# EFFECTS OF DIAMETER OF PROTRUSIONS AND DISCHARGE PER UNIT WIDTH IN FISH LADDER FOR *ANGUILLA JAPONICA* ON MIGRATION RATE OF *ANGUILLA JAPONICA*

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Studies on biology and environment of *Anguilla japonica* have been advanced in recent years. However, little is known about fish ladder for them and migrating characteristics of them. Especially, special fishways are necessary for demersal fish like young *Anguilla japonica*. This study was made to evaluate effects on migration rates of *Anguilla japonica* by changing diameter of protrusions and discharge per unit width in fish ladder. It was found that migration rates increase with the increase of discharge per unit width in each diameter of protrusions. Besides, the migration route sinuosity of them is increasing, and the averaged migrating speed is decreasing with the increase of discharge per unit width and diameter of protrusions.

## 1 INTRODUCTION

*Anguilla japonica* are very familiar with Japanese people and essential fish in food cultures. However, population of them has been decreasing in recent years, so they were being designated as an endangered species. As of now, some of studies on their biology has proceeded. Tsukamoto *et al.* [1] found that spawning areas of *Anguilla japonica* are near the west sea of Mariana Islands. Yokouchi *et al.* [2] discovered that forms of *Anguilla japonica* differ according to river system, and they tend to become not only many populations of female but also large-sized as water body size is larger in the river. Besides, Miller *et al.* [3] pointed out that overfishing of them and the deterioration of the river environment will cause their populations decline. Thus, studies on biology and environment of *Anguilla japonica* are advanced. In the other hands, little is known about studies on migration and fishway of *Anguilla japonica*. Fishways have been provided as a means of solving the problem that dams and weirs impede migration of fish. There are various kinds of fishways; pool-and-weir fishway, vertical slot fish ladder, ice harbor-type fishway and so on [4,5]. However, many fishways are pool-and-weir fishway, and it is thought that demersal fish is difficult to migrate in this fishway [6-8]. Therefore, special fishways are necessary for demersal fish like *Anguilla japonica*.

Studies on fish ladder for *Anguilla anguilla* and *Anguilla rostrata* have been started since decades ago. These fish ladders for *Anguilla anguilla* have been used by setting brushes and columnar protrusions in bottom surfaces. Research on fish ladder setting brushes has been conducted. Knights & White [9] reported that larval *Anguilla anguilla* migrate the river easily under the condition that spaces of nylon brushes are set to less than 150mm. Besides, Porcher [10] pointed out that the best spaces of brushes in the slope are 7mm for young *Anguilla anguilla* and 14mm for small and yellow *Anguilla japonica*.

In addition, fish ladder setting columnar protrusions has been studied for more than a decade. Solomon & Beach [11] introduced that fish ladder for *Anguilla anguilla* and *Anguilla rostrata* in North America sets columnar protrusions which is diameter 50.8mm and height 101.6mm, and that fish ladder for *Anguilla anguilla* in France sets columnar protrusions which is height 30mm. However, it is not a clear whether these standards are pertinent or not. Vowles *et al.* [12] showed that when columnar protrusions which dimeter is 4.5cm or 8.5cm set in each right and left side from a central axis of this fish ladder, *Anguilla anguilla* migrated at the case of diameter 4.5cm more than at diameter 8.5mm. However, this study is the inadequate experience because the discharge in this experiment is only one case and there are still room to examine other protrusions. Therefore, while some fish ladders for *Anguilla anguilla* and *Anguilla rostrata* are used in Europe and America, little is known about appropriate columnar protrusions in fish ladder for them. Furthermore, number of fish ladder for *Anguilla japonica* in Japan is few, and few reports are available on fish ladder for *Anguilla japonica*.

This investigation on migration rates of *Anguilla japonica* was conducted by changing diameter of protrusions and discharge per unit width in fish ladder in order to clarify appropriate fish ladder for them.

## 2 EXPERIMENTAL DEVICE AND METHODS

Figure 1. shows an experimental device consisting of two tanks and the fish ladder. This tank has a length ( $L_x$ ) of 600mm, a width ( $B_z$ ) of 400mm, and a height ( $H_y$ ) of 300mm. The fish ladder has a length ( $L$ ) of 1000mm, a width ( $B$ ) of 300mm, and a height of 150mm in side wall ($\Delta h$). This fish ladder is painted gray and is connected by two tanks at a slant angle of 15 degree. Fish ladder width ( $B$ ) was determined referencing fish ladder for *Anguilla anguilla*. Besides, many fish ladder for them are at a slant angle of 12°~55° in Europe, so we adopted the gentle angle of 15° in this experiment.

Figure 2. shows an arrangement of protrusions. This bodies are columnar protrusions made of polyvinyl chloride and are arranged zigzag in each space of 10mm. The diameter of protrusions ( $D$ ) are set to four patterns of 15, 25, 40 and 50 (mm) and the height is 100mm. The origin (0, 0) of the two dimensional ($x$, $y$) coordinate is the left bank of the upper reach in this fish ladder.

Table 1. shows the experimental cases. The diameter of protrusions ( $D$ ) were set to four patterns as above and discharge per unit width ( $q_L$ ) were set to three patterns of $1.2\times10^2$, $7.1\times10^2$ and $1.64\times10^3$ ($mm^2/s$). At this time, the water depth in this fish ladder ( $h_L$ ) was about 2, 6 and 10 (mm), respectively. Water is provided from the upstream tank and drainage discharge is adjusted in downstream tank, so the water depth in downtown tank ( $h$ ) was about 250mm in all cases. Moreover, the water temperature was about 20°C in all cases.

Figure 3. shows young *Anguilla japonica* used in this experiment. Averaged body length ( $\overline{B_L}$ ) is about 150mm. They were captured in Japan and reared for 8 months. There is the characteristic to migrate the river positively in their growth stage. 20 young *Anguilla japonica* were used for this experiment, and they were used only once per experiment. They were inserted in the downstream tank. After it is confirmed that *Anguilla japonica* settled down, this migrating experiment was conducted for 30 minutes. Trajectory of *Anguilla japonica* is recorded with the digital video camera. Number of pixel of the digital video camera is 1440×1080, and recording speed is 30fps. The swimming positions of *Anguilla japonica* were obtained with the aid of the digital video camera. Besides, the number of *Anguilla japonica* migrating was counted.

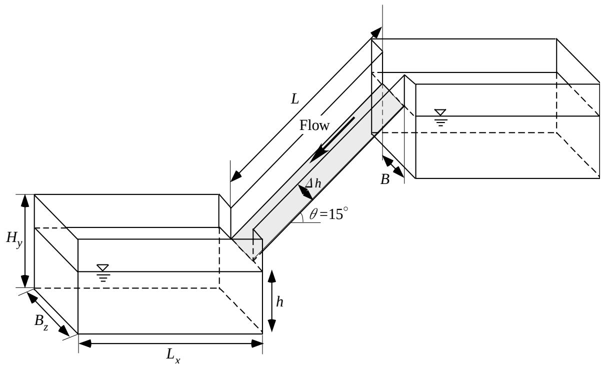



Figure 1. Experimental device

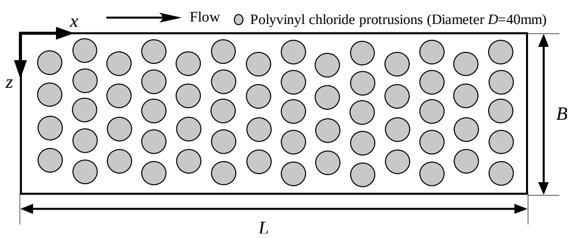



Figure 2. Arrangement of protrusions

Table 1. Experimental cases

| Water depth in fish ladder $h_L$ (mm) | Discharge per unit width $q_L$ ($mm^2/s$) | Diameter of protrusions $D$ (mm) | | | |
|---|---|---|---|---|---|
| | | 15 | 25 | 40 | 50 |
| 2 | $1.2\times10^2$ | D15-2 | D25-2 | D40-2 | D50-2 |
| 6 | $7.1\times10^2$ | D15-6 | D25-6 | D40-6 | D50-6 |
| 10 | $1.64\times10^3$ | D15-10 | D25-10 | D40-10 | D50-10 |

Figure 3. *Anguilla japonica* used in this experiment

## 3 RESULTS AND DISCUSSION

### 3.1 Migration rates of *Anguilla japonica*

Migration rates of *Anguilla japonica* were calculated as the following Eq. (1).

$$\text{Migration rate} = \frac{\text{Number of } \textit{Anguilla japonica} \text{ that migrated in upstream tank } n}{\text{Number of } \textit{Anguilla japonica} \text{ that used to experiment } N(=20)} \tag{1}$$

Figure 4. shows the relationship between migration rates ( $n/N$ ) and discharge per unit width ( $q_L$ ) in each diameter of protrusions ( $D$ ). Migration rates ( $n/N$ ) in each discharge per unit width ( $q_L$ ) have decreased or increased with the increase of diameter of protrusions ( $D$ ), and there were not a clear tendency to the relationship between migration rates ( $n/N$ ) and diameter of protrusions ( $D$ ). On the other hand, Migration rates ( $n/N$ ) have a tendency to increase with the increase of discharge per unit width ( $q_L$ ) regardless of diameter of protrusions ( $D$ ). Accordingly, it is suggested that migration rates ( $n/N$ ) are effected by discharge per unit width ( $q_L$ ) rather than diameter of protrusions ( $D$ ).

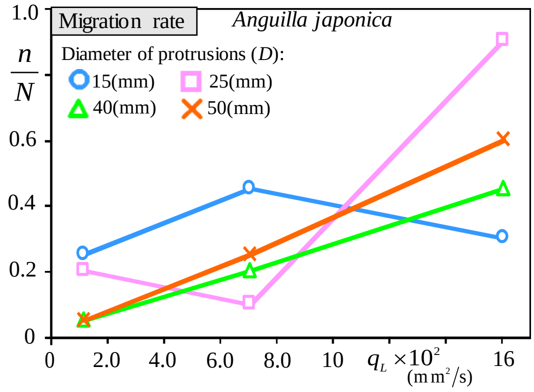



Figure 4. Migration rates of *Anguilla japonica* in each discharge per unit width

### 3.2 Challenge rates of *Anguilla japonica*

The number of *Anguilla japonica* challenging migration ( $N_c$ ) is the number of them entering this fish ladder from the downstream tank. Challenge rates of them were calculated as the following Eq. (2).

$$\text{Challenge rate} = \frac{\text{Number of } \textit{Anguilla japonica} \text{ that challenged } N_c}{\text{Number of } \textit{Anguilla japonica} \text{ that used to experiment } N(=20)} \tag{2}$$

Figure 5. shows the relationship between challenge rates ( $N_c/N$ ) and discharge per unit width ( $q_L$ ) in each diameter of protrusions ( $D$ ). It wasn't confirmed that there are a great difference in challenge rates ( $N_c/N$ ) with change of discharge per unit width ( $q_L$ ), as opposed to migration rates ( $n/N$ ). On the other hand, there were not a clear tendency to the relationship between challenge rates ( $N_c/N$ ) and discharge per unit width ( $q_L$ ) in each diameter of protrusions ( $D$ ).

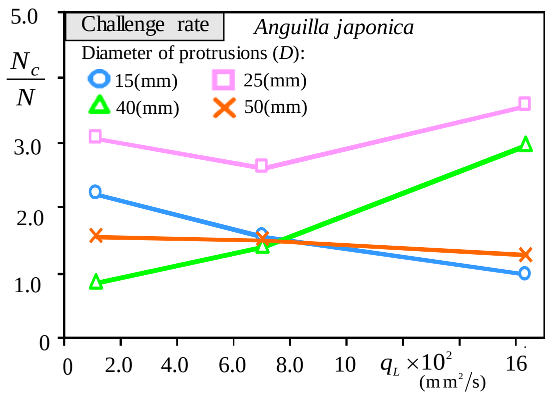
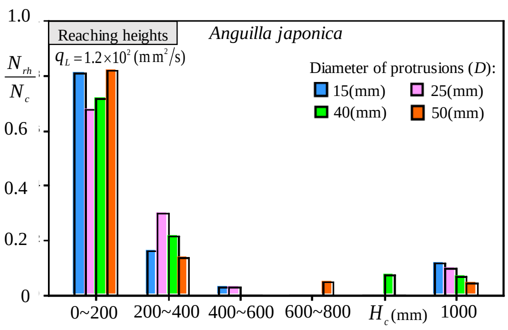


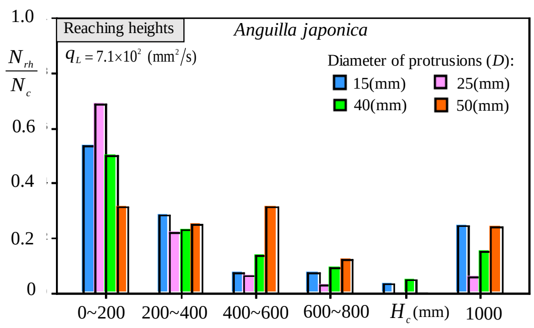

Figure 5. Challenge rates of *Anguilla japonica* in each discharge per unit width

### 3.3 Reaching heights of *Anguilla japonica*

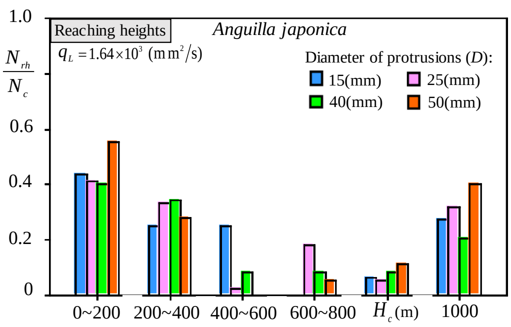
The number of reaching heights of *Anguilla japonica* in each case is $N_{rh}$, and reaching rates ($N_{rh}/N_c$) are the value that the number of reaching heights ($N_{rh}$) is divided by the number of them challenging migration ($N_c$). Besides, reaching heights ($H_c$) are counted in every 200mm range from the lower edge of slopes in this fish ladder. Figure 6. (a)~(c) show frequency distribution of relationships between reaching heights of them *a* ($H_c$) and reaching rates ($N_{rh}/N_c$) in each discharge per unit width ($q_L$). When they migrate in the upstream tank, reaching heights of them ($H_c$) are 1.0m. The minimum discharge per unit width $q_L$ =1.2×10$^3$mm$^2$/s shows that reaching rates ($N_{rh}/N_c$) are high in $H_c$ =0~200(mm) and are drastically decreased as the higher of reaching heights ($H_c$). This decreasing trend with the increase of reaching heights ($H_c$) has been de-escalating with the increase of discharge per unit width ($q_L$). Therefore, it is assumed that reaching heights ($H_c$) have been higher with the increase of discharge per unit width ($q_L$), and migration rates ($n/N$) have increased. On the other hand, *Anguilla japonica* arrive at reaching height $H_c$ =0~200(mm) in the low discharge per unit width ($q_L$), so it is assumed that there were not a clear relationships between challenge rates ($N_c/N$) and discharge per unit width ($q_L$).




(a) $q_L$ =1.2×10$^3$mm$^2$/s




(b) $q_L$ =7.1×10$^3$mm$^2$/s

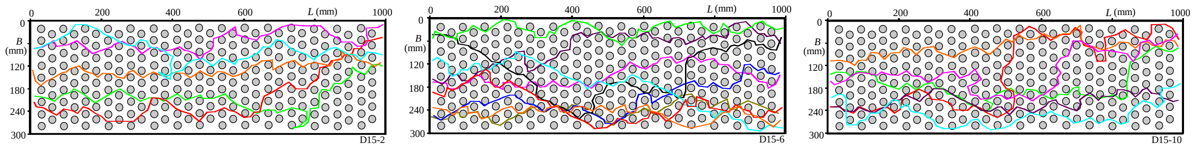



(c) $q_L$ =1.64×10$^4$mm$^2$/s

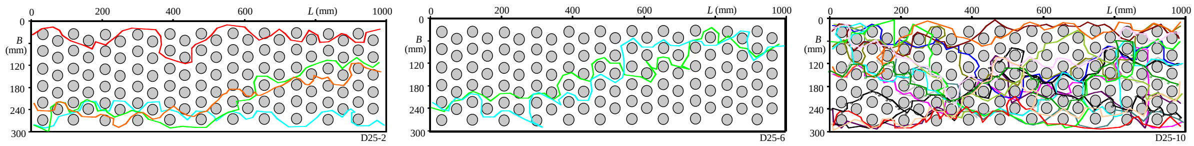
Figure 6. The frequency distribution reaching heights

### 3.4 Migration routes of *Anguilla japonica*

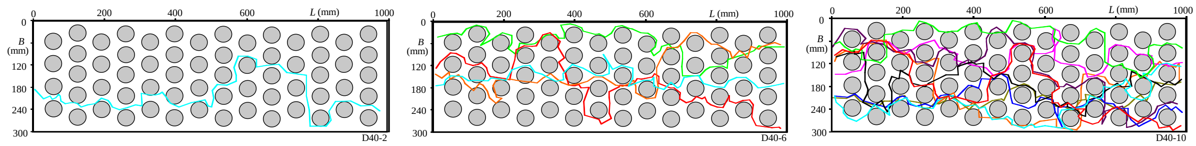
Figure 7. (a)~(d) show migration routes of *Anguilla japonica* in each diameter of protrusions ( $D$ ). It was found that they migrated with rolling their bodies around protrusions by their serpentine movement in all cases. Besides, it is observed that they migrate more serpentine movement with the increase of diameter of protrusions ( $D$ ) and discharge per unit width ( $q_L$ ).



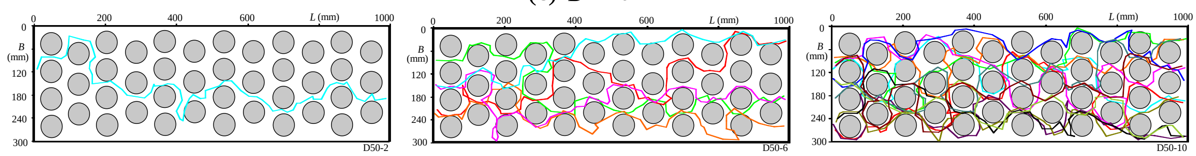

(a) $D$ =15mm




(b) $D$ =25mm




(c) $D$ =40mm




(d) $D$ =50mm

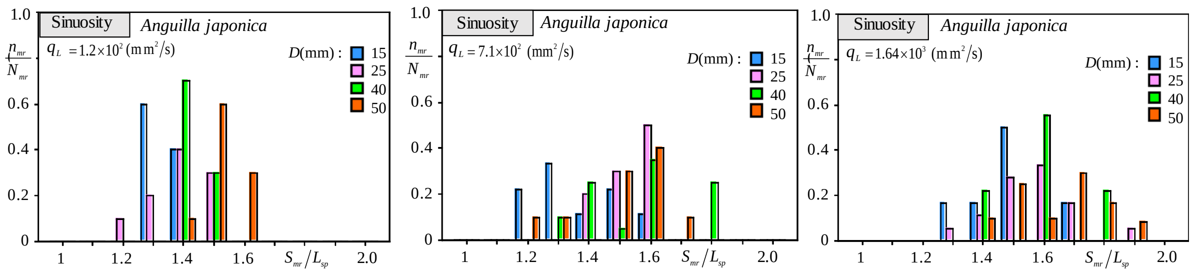
Figure 7. Migration routes of *Anguilla japonica*

### 3.5 Migration route sinuosity of *Anguilla japonica*

The length of shortest possible path ( $L_{sp}$ ) is the length of the shortest possible distance for each configuration of protrusions. The length of actual migrating paths ( $S_{mr}$ ) is the length of actual migrating routes of *Anguilla japonica*. The migration route sinuosity of *Anguilla japonica* ( $S_{mr}/L_{sp}$ ) is defined as the following Eq. (3).

$$\text{Migration route sinuosity} = \frac{\text{Length of actual migrating routes } S_{mr}}{\text{Length of the shortest possible distance for each configuration of protrusions } L_{sp}} \quad (3)$$

Figure 8. (a)~(c) show the frequency distribution of migration route sinuosity of them ( $S_{mr}/L_{sp}$ ) in each discharge per unit width ( $q_L$ ). The migration route sinuosity of them ( $S_{mr}/L_{sp}$ ) has a tendency to increase with the increase of diameter of protrusions ( $D$ ) in each discharge per unit width ( $q_L$ ). Thus, it is suggested that the length of their migrating routes has increased for the increase of diameter of protrusions ( $D$ ). In addition, the migration route sinuosity of them ( $S_{mr}/L_{sp}$ ) has a tendency to increase with the increase of discharge per unit width ( $q_L$ ) in each diameter of protrusions ( $D$ ). It was confirmed that they have a tendency to use protrusions by their serpentine movement because when they linearly migrate with the increase of discharge in fish ladder, they are swept away at the downstream. Therefore, it is assumed that the length of actual migrating routes has increased with the increase of discharge per unit width ( $q_L$ ). Accordingly, it was proven that they migrate while using protrusions and the migration route sinuosity has increased with the increase of diameter of protrusions ( $D$ ) and discharge per unit width ( $q_L$ ).




(a) $q_L$ =1.2×10$^3$mm$^2$/s (b) $q_L$ =7.1×10$^3$mm$^2$/s (c) $q_L$ =1.64×10$^4$mm$^2$/s

Figure 8. The frequency distribution of migration route sinuosity

### 3.6 Averaged migrating speed of *Anguilla japonica*

Migrating speed ($V$) was calculated by lengths of their migrating route and their migrating times, and $\overline{V}$ is averaged migrating speed. Averaged migrating speed ($\overline{V}/\overline{B_{Lm}}$) is the value that $\overline{V}$ is divided by averaged body length of *Anguilla japonica* that migrated ($\overline{B_{Lm}}$). Figure 9. shows the averaged migrating speed of them in each diameter of protrusions ($D$). The averaged migrating speed ($\overline{V}/\overline{B_{Lm}}$) has a tendency to decrease with the increase of discharge per unit width ($q_L$) in each diameter of protrusions ($D$). Besides, the averaged migrating speed ($\overline{V}/\overline{B_{Lm}}$) has decreased with the increase of diameter of protrusions ($D$) in each discharge per unit width ($q_L$). Considering Figure 8., it became a clear that they migrate while using protrusions and the sinuosity has increased with the increase of diameter of protrusions ($D$) and discharge per unit width ($q_L$). Therefore, it is assumed that they wind their bodies around protrusions, so the migrating time has increased and the migrating speed had a tendency to decrease.

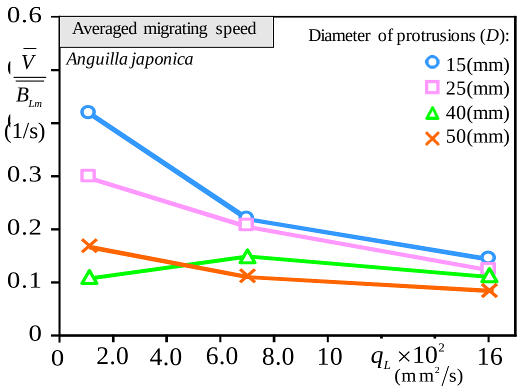



Figure 9. Averaged migrating speed

## 4 CONCLUSION

This investigation on migration rates of *Anguilla japonica* was conducted by changing diameter of protrusions and discharge per unit width in fish ladder in order to clarify appropriate fish ladder for them. As a result, it was found that following.

(1) Migration rates increase with the increase of discharge per unit width regardless of diameter of protrusions. On the other hand, there were not a clear tendency to the relationship between migration rates and diameter of protrusions.
(2) Reaching heights of *Anguilla japonica* become higher with the increase of discharge per unit width.
(3) The migration route sinuosity of *Anguilla japonica* increases and the migrating speed decreases with the increase of diameter of protrusions and discharge per unit width.

## 5 ACKNOWLEDGEMNETS

This study was supported by Grants-in-aid for Scientific Research (17K06580) when the study conducts. Finally, the authors are grateful to Marusho Corporation for providing *Anguilla japonica* treated in this paper.

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