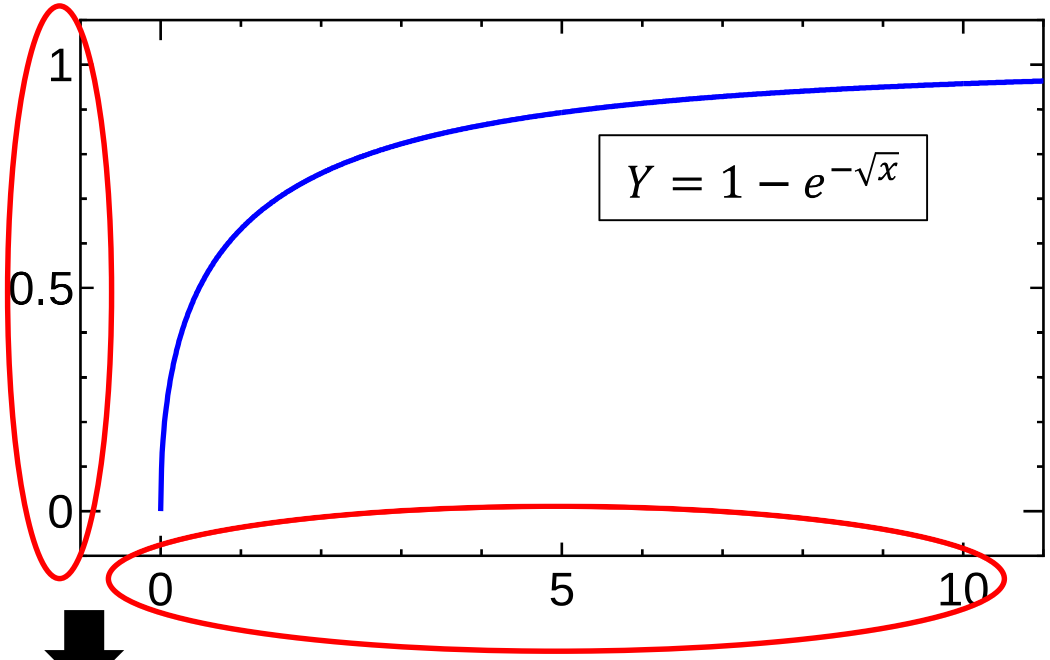
4. The estimation formula on scour

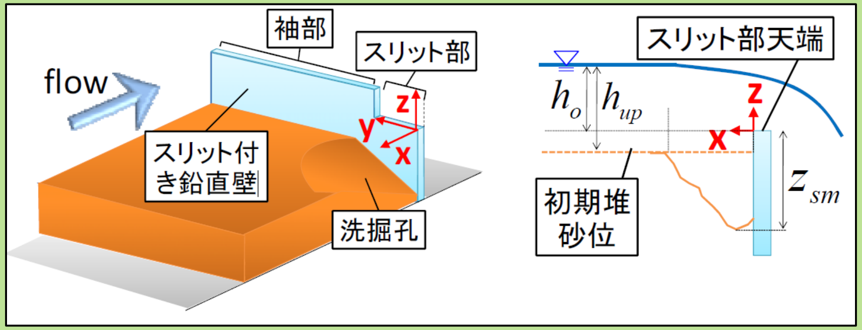
Weibull Function : $Y = 1 - e^{-\sqrt{x}}$



Previous research using Weibull Function

Ohta *et al.*(2012)

They investigated temporal evolution of the scour hole in front of the wall using Weibull function.



* Local scour in the upstream region of dam gates (Part 1) - Temporal evolution of scour hole geometry- CRIEPI Research Report Ohta *et al.*(2012)

The horizontal axis is the time, the vertical axis is the scour depth.

We tried to design an estimation formula for scour depth

4. The estimation formula on scour

We tried to design an estimation formula for scour depth.

1st. We made the overflow time and the scour depth dimensionless as follows.

Non-dimensional Scour Depth

D_n : Non-dimensional Scour Depth, D: Scour Depth [m]

$$D_n = \frac{D(t)}{5.83R_N}$$

The denominator $5.83R_N$ was based on the value of Arikawa *et al*.(2014)

$$\boldsymbol{R_N = g^{-\frac{1}{4}} q^{\frac{1}{2}} Z_f^{\frac{1}{4}}}\ [m]$$ （Noguchi *et al*.(1997))

g : gravitational acceleration $[m/s^2]$

q : per unit width flow rate$[m^2/s]$

Zf : overflow height [m]

Previous research

$D_{max} = 5.83R_N$ Arikawa *et al*.(2014)

4. The estimation formula on scour

1st. We made the overflow time and the scour depth dimensionless as follows.

Non-dimensional time

t_n : Non-dimensional Overflow Time, t: Overflow time [s]

$$t_n = \frac{u_*}{\gamma_a R_N} t$$

R_N : the theory vortex designed by Noguchi *et al.*(1997)

u_* : the critical friction velocity indicated by Iwagaki's formula as follows

$u_* = \sqrt{8.41 \times (d)^{11/32}}$ [c m/s] (0.0065cm < d < 0.0565cm)

d : particle diameter [cm]

γ_a : the experimental constant

From experimental result…

4. The estimation formula on scour

$$t_n = \frac{u_*}{\gamma_a R_N} t$$

??

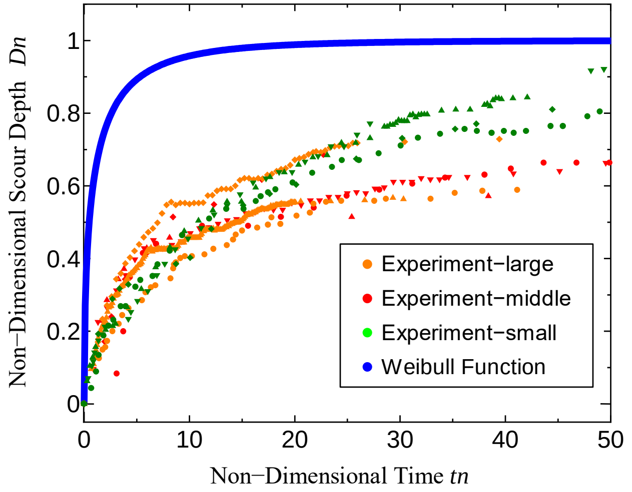
In order to determine the experimental constant γ_a, we compared the γ_a with the experimental value.

$$\gamma_a = 1, 10, 20, 30$$

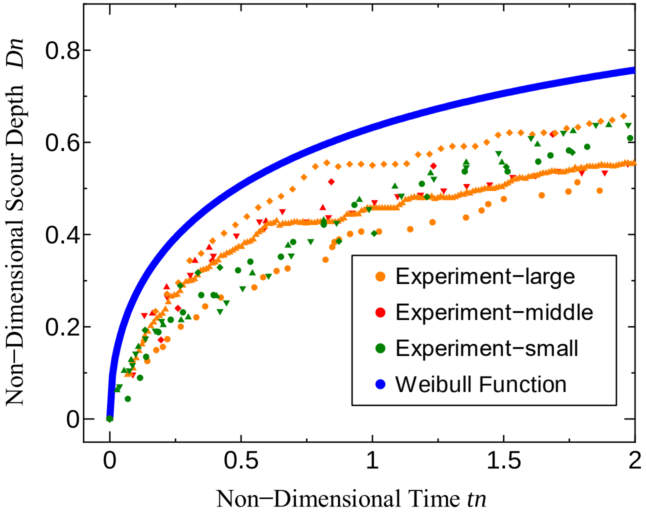
Weibull Function : $Dn = 1 - e^{-\sqrt{t_n}}$

$$\left(D_n = \frac{D(t)}{5.83 R_N}, \quad t_n = \frac{u_*}{\gamma_a R_N} t\right)$$

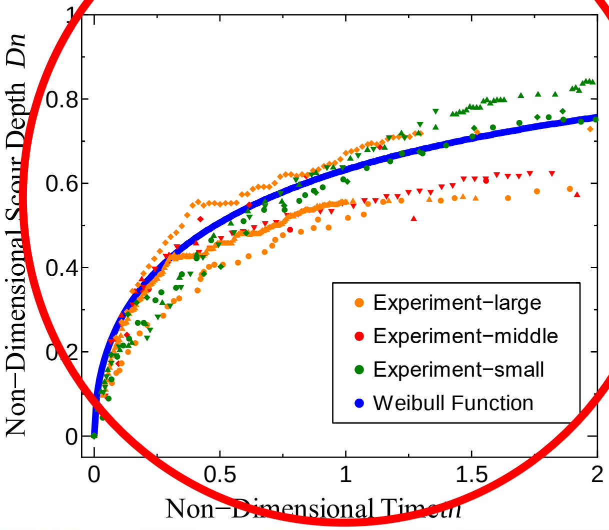
$\gamma_a = 1$



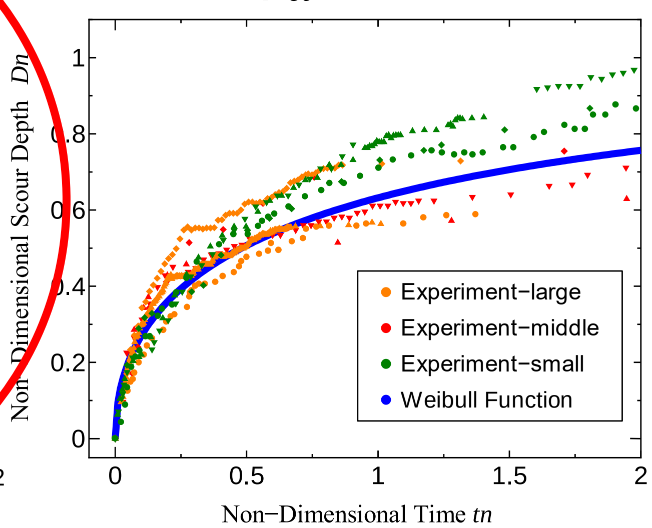
$\gamma_a = 10$



$\gamma_a = 20$



$\gamma_a = 30$

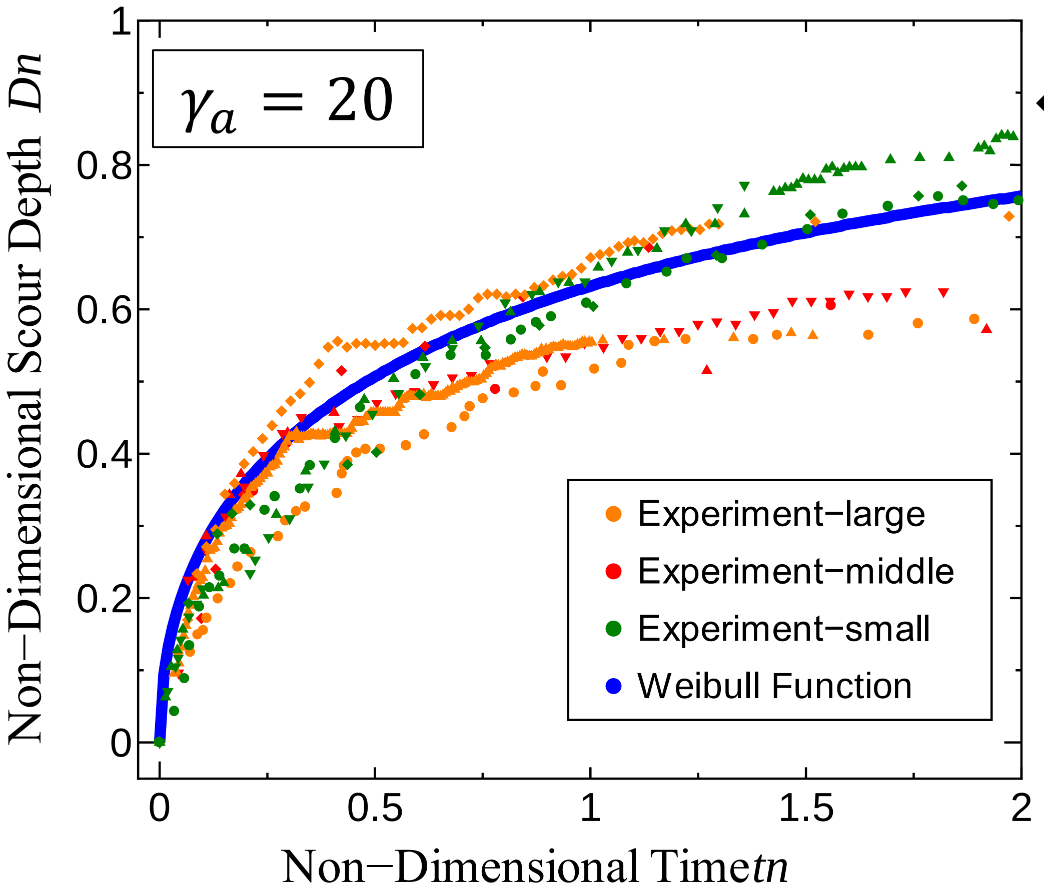


4. The estimation formula on scour

As a function of The Scour Depth, we use a Weibull Function as follows

Weibull Function : $Dn = 1 - e^{-\sqrt{t_n}}$

$\left(D_n = \frac{D(t)}{5.83 R_N}, \quad t_n = \frac{u_*}{\gamma_a R_N} t\right)$



The left figure shows the result of the estimation formula and the observed value.

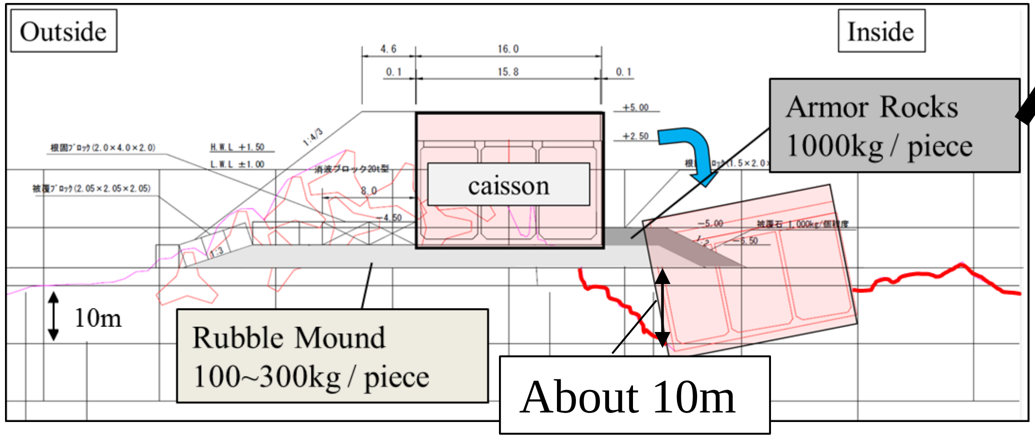
The Weibull Function correspond roughly well with the observed value.

4. The estimation formula on scour

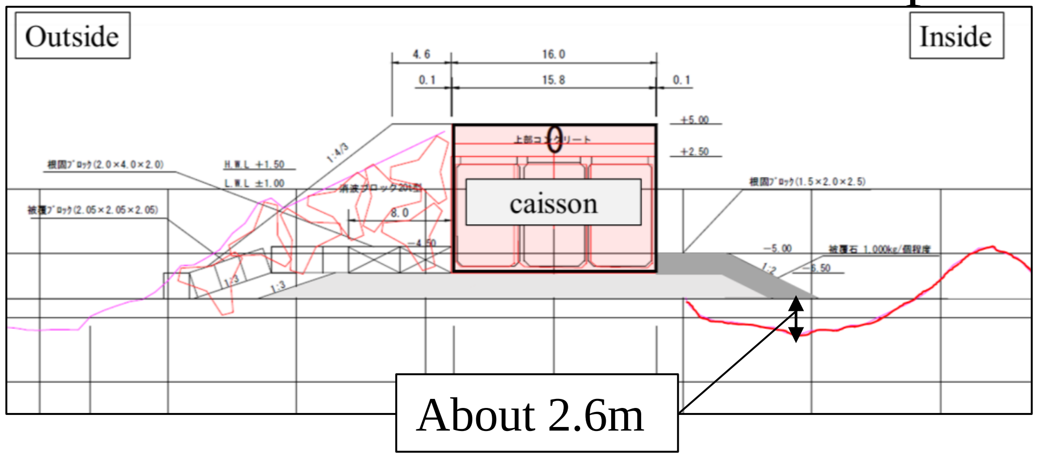
We attempted to estimate the scour depth at Hachinohe Port using the estimation formula.

Cross Section after disaster at Hachinohe Port

Collapse



Not Collapse



The armor rocks and the rubble mound were installed on the sand ground at Hachinohe Port. However, they were also scoured and washed away.

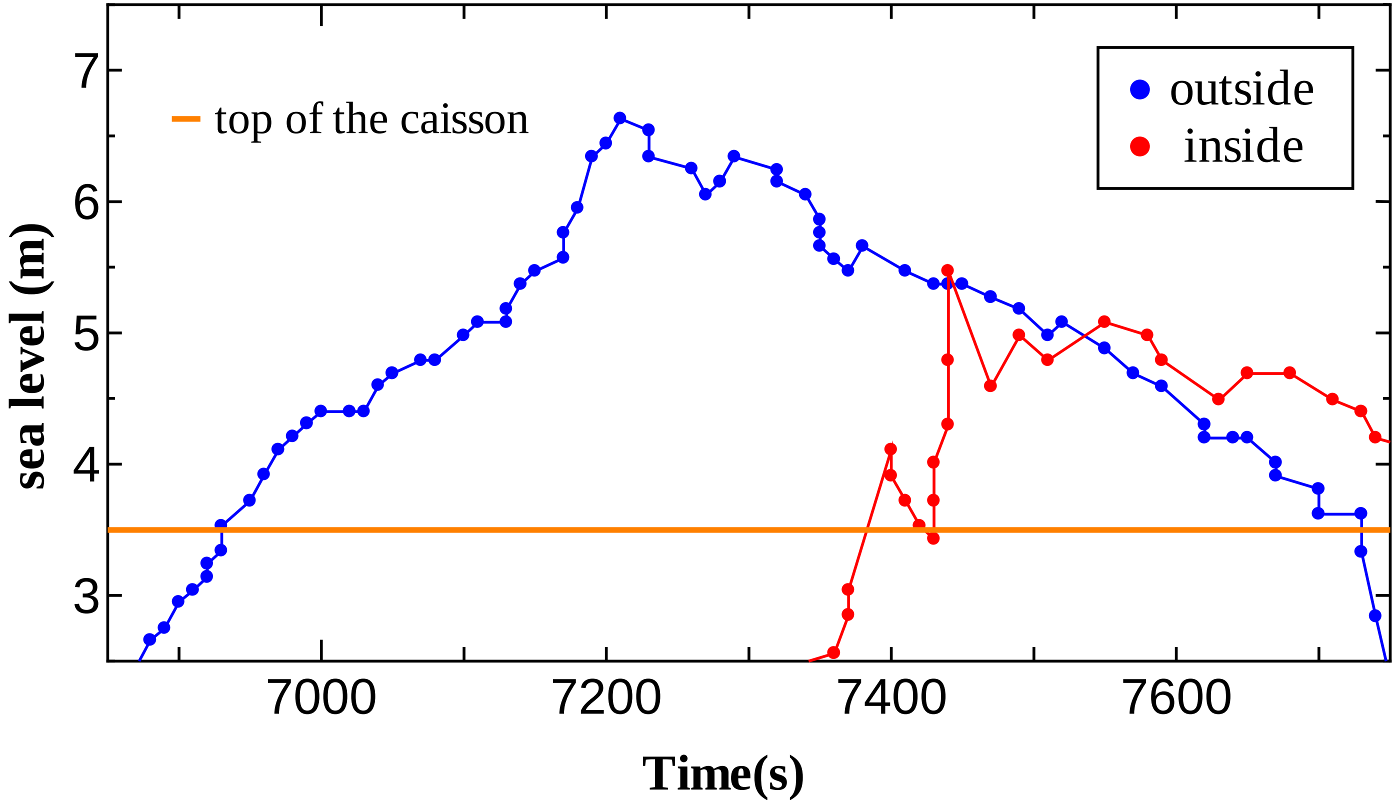
But...

The estimation formula is based on sand

We investigated an adequacy of the estimation formula assuming that the ground material is only sand layer.

4. The estimation formula on scour

Calculation result of tsunami water level at Hachinohe Port



Estimation formula : $Dn = 1 - e^{-\sqrt{t_n}}$

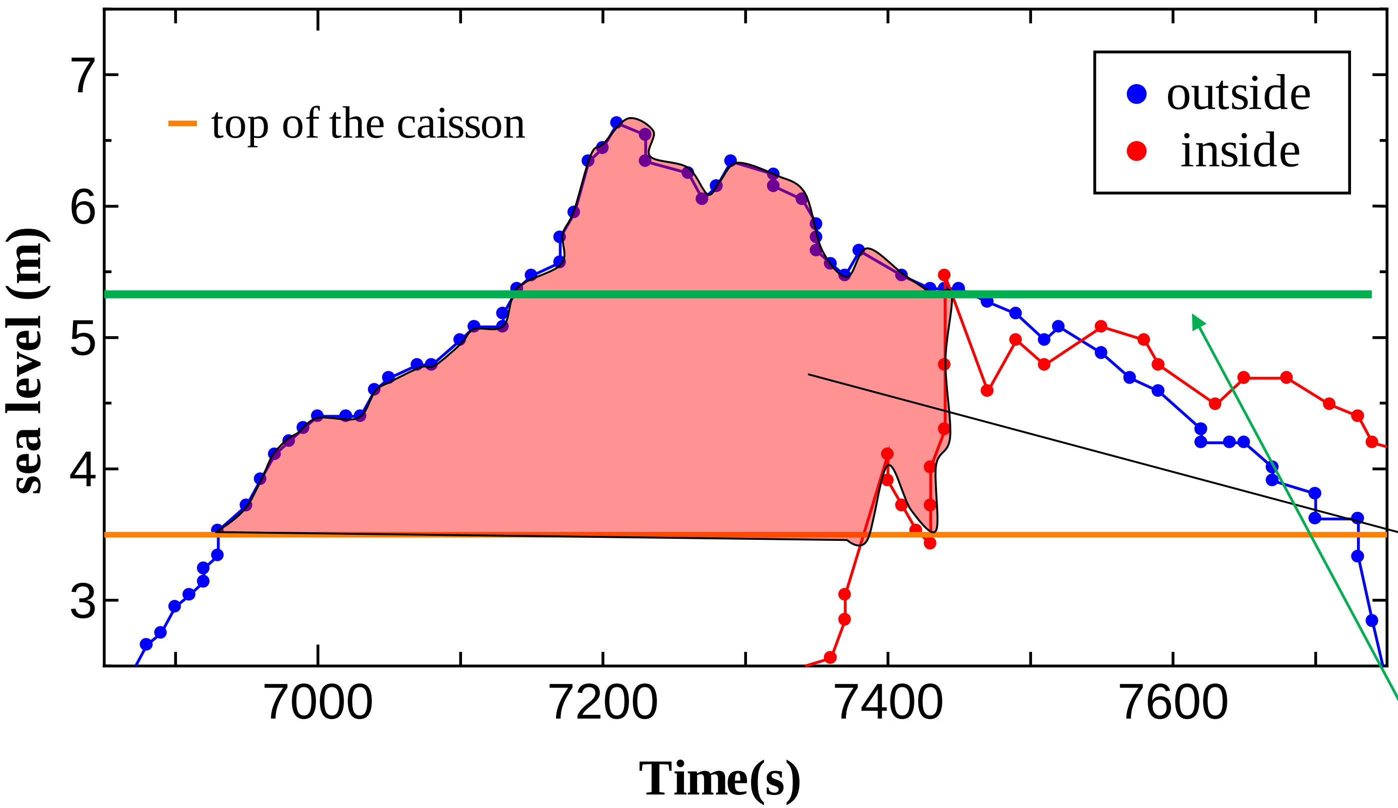
This formula can not evaluate the scour depth in unsteady overflow as shown in left figure

Therefore, we investigated the scour depth assuming that the overflow rate is constant.

*Refer to Ministry of Land, Infrastructure ,Transport and Tourism

4. The estimation formula on scour

Calculation result of tsunami water level at Hachinohe Port



*Refer to Ministry of Land, Infrastructure ,Transport and Tourism

To determine the constant overflow rate…

1. We calculate a surface area using free spreadsheet program as shown in left figure.

2. The value of the surface area is divided by the overflow time (480s), and an average of the overflow sea level is determined.

This surface area is about $900[m \cdot s]$
&
The overflow time is about $480[s]$

The average of the overflow water level is about $1.88[m]$

4. The estimation formula on scour

The average of the overflow water level is about 1.88[m]

The Homma`s overflow formula for the overflow rate

$$q = 0.35h\sqrt{2gh}$$

$$q = 0.35 \times 1.88 \times \sqrt{2 \times 9.8 \times 1.8} = 3.91[m^2/s]$$

1. Determination of the non-dimensional time t_n

$$t_n = \frac{u_*}{\gamma_a R} t = \frac{1.31}{20 \times 221} \times 480 = 0.142$$

2. Substitution the t_n for the non-dimensional scour depth D_n

$$\mathrm{Dn} = 1 - e^{-\sqrt{0.142}} = 0.314$$

3. Substitution the D_n for the non-dimensional scour depth formula

$$D_n(480) = 5.83 \times R \times D_n = 5.83 \times 221 \times 0.314 = 405[cm]$$

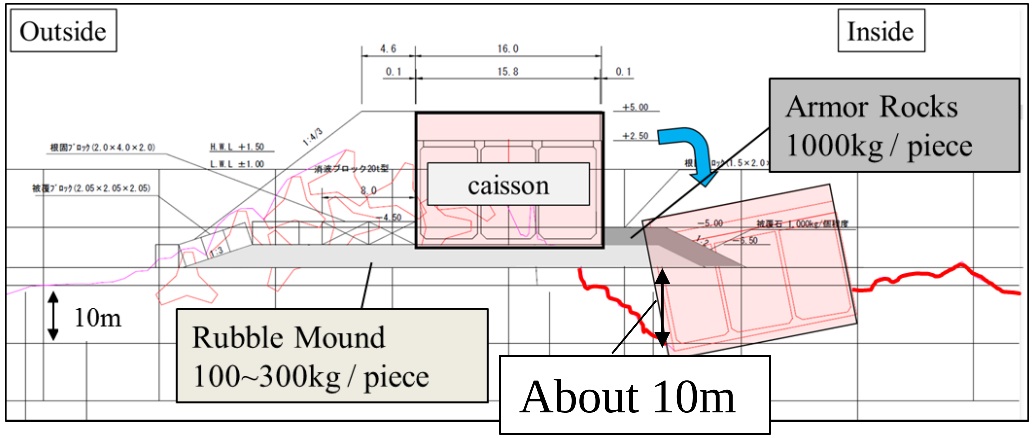
The estimation scour depth : 4.05m

Conditions

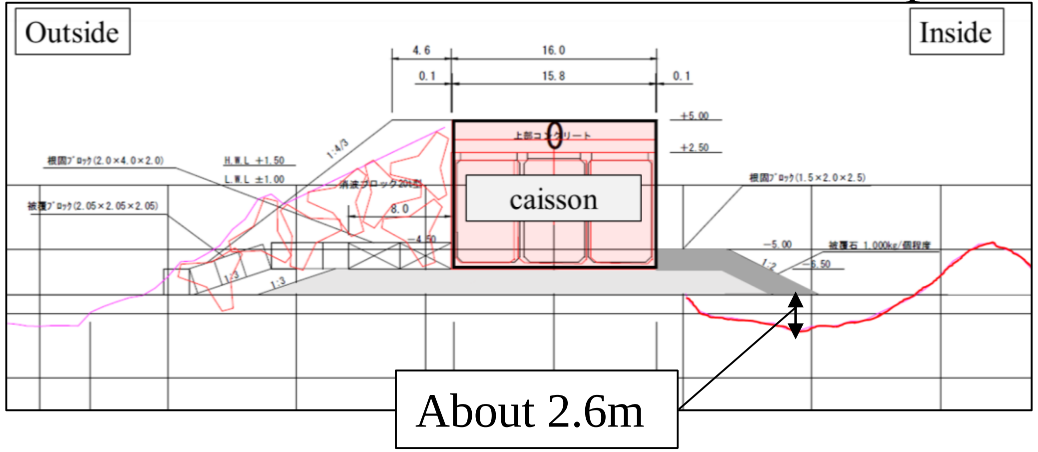
$q[m^2/s]$	3.91
$z_f[m]$	15
$g[m/s^2]$	9.8
$d[cm]$	0.001
$R_N[cm]$	221
γ_t	20
$u^*[cm/s]$	1.31
$t[s]$	480

4. The estimation formula on scour

Collapse



Not Collapse



The estimation total scour depth :4.05m

The actual scour depth at Hachinohe Port : 2.6m~10m

The order of the scour depth between the estimated value and the actual value is roughly the same.

FUTURE TASK

Conducting the scour experiment using rubble mound and armor rocks.

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1. Introduction
2. Experiment
3. Result of the experiments
4. The estimation formula on scour
5. Conclusion

5. Conclusion

We conducted the scour experiments and attempted to suggest a estimating formula on scour depth,
The conclusions are below.

- The Noguchi's formula $D = 2.1R_N$ evaluate the scour depth in 200s after the overflow, and the Arikawa's formula $D = 5.83R_N$ evaluate the scour depth in 4000s after the overflow.
- We attempted to suggest a estimating formula on scour depth using non-dimensional time and non-dimensional scour depth as below.

$$Dn = 1 - e^{-\sqrt{t_n}} \qquad \left(D_n = \frac{D(t)}{5.83R}, t_n = \frac{u_*}{\gamma_a R_N} \mathrm{t}\right)$$

- The result of the estimating formula was fit the field survey result of the Great East Japan Earthquake.

Thank you for your listening