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On ice pile-up height at the front of structure due to tsunami with sea ice

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ABSTRACT

There is much potential for damage due to tsunami with sea ice since megaquake in the vicinity of Chishima Trench, where locates at the south-eastern part of Hokkaido, Japan could happen any time. Though return period of earthquake here is from 340 to 380 years, more than 400 years have passed since the most recent major earthquake. In addition, on the 4th of March 1952, the Tokachi-oki earthquake (M8.2) occurred in the south-eastern part of Hokkaido, Japan. It created a tsunami 1-2m high on the eastern coast of Hokkaido, which, together with remaining sea ice, caused damage to residences and infrastructure. This action is likely to close roads and isolate settlements. A disaster prevention plan for opening roads to stricken areas is important for transport of goods and people. Therefore, it is crucial to understand the impact of sea ice on road structures when a tsunami occurs in a sea-ice-infested area. The purpose of this research is to give a useful information on the interaction between sea ice and structures to help road opening plan. More than 200 indoor-model tests have been conducted to determine the interaction mechanism between sea ice and road structures using models of sea ice made of poly-propylene. A method for estimating sea ice pile-up height at the front of a road structure is proposed here referring to Kovacs and Sodhi (1979). It is found that ice pile-up height is influenced by especially angle of repose of sea ice piece.

KEY WORDS: Ice pile-up; Tsunami; Earthquake

INTRODUCTION

On the 4th of March 1952, the Tokachi-oki earthquake (M8.2) occurred in the south-eastern part of Hokkaido, Japan. It created a tsunami 1-2m high, which, together with remaining sea ice, caused damage to residences and infrastructures. The pieces of sea ice were around 2m square (5m square as maximum) and 0.6m thick (1.3m thick as maximum) (Report of the Tokachi-oki Earthquake, 1954: Kioka, 2013a : Kioka, 2013b). Also, the 2011 Tohoku tsunami caused water to rise due to ice jam that occurred in the river and impact of ice on the water gate (Yoshikawa, 2012). In addition, it is reported that there is much potential for damage due to tsunami with sea ice since megaquake in the vicinity of Chishima Trench, where locates at the south-eastern part of Hokkaido, Japan could happen any time. Though return period of earthquake here is from 340 to 380 years, more than 400 years have passed since the most recent major earthquake. Other damage caused by tsunami run-up with ice floes have been reported (Kioka, 2015: Kioka, 2016). This action is likely to close roads and isolate settlements. However, there has been little research reported on the interaction between sea ice and road structures. Opening roads to stricken areas is important for transportation route for relief goods and people. This requires elimination of roads obstacles. Therefore, it is crucial to understand the interaction between sea ice and road structures when a tsunami occurs in a sea-ice-infested area. In the Sea of Okhotsk, sea ice can be seen overtopping breakwaters even during bad weather, as shown in Figure 1. In the present study, 238 indoor-model tests were conducted to determine the interaction mechanism between sea ice by run-up tsunami and road structure. The sea ice shape, size and thickness (11types) in addition to water level difference and road structure height were considered as parameters. Also, the model by Kovacs and Sodhi (1979) was applied to estimate ice pile-up height in front of the road structure.

Figure 1. Sea ice overtopping breakwaters in the Sea of Okhotsk (2015 not Tsunami)

TEST AND TEST CONDITIONS

Figure 2 shows the experimental device with a scale factor of 1/50, following the similarity rule of Froude. Width and length of channel are 0.4m and 9m, respectively. Ice floes were simulated by disk-shaped pieces and cuboid pieces made of poly-propylene (density: 0.912 g/cm^3) with 11 types of size D and thicknesses t shown in Figure 3 and Table 1.

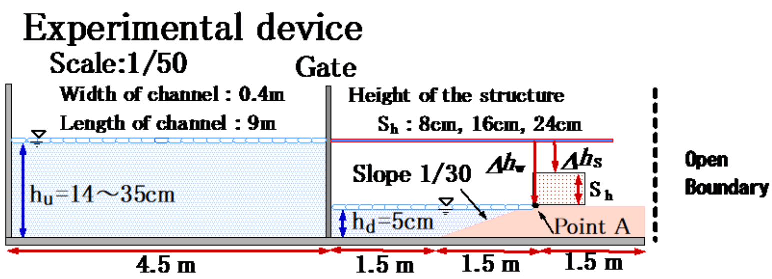


Figure 2. Experimental device

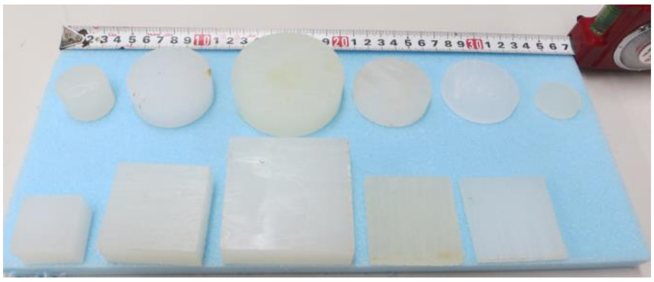


Figure 3. Poly propylene (11types)

Table 1. Ice floe model cases

***D* cm**	***t* cm**	**Shape**
3	2	CP
5	2	CP
7	2	CP
5	1	CP
5	0.5	CP
1.5	0.5	DSP
3	2	DSP
5	2	DSP
7	2	DSP
5	1	DSP
5	0.5	DSP

CP (cuboid pieces)
DSP (disk-shaped pieces)

A tsunami was then created by opening the gate suddenly. The sizes of the model sea ice at actual scale correspond to 1.5, 2.5 and 3.5m and the thickness correspond to 0.25m, 0.5m and 1m. Upstream water depth h_u was varied from 14cm to 38cm, and downstream water depth h_d and sea-bed slope were kept at 5cm and 1/30, respectively.

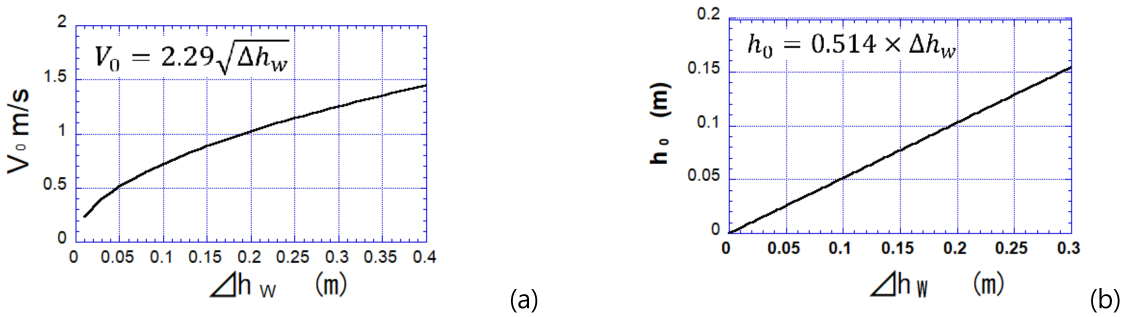


Figure 4(a)(b). Regression curves for (a) water velocity V_0 and (b) water depth h_0 at Point A.

Model road structure heights S_h were taken as 8cm, 16cm and 24cm. Dimensions Δh_w and Δh_s were considered as shown in Figure 2. Point A is a reference position where water velocity V_0 and water depth h_0 without the model structure were measured to obtain regression curves before the tests (Figure 4 (a)(b)). Indoor model tests were conducted for 238 cases to determine the interaction mechanism between sea ice caused by run-up tsunami and road structure by videotaping. Note that there was only one sea ice size and shape in each of the 11 test conditions, no mixing of ice pieces in any test.

TEST RESULTS

From these 238 cases, the interactions between sea ice by run-up tsunami and road structure were observed as shown in Figure 5(a), and the interactions can be divided into 3 types as shown in Figure 5(b), namely, sea ice piled up in front of structure (Type-A), sea ice remaining on structure with sea ice pile-up (Type-B), and sea ice over-topping structure (Type-C).

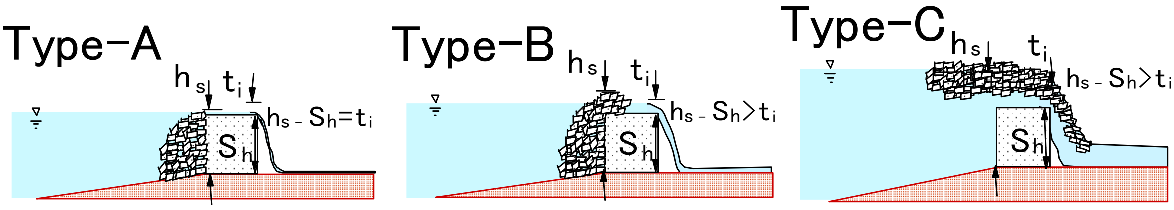
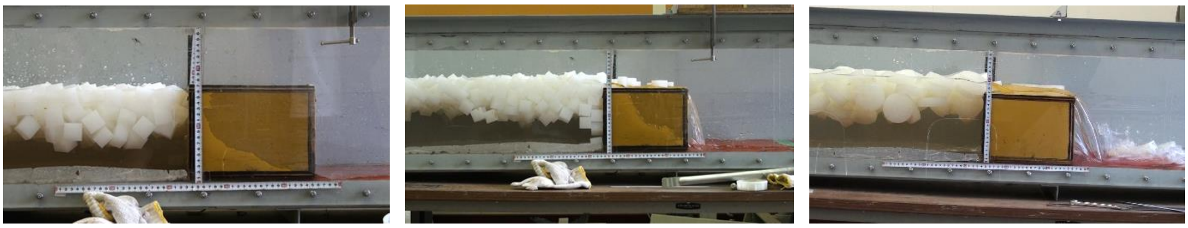


Figure 5(a). Three interaction types (Schematic)



(1) (2) (3)

Figure 5(b). Three interaction types (Tests)

(1) Type-A S_h=16cm, Δh_w=17cm, Δh_s=1cm, D=3cm(cuboid) t=2cm

(2) Type-B S_h=16cm, Δh_w=20cm, Δh_s=4cm, D=3cm(cuboid) t=2cm

(3) Type-C S_h=16cm, Δh_w=21cm, Δh_s=5cm, D=7cm(disk-shaped) t=2cm

Pile-up height h_s against dimension Δh_w, which relates to tsunami height, is investigated through the ice pile up model proposed by Kovacs & Sodhi (1979) (see Figure 6). In the model, the increase in gravitational potential energy for ice pile-up volume is equal to the work done by external force. The conservation of mass inside ice pile-up is also considered, and the following equation was derived.

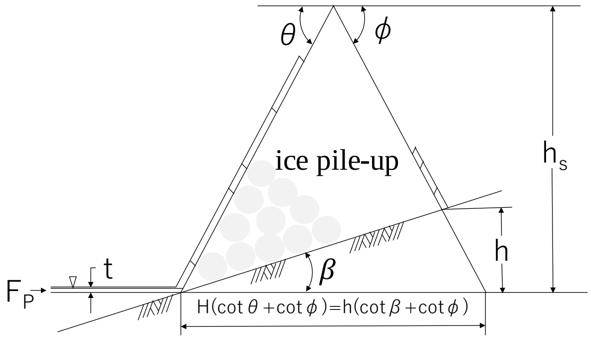


Figure 6. Ice pile-up model (Kovacs & Sodhi,1979)

$$F_p = \frac{1}{2}\rho_i g h_s t \frac{Q(\theta,\emptyset,\beta)}{P(\theta,\emptyset,\beta)} \quad \textbf{[1]}$$

$$P(\theta,\emptyset,\beta) = \frac{(tan\theta - tan\beta)(tan\theta + tan\emptyset)}{(tan\beta + tan\emptyset)tan^2\theta} \quad \textbf{[2]}$$

$$Q(\theta,\emptyset,\beta) = \frac{(tan\theta + tan\emptyset)}{tan\theta \times tan\emptyset} - \frac{(tan\theta + tan\emptyset)^3 tan^2\beta}{(tan\beta + tan\emptyset)^2 tan^3\theta tan\emptyset} \quad \textbf{[3]}$$

where, h_s: ice pile-up height, F_p: external force, ρ_i: ice density, t: ice floe thickness, g: gravitational acceleration. Angles θ, β and ϕ are shown in Figure 6.

From Figure 2, the slope of 1/30 corresponds to $\beta \fallingdotseq 1.9$ (deg.), and this gives us

$Q(\theta, \emptyset, \beta)/P(\theta, \emptyset, \beta)$ close to 1. Here, coefficient C_R is introduced to consider only the effect of angle θ of repose for simplicity.

Therefore,

$$F_p = \frac{1}{2} C_R \rho_i g h_s t \quad \textbf{[4]}$$

On the other hand, Kioka (2013a) considered this external force F_P as a drag force F_D **[5]**.

$$F_p = \frac{1}{2} \rho_w C_D {V_0}^2 t \quad \textbf{[5]}$$

where, ρ_w: sea water density, C_D: drag coefficient, V_0: water velocity

By using regression curve for V_0 (Figure 4(a)) against Δh_w, and $C_p=C_D/C_R$, equating equation [4] and equation [5], yields the following relation **[6]**.

$$h_s = \frac{2.29^2 \rho_w C_P}{\rho_i g} \Delta h_w \quad \textbf{[6]}$$

where, C_P: coefficient for ice pile-up height.

Using Type-A and Type-B data, the relation between dimension Δh_w and ice pile up height h_s is plotted in Figure 7(a)-(k)**.** Coefficients C_P, which are related to the slope of the line in Figure 7(a)-(k), are found to be from 1.65 to 1.9 depending on various shape, size and thickness.

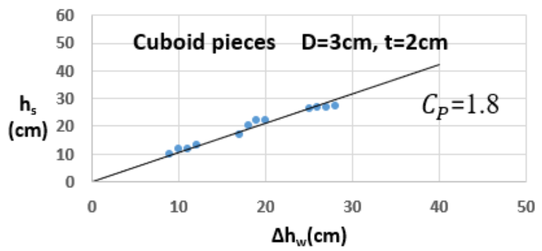
Next, Figure 8(a)-(k) show the plots of interaction types on the plane of Δh_w and Δh_s. In order to examine the transition from the interaction Type A to Type-B, ice pile up height h_s is compared to structure height S_h (=Δh_w - Δh_s) with an additional height t_i, which is introduced here and defined as (h_s - S_h) satisfying Type A.

Using also equation **[6]** and S_h (=Δh_w-Δh_s), equation **[7]** is obtained.

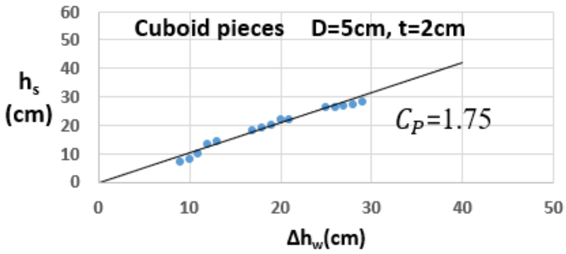
$$\Delta h_s = \left[1 - \frac{2.29^2 \rho_w C_P}{\rho_i g}\right] \Delta h_w + t_i = k \times \Delta h_w + t_i \quad \textbf{[7]}$$

where, t_i: additional height, k: constant depends on C_p.

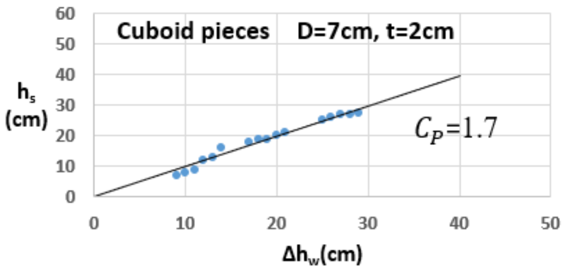
A maximum height of (h_s - S_h) satisfying Type A is taken here as t_i=3cm in Figure 8(a)-(k) to determine line of boundary between Type-A and Type-B. And, using ρ_i=912[kg/m^3], g=9.8[m/s^2], ρ_w=1000[kg/m^3], constant k=0.032, -0.003, -0.027, -0.056, -0.085, and -0.115 are obtained depending on C_P=1.65, 1.7, 1.75, 1.85, 1.9, respectively. These equations give the lower boundary of Type-B&C as reference lines. Note that Δh_w is greater than 8cm here since $\Delta h_w > S_h$**.**



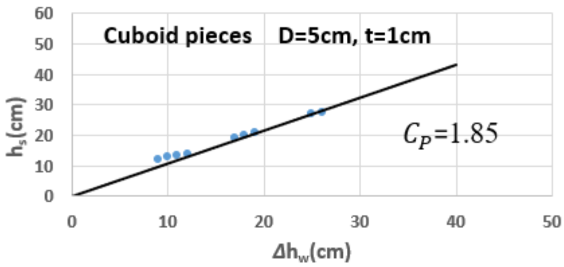
(a) (*D*=3cm, *t*=2cm) Cuboid pieces



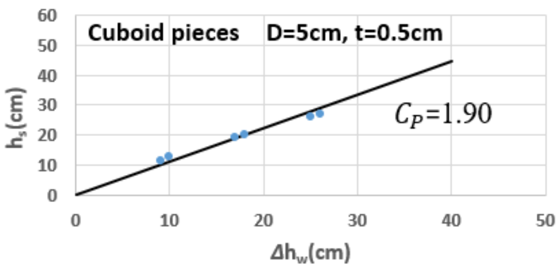
(b) (*D*=5cm, *t*=2cm) Cuboid pieces



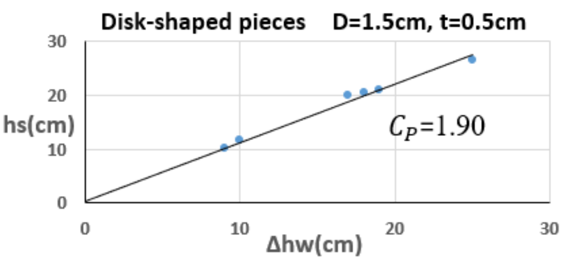
(c) (*D*=7cm, *t*=2cm) Cuboid pieces



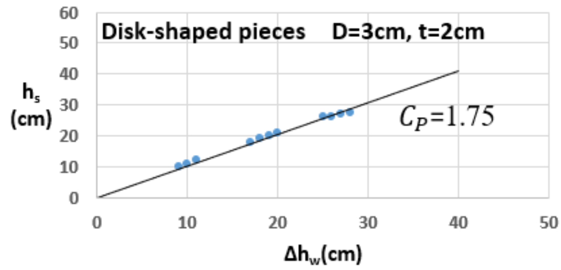
(d) (*D*=5cm, *t*=1cm) Cuboid pieces



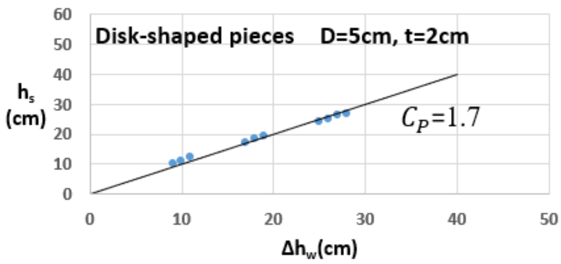
(e) (*D*=5cm, *t*=0.5cm) Cuboid pieces



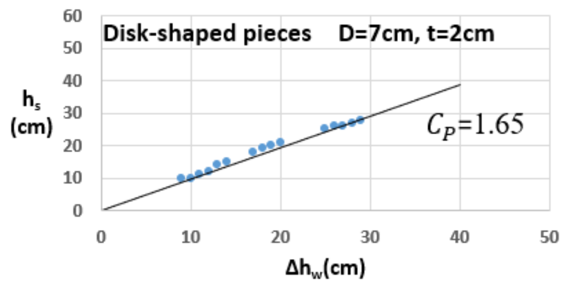
(f) (*D*=1.5cm, *t*=0.5cm) Disk-shaped pieces



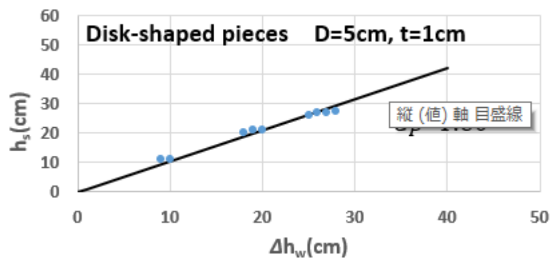
(g) (*D*=3cm, *t*=2cm) Disk-shaped pieces



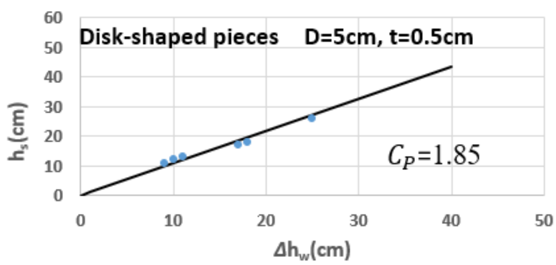
(h) (*D*=5cm, *t*=2cm) Disk-shaped pieces



(i) (*D*=7cm, *t*=2cm) Disk-shaped pieces

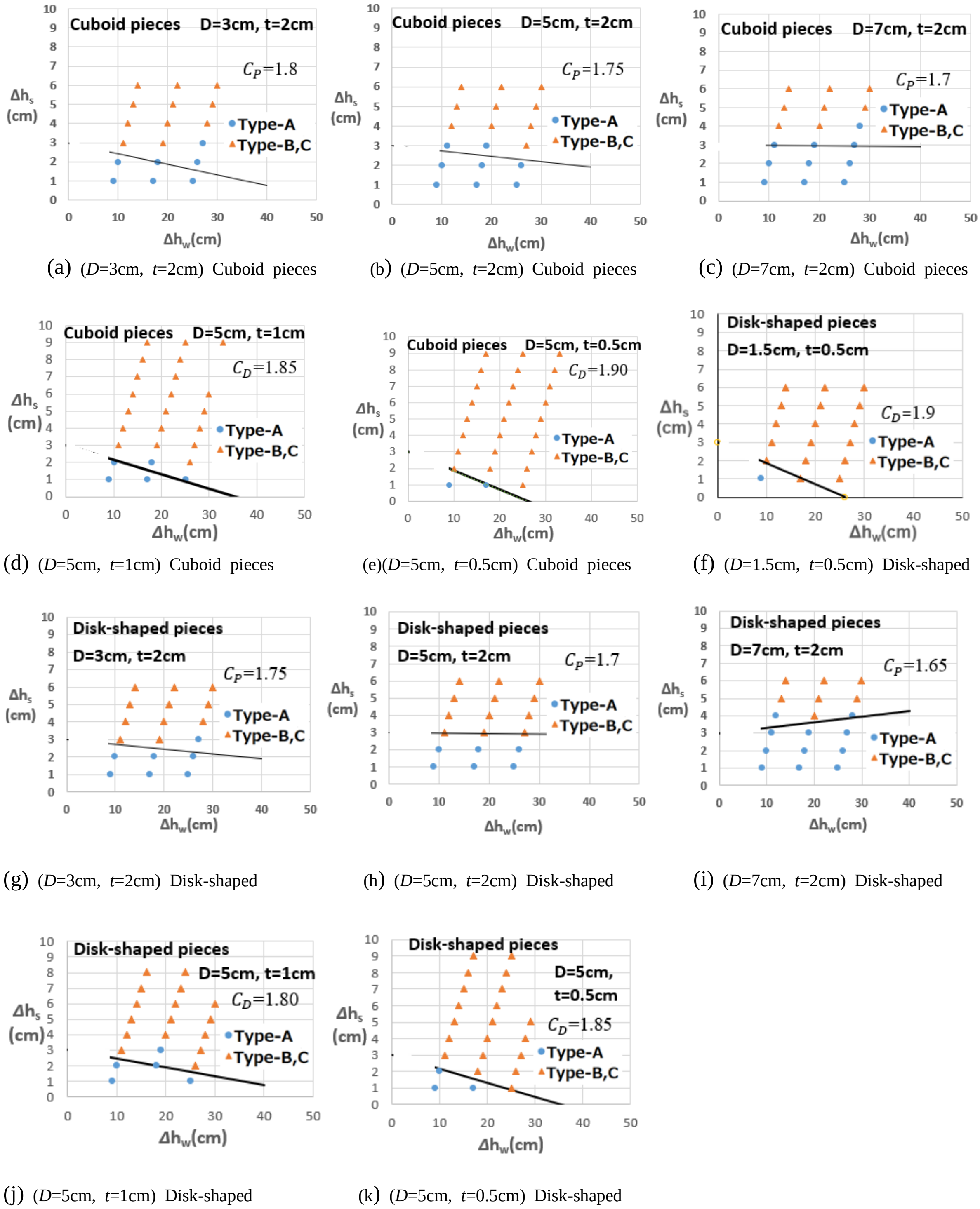


(j) (*D*=5cm, *t*=1cm) Disk-shaped pieces



(k) (*D*=5cm, *t*=0.5cm) Disk-shaped pieces

Figure 7. (a)-(k) Δh_w vs. h_s for Type-A and Type-B test data.



(a) (*D*=3cm, *t*=2cm) Cuboid pieces (b) (*D*=5cm, *t*=2cm) Cuboid pieces (c) (*D*=7cm, *t*=2cm) Cuboid pieces

(d) (*D*=5cm, *t*=1cm) Cuboid pieces (e)(*D*=5cm, *t*=0.5cm) Cuboid pieces (f) (*D*=1.5cm, *t*=0.5cm) Disk-shaped

(g) (*D*=3cm, *t*=2cm) Disk-shaped (h) (*D*=5cm, *t*=2cm) Disk-shaped (i) (*D*=7cm, *t*=2cm) Disk-shaped

(j) (*D*=5cm, *t*=1cm) Disk-shaped (k) (*D*=5cm, *t*=0.5cm) Disk-shaped

Figure 8. (a)-(k) Interaction types on the plane of $\triangle h_w$ and $\triangle h_s$ with line of boundary between Type-A and Type-B.

Also, angle θ of repose was measured 5 times for each piece size, and average was estimated. Figure 9 shows coefficient for ice pile up height C_P vs. angle θ of repose. For two types of pieces, as C_P increases with increasing θ and decreasing size and thickness. Note that C_D depends on Reynolds No, and C_D of cuboid pieces is greater than that of disk- shaped pieces, for test condition here. So, C_P depends on size, thickness, shape, and angle θ of repose of pieces.

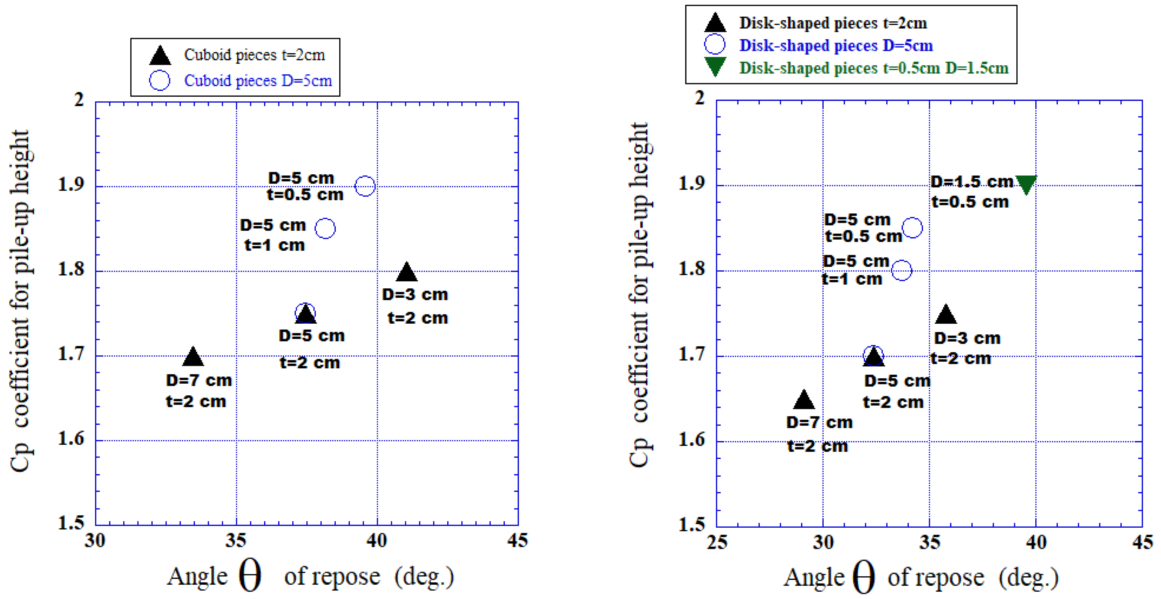


Figure 9. θ of repose vs. C_P. (Cuboid pieces and Disk-shaped pieces)

The following equation **[8]** is obtained using equation **[6]** and regression curve for h_0 (Figure 4(b)) against Δh_w.

$$\frac{h_s}{D} = \frac{\rho_w C_P}{\rho_i} \times F_{r0}^{\,2} \times \left(\frac{h_0}{D}\right) \qquad \textbf{[8]}$$

where, F_{r0}: Froude No. at Point A (Figure 2). F_{r0}=1.02 is obtained here from regression curves as shown in Figure 4(a)(b).

Also, test data on h_s/D is plotted against h_0/D with reference line for C_p=1.9 as shown in Figure10. Once h_0 (taken as flood water depth) and D are given, we can estimate h_s. So, this figure would be available for a disaster prevention plan for a tsunami in an ice infested sea.

CONCLUSIONS

The interaction between structure and sea ice by run up tsunami can be divided into three

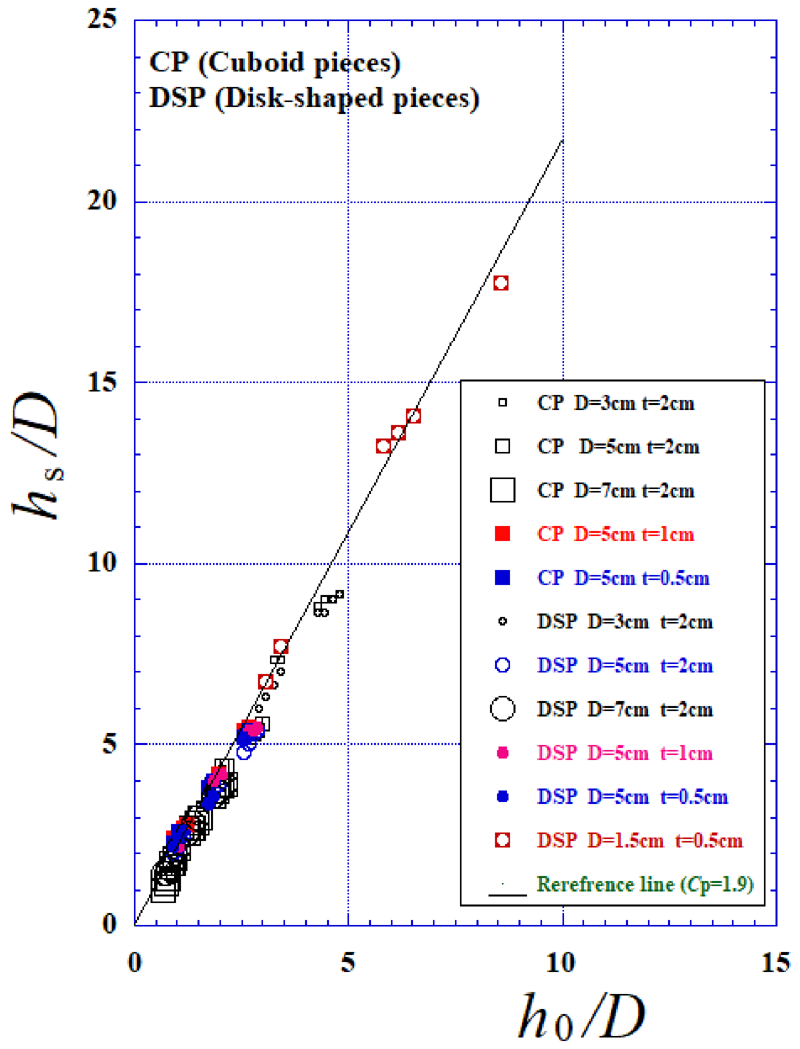


Figure 10. h_s/D vs. h_0/D

types. The height of sea ice piled up in front of a structure can be estimated from sea water density ρ_w, sea ice density ρ_i, coefficient C_p for ice pile up height and the difference Δh_w between upstream water height and reference height at the bottom of the structure. Once flow depth h_0 and size D of floe are given, ice piled up height h_s would be estimated referring Figure 10. These findings will be useful in developing a disaster prevention plan for tsunami in ice infested sea, since elimination of road obstacles is required to rush relief goods and people to the stricken area.

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