# CONDITIONS OF ARCHING AT BRIDGE PIERS DUE TO ICE SHEETS

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## ABSTRACT

In rivers which freeze over, ice jams may be developed by ice sheets which flow down the stream in the snow melting season of spring. They may cause floods as well as damage hydraulic structures and bridge piers. Ice jams which cause such disasters are likely to occur at bridge piers. Ice jams are said to develop in the following manner: a group of ice sheets forms an arch at the pier with the pier acting as a fulcrum, trapping oncoming ice sheets downstream; ice sheets and ice pieces develop into jam-shaped formations. Accordingly, the development of ice jams at the bridge pier is determined by whether there is an arch formed due to ice sheets.

The authors et al. have conducted systematic experiments related to conditions of arching at bridge piers for the past few years. While most of the experiments on parameters influencing ice arching were carried out using a model ice sheet with a uniform size, this paper reports conditions of arching when several bridge piers were installed at regular intervals and two types of model ice sheets with different sizes (10 x 10 cm; 5 x 5 cm) were used varying the mixing ratios. The results of the experiment clarified the following: arching is considerably affected by the mixing ratio; the tendency of arching significantly depends upon the cross-sectional form of the pier; arches are more likely to form if small-size ice sheets are mixed with large-size ice sheets at a certain ratio than when only large-size ice sheet are used; in reference to the relationship between bridge pier intervals (span) and the mixing ratio, the likeliness of arching can be reversed if the span exceeds the critical value of 45 cm, depending upon the mixing ratio; if the nose of bridge pier is inclined, there is a distinct difference in arching depending upon the mixing ratio.

## 1. INTRODUCTION

A thorough consideration must be paid to the interactions between ice sheets and bridge piers when designing a pier in a cold region river which freezes over in winter. The standard specifications of bridge design in cold region nations, such as the U.S., Canada and Russia, indicate a full consideration is paid not only to various rules concerning structure, hydraulics, and materials in designing the superstructure, substructure and foundation but also to the impact of ice upon bridge piers. In spite of a relatively detailed description of ice forces upon bridge piers such guidelines do not cover specific measures for defining the installation location for bridge piers and their spans.

In most rivers of cold region nations in the northern hemisphere, ice starts to melt from upstream, different from rivers in Japan. When such rivers develop ice jams caused by ice sheets floating down in the melting season of spring, hydraulic structures and bridge piers suffer damage while trapped water is likely to overflow, leading to floods. Ice jams which cause such damage are frequently observed to develop at bridge piers.

Ice jams which form at the piers are said to develop by way of the following: a group of ice sheets floating down the river forms an arch at the piers with the piers acting as a fulcrum; the arch traps the oncoming ice sheets floating downstream; ice sheets and ice pieces gather to develop into jams. Consequently, the development of ice jams at the bridge piers heavily depends upon whether an arch is formed by ice sheets. The study aims at clarifying, among various impacts of ice sheets upon bridge piers, the conditions under which arching occurs due to ice sheets at the bridge piers which can lead to ice jams. The research results will serve to decide the optimal location of installing bridge piers and their installation intervals.

## 2. THE PAST RESEARCH ON CONDITIONS OF ARCHING DUE TO ICE SHEETS

Among the past experimental research on the parameters influencing ice arching due to ice sheets, an experiment conducted by Calkins (1978) used model ice sheets. This research focused on a single span and varied the span and conditions of ice sheets. For the construction of new bridge piers, Smith (1981), planned four types of bridge piers and conducted an experiment of arching on each type of pier. Based upon the results of the experiment, he selected and applied the pier style least likely to form an arch by ice sheets. On the other hand, Babic et al. (1992) and Melanie et al. (1994) carried out simulation experiments on arching at the both banks of the river channel acting as the fulcrums, using the discrete element method. The results are different from those of other experiments.

We have conducted systematic experiments on the conditions of arching when there are more than two bridge piers. Hara et al. (1993), in similar experiments, used two types of prototype models with scales of 1/50 and 1/150, respectively, and verified that there is a law of similitude in accordance with Froude number on the whole. Moreover, Hara et al. (1994) through an experiment which varied the cross-sectional shape of a bridge pier and nose inclination, clarified the impact of such factors upon arching. The following is concluded from the experiments:

- There is a general accord in the results of the experiments with different scales of prototype but with a similar Froude number, thereby the law of similitude was valid.
- If the size of ice sheets (a) and span (b) are fixed, as the movement of ice sheets is slower, an arch is formed with a lower ratio of ice sheets covering the river surface.
- No significant effect by the cross-sectional shape of the pier is observed upon arching. A perpendicular pier with a semicircular cross-section, and without nose inclination is least likely to form an arch.

Most of the above-mentioned past research was conducted using models of ice with a uniform size, with the one exception of Calkins who mixed different sizes of ice sheets. However, no experiment has been conducted under conditions when more than two bridge piers were installed.

Our research, consequently, aims at clarifying the impact of ice sheets upon the conditions of arching through a variation of mixing ratios of the two sizes of models when there are more than two piers.

## 3. CONDITIONS OF ARCHING WHEN MIXING ICE SHEETS OF DIFFERENT SIZES

### 3.1 Method of the Experiment

In the experiment, we used a 11 m-long, 2 m-wide and 0.6 m-deep watercourse as shown in Fig. 1. The scale that was decided on was approximately 1/50 based upon the size, thickness of the ice sheet, and the width of bridge pier. Two types of model piers with different cross-sections were used: rectangular and semicircular. The pier with a rectangular cross-section was 4 cm-wide, 10 cm-long, and 50 cm-high steel made. They were prepared with two different kinds of nose: perpendicular and inclined by 60°. Steel boxes with the same size as the rectangular model were prepared for the pier with a semicircular cross-section and provided with a mortar semicircular nose on the upstream side of the box. This perpendicular nose was used exclusively for the semicircular model.

The feeder installed on the watercourse can feed model ice sheets within the velocity range of 0-30 cm/sec. The experiment was carried out by varying the ratio of the model ice sheets covering the surface of water between 10-100 %, and by adjusting the speed of feeding ice sheets.

The traveling speed of the ice sheet was set at a uniform value of approximately 10 cm/sec. Three different clear span ($b_1$) of the piers were tested in the experiment: 26 cm, 36 cm, and 46 cm. Two types of model ice sheet were used: square with 10 cm sides and 5 cm sides and with the width of 1 cm. When the ice sheets used in one experiment converted to 10 cm sides ice sheets, about 800 of them were used. The model ice sheet was polypropylene board with the density of 0.9 g/cm. The friction coefficient between the model ice sheets was almost the same as the dynamic friction coefficient between natural ice sheets (0.1-0.2).

The whole process of the experiment was recorded with a video camera installed just above the model piers. The results of the experiment were analyzed based upon the video recording. The criteria as to whether there was an arch formed or not was determined as follows: if an arch forms over the whole width of the watercourse and remains still for over 10 minutes, it was classified as an arching and indicated as ● in Figs.; if, on the other hand, no arch was formed or if only an ephemeral arch formed lasting for only 20-30 seconds, it was classified as no arching and indicated as ○. If an arching lasted only a few minutes, it was classified as a transitive arching and indicated as ▲.

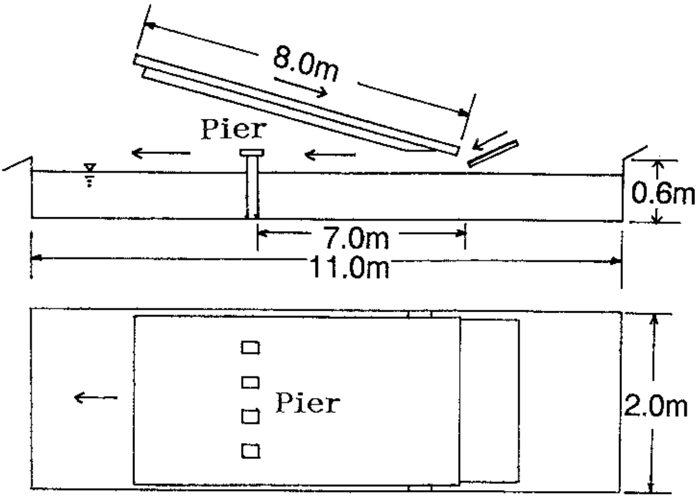

Fig. 1. The watercourse for 'arching' experiment

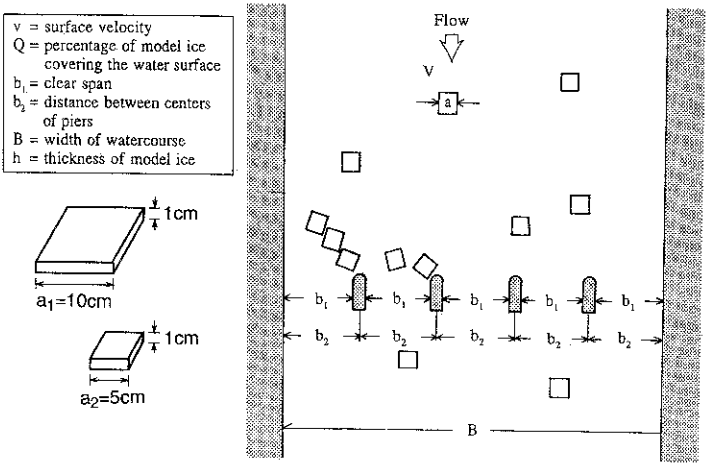

Fig. 2. Specifications of the experiment

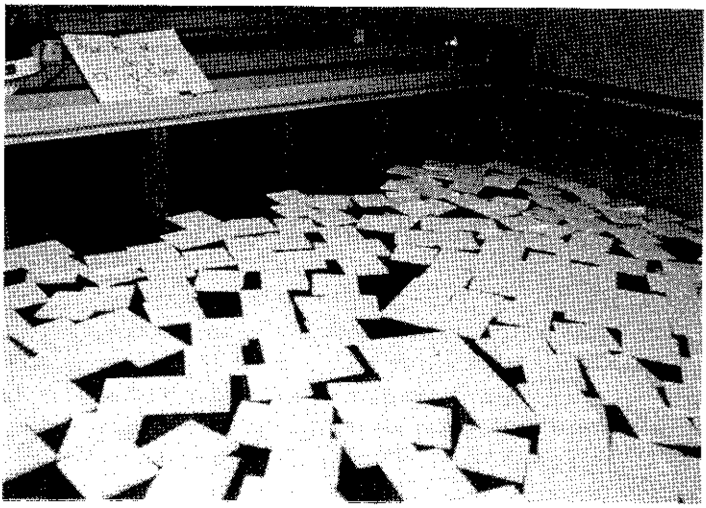

Photo 1. The case when an arch is formed

3.2 The Effects upon Arching by the Mixing Ratio of Different Sizes of Ice Sheets

To examine the effects of the mixing ratios of 10 cm model ice sheets and 5 cm model upon conditions of arching, we conducted an experiment under the following conditions and confirmed whether there was an arching. The span was fixed at 30 cm ($b_1$ = 26 cm). The ratio of mixing ice sheets varied using the following 5 stages: 10 cm ($a_1$) is 100 %, 10 cm ($a_1$): 5 cm ($a_2$) = 75:25, 50:50, 25:75, and 5 cm ($a_2$) is 100 %. With each mixing ratio, the ratio of ice sheets covering the water surface was changed. The bridge piers with a rectangular and a semicircular cross-sections were used with nose inclination of 90° (perpendicular). The traveling velocity of the ice sheets was approximately 10 cm/sec.

Figs. 3 and 4 illustrate the results of experiments for rectangularandsemicircular pier models, respectively. The horizontal axis A indicates the covering ratio of ice sheets with sides of 10 cm ($a_1$) over the total area of ice sheets on the water surface. This was introduced by the following equation (1) based upon the method of Calkins (1978). Accordingly, A = 0 indicates the example using model ice sheets with sides of 5 cm ($a_2$) exclusively and A = 1 shows model ice sheets with sides of 10 cm ($a_1$) were used exclusively. As A becomes closer to 1, the percentage of ice sheet with sides of 10 cm covering the water surface increases.

$$A = \frac{n_1 A_1}{n_1 A_1 + n_2 A_2} \quad \text{.....................................................(1)}$$

Where A = the covering ratio of ice sheet with sides of 10 cm over the total area of ice sheets on the water surface

$n_1$ = the number of ice sheets with sides of 10 cm ($a_1$)
$n_2$ = the number of ice sheets with sides of 5 cm ($a_2$)
$A_1$ = the area of one ice sheet with sides of 10 cm ($cm^2$)
$A_2$ = the area of one ice sheet with sides of 5 cm ($cm^2$)

The results revealed the following. An arch was formed for both kinds of bridge piers with approximately the same covering ratio (Q) as the case which used larger ice sheets exclusively when the covering ratio (A) of larger ice sheets over the total area of whole ice sheets exceeded a certain level. However, the value of A, forming an arch with about the same Q as the case using exclusively larger ice sheets showed a difference depending upon the cross-sectional shape. While A is 0.7 (indicating that ice sheets with sides of 10 cm covers 70 % of the total area of ice sheets) in the case of the pier with a rectangular cross-section, A is 0.40 in the case of the pier with a semicircular cross-section. This shows that a bridge pier with a semicircular cross-section is more likely to form an arch than the rectangular cross-section pier at a lower ratio of A.

When A was approximately 0.7 or over in the case of the rectangular pier and 0.40 or over in the case of the semicircular pier, an arch was formed with Q about the same as the case exclusively using ice sheets with sides of 10 cm. A close examination, however, reveals that as these values of A become closer to 1.0, the covering ratio of ice sheets over the water surface (Q) forming an arch tends to become higher. In other words, an arch is more likely to form in the case mixing the 5 cm model ice sheets at a certain ratio with the 10 cm model ice sheets than in the case exclusively using the 10 cm model.

Consequently, the value of A with the mixing ratio of ice sheets most likely to form an arch is 0.7 for the pier with a rectangular cross-section and 0.4 for the pier with a semicircular cross-section. In terms of the covering ratio of the two kinds of model ice sheets, 10 cm and 5 cm, over the total area of ice sheets on the water surface is 7: 3 for the pier with a rectangular cross-section and approximately 4: 6 for the pier with a semicircular cross-section.

### 3.3 Conditions of Arch Formation when Span And Mixing Ratios Are Varied

Piers with a rectangular cross-section were used. The mixing ratio of model ice with sides of 10 cm and 5 cm was set at three levels: 50:50, 75:25 and 100:0. Due to the aforementioned relation between the mixing ratio and arching, when model ice with sides of 10 cm were less than 50 % of the total of model ice, arching hardly occurred. (The experimental results of Hara (1994) were used as data when model ice sheets with sides of 10 cm were exclusively used.) It was not possible to maintain the mixing ratio perfectly in the experiment. Therefore, there was an error allowance for each ratio. The span of the bridge piers (b) was set at three different values: 30 cm, 40 cm and 50 cm. Their clear spans (net distance) were 26 cm, 36 cm and 46 cm, respectively. An average value of the sides of ice models (a) was calculated by equation (2), according to Calkins' method (1978).

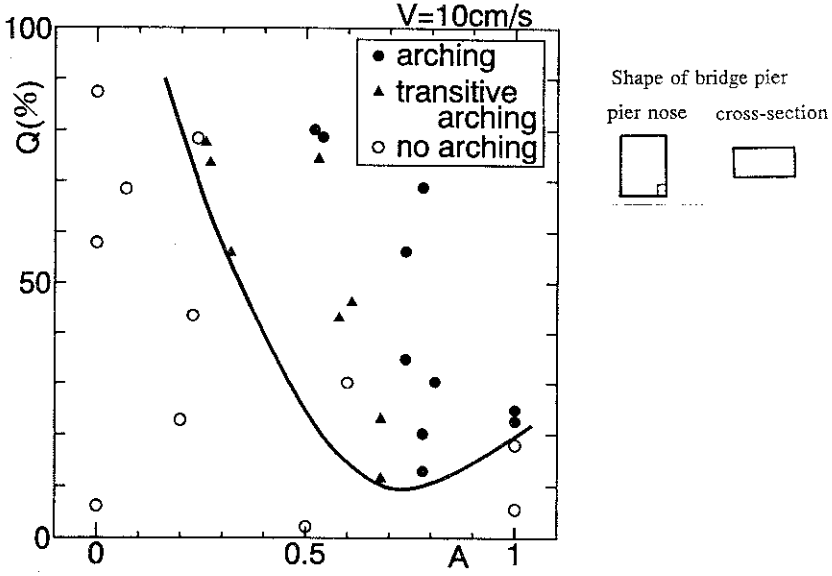

Fig. 3. Relationship between the mixing ratio of ice sheets and arching in the case of the pier with rectangular cross-section

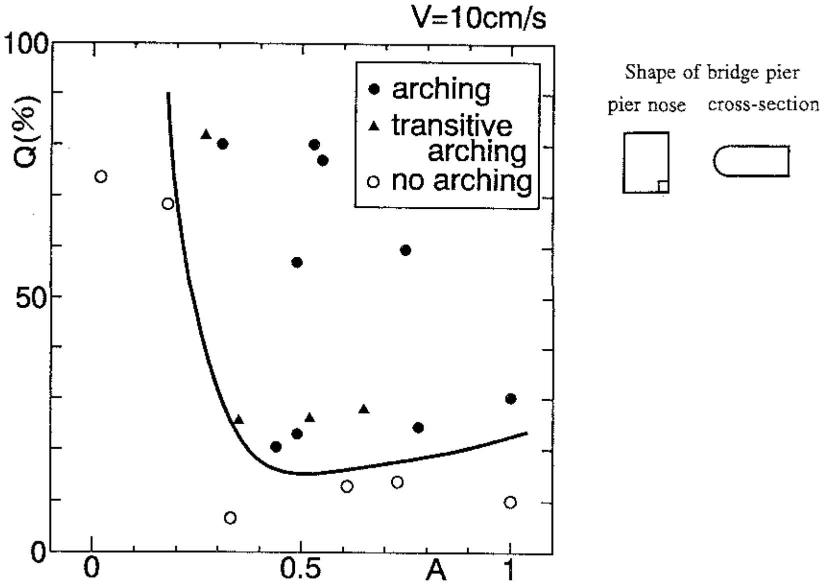

Fig. 4. Relationship between the mixing ratio of ice sheets and arching

$n_1$ = the number of ice sheets with sides of 10 cm ($a_1$)
$n_2$ = the number of ice sheets with sides of 5 cm ($a_2$)
$A_1$ = the area of one ice sheet with sides of 10 cm (cm$^2$)
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The results revealed the following. An arch was formed for both kinds of bridge piers with approximately the same covering ratio (Q) as the case which used larger ice sheets exclusively when the covering ratio (A) of larger ice sheets over the total area of whole ice sheets exceeded a certain level. However, the value of A, forming an arch with about the same Q as the case using exclusively larger ice sheets showed a difference depending upon the cross-sectional shape. While A is 0.7 (indicating that ice sheets with sides of 10 cm covers 70 % of the total area of ice sheets) in the case of the pier with a rectangular cross-section, A is 0.40 in the case of the pier with a semicircular cross-section. This shows that a bridge pier with a semicircular cross-section is more likely to form an arch than the rectangular cross-section pier at a lower ratio of A.

When A was approximately 0.7 or over in the case of the rectangular pier and 0.40 or over in the case of the semicircular pier, an arch was formed with Q about the same as the case exclusively using ice sheets with sides of 10 cm. A close examination, however, reveals that as these values of A become closer to 1.0, the covering ratio of ice sheets over the water surface (Q) forming an arch tends to become higher. In other words, an arch is more likely to form in the case mixing the 5 cm model ice sheets at a certain ratio with the 10 cm model ice sheets than in the case exclusively using the 10 cm model.

Consequently, the value of A with the mixing ratio of ice sheets most likely to form an arch is 0.7 for the pier with a rectangular cross-section and 0.4 for the pier with a semicircular cross-section. In terms of the covering ratio of the two kinds of model ice sheets, 10 cm and 5 cm, over the total area of ice sheets on the water surface is 7: 3 for the pier with a rectangular cross-section and approximately 4: 6 for the pier with a semicircular cross-section.

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$$a = \frac{n_1 a_1 + n_2 a_2}{n_1 + n_2} \quad \text{......................................................}(2)$$

Where a = the average value of sides of ice floes which cover the water
$a_1$ = the side of the larger model ice (10 cm)
$a_2$ = the side of the smaller model ice (5 cm)

Table 1. The order of mixing ratios under which arching was most likely to occur

**Rectangular ( Inclination with 90°)**

| b1 | 1st | 2nd | 3rd |
|---|---|---|---|
| **26** | **75:25 ( 3.1%)** | **100: 0 (24,3%)** | **50:50 (30.9%)** |
| **36** | **75:25 (11.8%)** | **100: 0 (35.2%)** | **50:50 (42.9%)** |
| **46** | **75:25 (32.2%)** | **100: 0 (46.5%)** | **50:50 (54.4%)** |

**Rectangular ( Inclination with 60°)**

| b1 | 1st | 2nd | 3rd |
|---|---|---|---|
| **26** | **75:25 (0.05%)** | **50:50 (12.7%)** | **100: 0 (19.8%)** |
| **36** | **75:25 ( 1.2%)** | **100: 0 (30.4%)** | **50:50 (33.0%)** |
| **46** | **75:25 (14.2%)** | **100: 0 (41.8%)** | **50:50 (69.1%)** |

Figs. 5 to 7 show the results of experiments when the mixing ratio of these two sizes of model ice and the span were varied. The critical curves of arching are shown in Fig. 8. When the mixing ratio of model ice with sides of 10 cm and 5 cm was at 100:0 or 50:50, the experiment results were almost same. However, when the mixing ratio was at 75:25, the result was different. In this mixing ratio, as the span became smaller, arching was increasingly more likely to occur. When b (clear span) was 30 cm, arches were formed even when the value of Q (ice cover ratio over the water surface) was around 10 %.

When Q was 50 % and the value of $a/b_1$ was larger than 0.17, arches were likely to be formed with the mixing ratio at 75:25. Conversely, when the value of $a/b_1$ was smaller than 0.17, arches were likely to be formed at the mixing ratios of 50:50 and 100:0. Table 1 shows the mixing ratio of model ice according to the order of arch formation which tended to occur for respective length of span, b. The figures in parentheses are the ice cover ratios over the water surface when arches are formed (Q). It is obvious from the table that when the span was between 30 cm and 50 cm, arching was most likely to occur with the mixing ratio of 75:25. Arching was less likely to occur with the ratio of 100:0 and even less likely at 50:50.

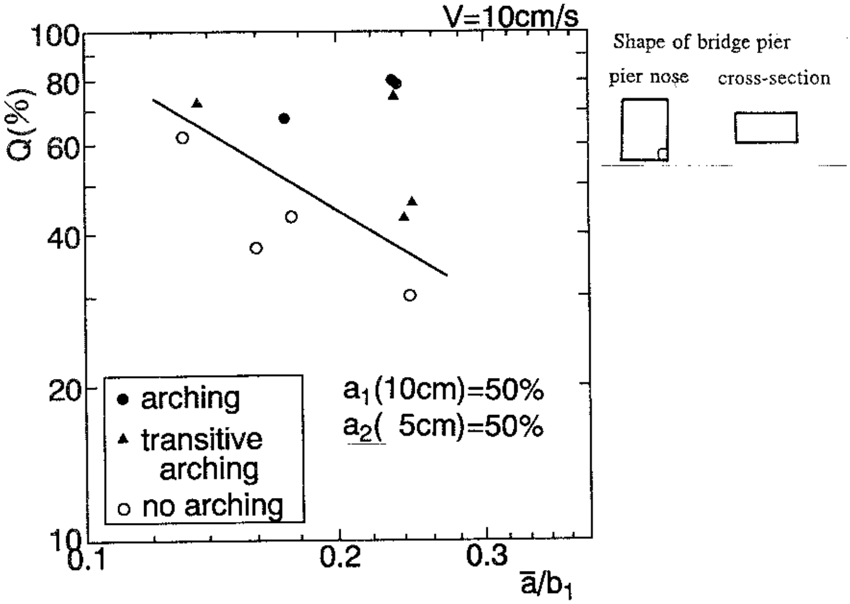

Fig. 5 Critical state of arching: 10 cm:5 cm = 50:50 (Nose 90°)

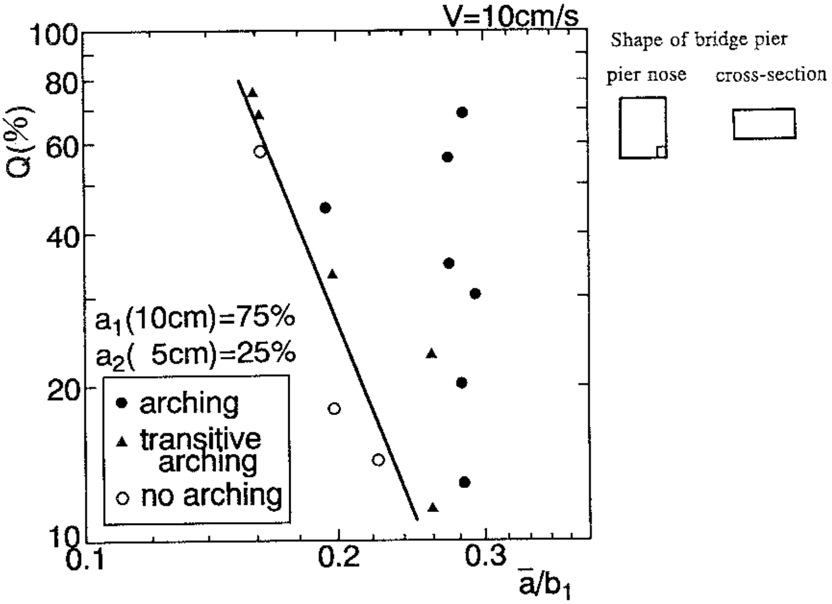

Fig. 6 Critical state of arching : 10 cm:5 cm = 75:25 (Nose 90°)

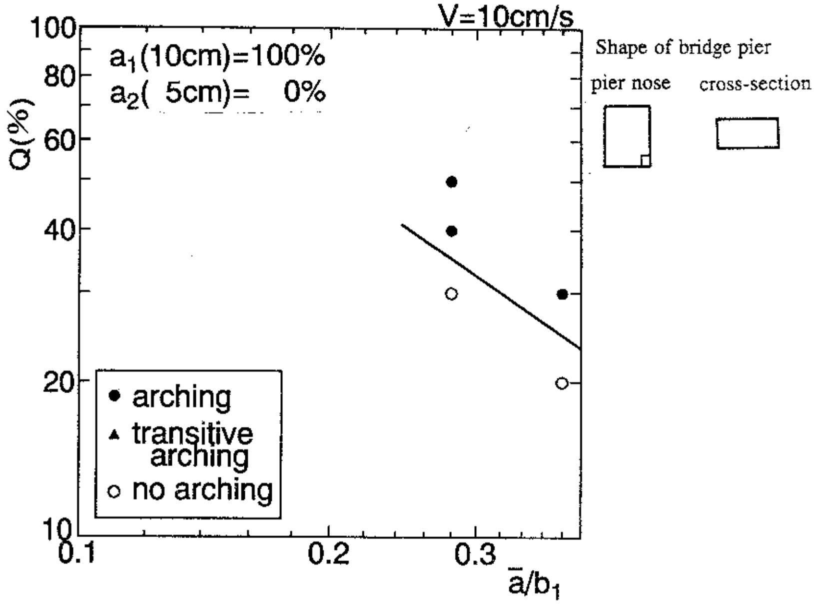

Fig. 7. Critical state of arching: 10 cm:5 cm = 100:0 (Nose 90°)

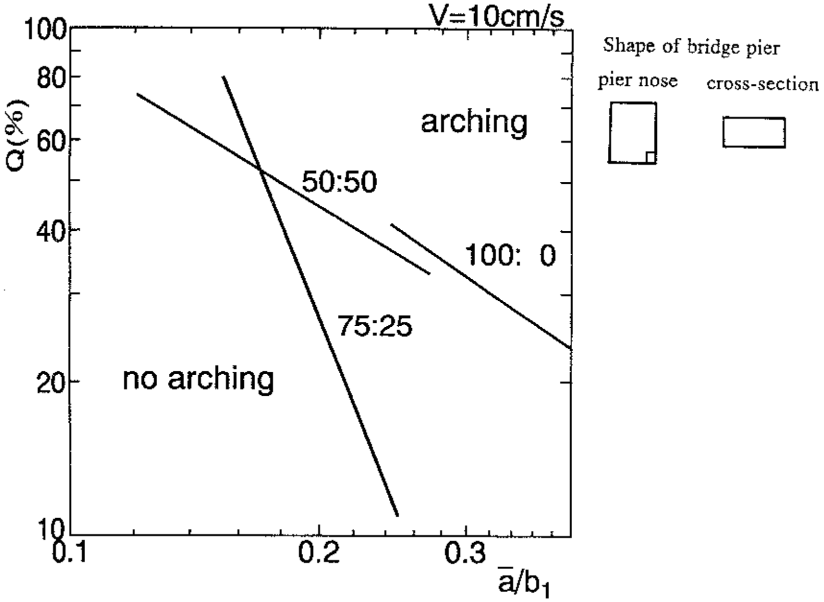

Fig. 8. The relation between the mixing ratio and critical state of arching (Nose 90°)

### 3.4 The Relationship between the Inclination of Pier Nose, the Mixing Ratio and Arching

We conducted an experiment using model piers where the nose was inclined at 60°. Their cross-sectional form was rectangular and the mixing ratio of model ice was set at 10 cm: 5 cm = 50:50, 75:25 and 100:0. Figs. 9 to 11 show the results. Fig. 12 shows the critical states of arching.

When the mixing ratio was at 50:50, arching was most likely to occur regardless of the length of span. The result was the same for the piers with an inclination of nose at 90° (perpendicular). The difference of critical states of arching between the mixing ratio of 50:50 and 100:0 is as follows: except when b was 30 cm, arches were likely to form when model ice with sides of 10 cm were exclusively used. On the other hand, when b was 30 cm, arches were likely to form at the ratio of 50:50.

Figs. 5 and 6 show the results of experiments when the inclination of the pier nose was at 60°. Figs. 9 and 10 show the results when perpendicular piers were used. Fig. 13 shows the results when the mixing ratio was 50:50 for both kinds of piers: inclination of the nose being 60° and 90° (perpendicular). Fig. 14 shows the results when the mixing ratio is 75:25. As clearly illustrated by these figures, when the mixing ratio is at 75:25, the difference in the degree of inclination of the nose did not make much difference. However, when the mixing ratio was 50:50, there was a significant difference in the tendency of arches to form when the degree of inclination of the nose was different. (Fig. 13). As shown in Fig. 13, before the point when the ice cover ratio over the water surface (Q) exceeded about 50 %, $a/b_1$ being 0.18 and the length of span (b) about 45 cm, arching was more likely to occur on piers where the nose inclination was 60° than where the nose inclination was 90°. However, these results reversed at the point. Furthermore, when the length of the span exceeded 45 cm, perpendicular piers were more likely to form arches than piers with a nose of inclination of 60°.

## 4. CONCLUSION

We summarized the results of the experiments as follows:

(1) In this experiment we used two kinds of model ice of different sizes: one where the sides were 5 cm and another with sides of 10 cm. When "A" exceeded a certain level, an arch was formed at "Q" , where Q was almost its corresponding value to A = 1.0 (when model ice with sides of 10 cm was exclusively used). This was true for both kinds of piers with rectangular and semicircular cross-sectional shapes. Where "A" was the ratio of the area covered by the larger model ice to the total area of model ice covered, and "Q" was the ratio of the area of model ice covered to the total area of the water surface.

(2) When the values of "A" exceeded 0.70 for piers with a rectangular cross-section and 0.40 for those with a semicircular cross-section, the values of "Q" when arches were formed were almost that of A=1.0. Therefore, the larger model ice sheets played a more important role than smaller ones in arch formation for the piers with a semicircular cross-section.

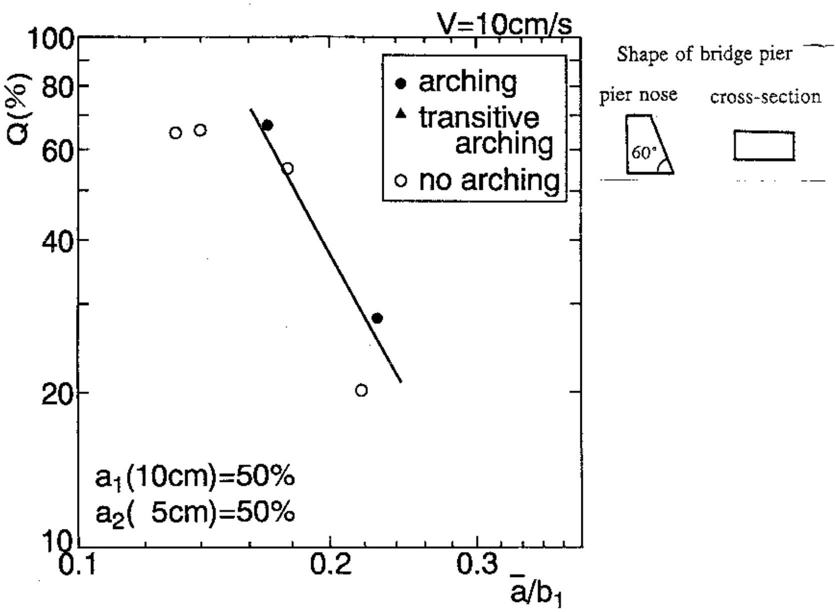

Fig. 9. Critical state of arching: 10 cm:5 cm = 50:50 (Nose 60°)

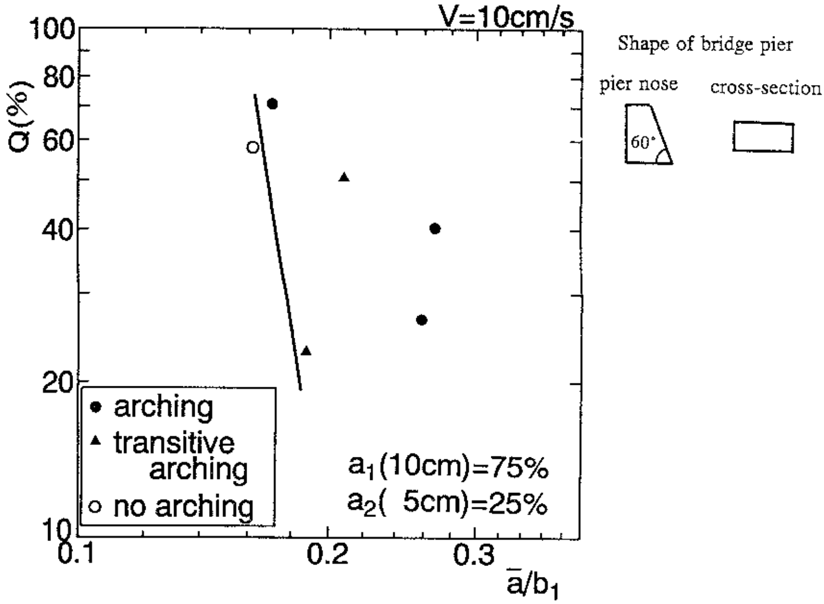

Fig. 10. Critical state of arching : 10 cm:5 cm = 75:25 (Nose 60°)

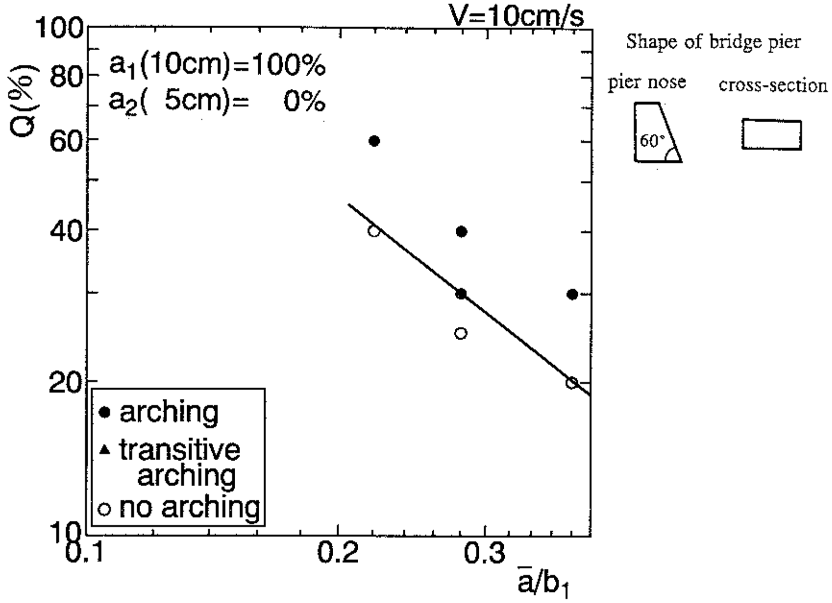

Fig. 11. Critical state of arching: 10 cm:5 cm = 100:0 (Nose 60°)

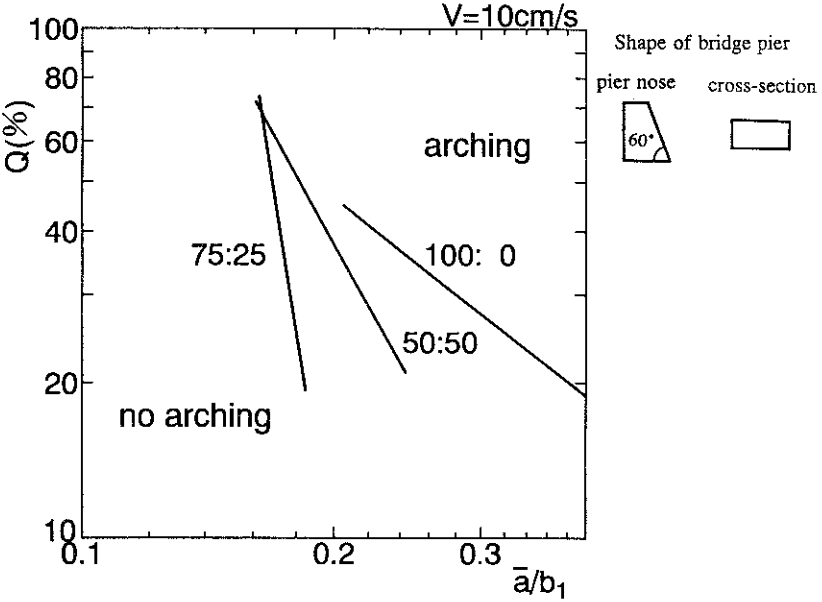

Fig. 12. The relationship between the mixing ratio and critical state of arching (Nose 60°)

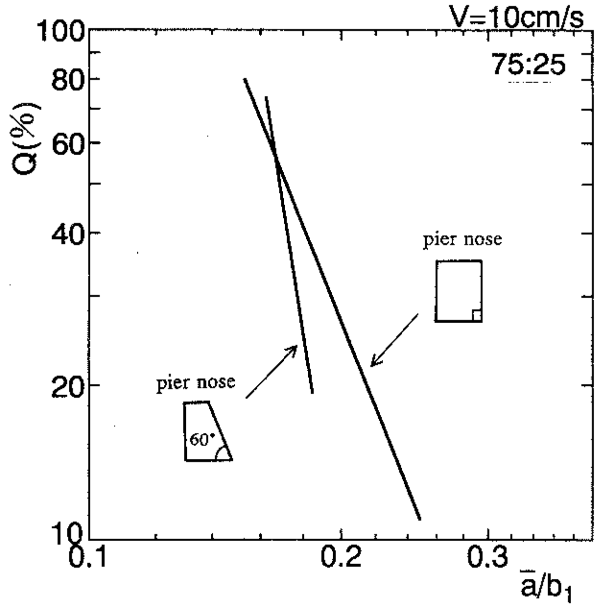

Fig. 13. Critical state of arching: 10 cm:5 cm = 50:50 (Nose 60° and 90°)

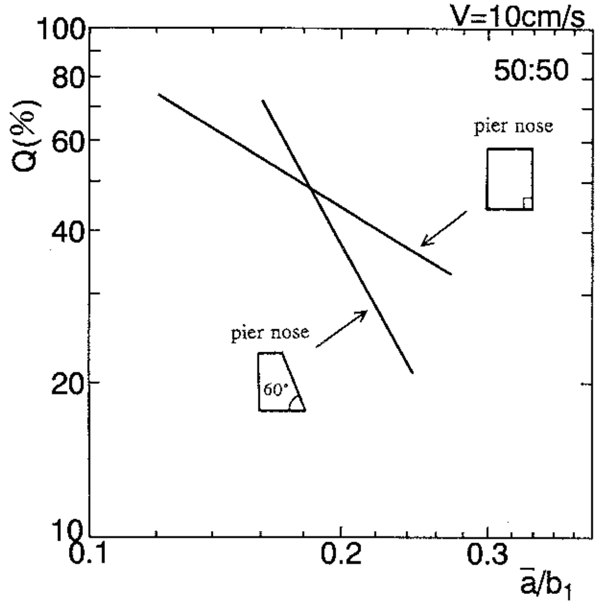

Fig. 14. Critical state of arching: 10 cm:5 cm = 75:25 (Nose 60° and 90°)

(3) Arch formation was likely to occur when a certain level of model ice sheets with sides of 5 cm were mixed with the 10 cm model ice sheets than when model ice sheets with sides of 10 cm were exclusively used. Arches were most likely to form when the values of "A" were 0.70 and 0.40 for the rectangular and semicircular cross-sectional pier forms, respectively. Thus, the ratios the area covered by the model ice with sides of 10 cm and 5 cm to the total area covered by model ice are 7:3 for piers with a rectangular cross-section and 4:6 for piers with a semicircular cross-section, respectively.

(4) When piers have a rectangular cross-section, the effect of the mixing ratio of two different sizes of model ice and bridge spans are as follows: within the range of the "b", span, 30-40 cm, arches were most likely to form at the mixing ratio of 75:25.

(5) When the mixing ratio was 75:25, the differences in the inclination of the nose did not affect arching. However, when the mixing ratio was 50:50, such difference did affect arching. The conditions were reversed when Q was 50 %, $a/b_1$ was 0.18 (b was about 45 cm). When b was larger than 45 cm, arching was more likely to occur on the perpendicular pier, but when b was smaller than 45 cm, arching was more likely to occur where a nose had an inclination of 60°.

Accordingly, arching was likely to occur when different sizes of model ice sheets were mixed. Also, the difference in the cross-sectional shape and the inclination of nose, span and mixing ratio affected arching considerably. Therefore, our future studies need to be explore (1) the relationships between the cross-sectional shape and inclination of nose, span, mixing ratio and arching by experiments using different sizes of model ice and (2) field studies on the distribution of ice floe sizes floating down actual rivers. These will help us to conduct future experiments under the conditions which closer to the natural conditions.

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