EFFECTS OF SLOPES AND SPACES OF PROTRUSIONS IN FISH LADDER FOR EELS ON MIGRATION RATE OF *ANGUILLA JAPONICA*

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ABSTRACT

In recent year, populations of *Anguilla japonica* have been decreasing sharply. This decrease is partly because it is estimated to be overfishing of *Anguilla japonica*, the deterioration of the river environment and so on. Migrating fishes are impeded by weirs and dams in the river. Fishways have been constructed to swimming fish like *Plecoglossus altivelis altivelis* in order to solve this problem. On the other hand, it is thought that special fishway is necessary for demersal fish like eels. Furthermore, studies on fish ladder for eels haven't been conducted. In the present study, an investigation on migration rate of *Anguilla japonica* was conducted under the condition that slope of fish ladder for eels and spaces of protrusions are changed. It was found that migration rates decreased with the increase of slopes and spaces of protrusions. Besides, *Anguilla japonica* migrated while using protrusions by serpentine movement.

INTRODUCTION

Anguilla japonica is a group of fish that belong to the order Anguilliformes family Anguilidae. They are demersal fish, so they have a poor swimming ability compared to swimming fish. Some of studies concerning their biology and farming has been advanced recently. Especially, Tsukamoto *et al*. (2011) made a great discovery that spawning ground of *Anguilla japonica* is in the west sea of Mariana Islands. However, there are many unsolved questions with respect to migrating process or swimming characteristics.

Japanese people eat many eels year after year. On the other hand, population of *Anguilla japonica* has been decreasing in recent years. Santos *et al*. (2016) pointed that the reasons of the population decreasing are overfishing of *Anguilla japonica*, the deterioration of the river environment and so on. Even among them, there are problems that weirs and dams in the river impede migration of fish. Fishways have been constructed to slove this problems. However, many fishways are pool-and-weir fishway to swimming fish. Therefore, special fishways are necessary for demersal fish like eels. In Japan, fish ladders for eels are still very few. In addition, studies on fish ladder for eels haven't been conducted. Fish ladder for eels (*Anguilla anguilla*) are used by setting brushes and roughness in bottom surface in Europe and America (see Clay, C.H., 1994, Solomon, D.J. & Beach, M.H., 2004, Legault, A., 1992). However, little is known about the best structure of fish ladders for eels. In the present study, an investigation on migration rates of *Anguilla japonica* was conducted under the condition that slopes of fish ladder for eels and spaces of protrusions are changed.

EXPERIMENTAL DEVICE AND METHODS

Figure 1 shows an experimental device consisting of two tanks and a fish ladder. This tank length (L_x) was 0.6m, width (B_z) was 0.4m, and height (H_y) was 0.3m. Fish ladder length (L) was 0.8m, width (B) was 0.2m, and height of side wall (Δh) was 0.05m. This fish ladder is painted gray. Fish ladder width (B) was determined referencing fish ladder for European eels (*Anguilla anguilla*).

Table 1 shows the experimental case. Quantity of flow (Q) providing in the upstream tank is 80 (ml/s), and the water depth (h) is 0.2m by setting displacement in downstream tank. Figure 2 shows an arrangement of protrusions. These protrusions are column made of polyvinyl chloride. The diameter of protrusions is 30mm and the height is 35mm. In this study, spaces of protrusions (d) were set to three patterns of 10, 20 and 30 (mm). Slops of fish ladder (θ) were set to three patterns of 15°, 30° and 45°. The left bank of the upper reach in this fish ladder is the origin position. x axis is taken in streamwise direction. z axis is taken in the transverse direction. The water depth in this fish ladder was about 5mm in all cases. Moreover, the water temperature was about 20°C in all cases.

Figure 3 shows young eels used in this experiment. Averaged body length ($\overline{B_L}$) is about 200mm. Young eels migrate the river positively. The number of young eels used to experiment was 20. They were inserted in 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 eels migrating was counted.

RESULTS AND DISCUSSION

Migration rates of *Anguilla japonica*

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

Migration rate

$$= \frac{\text{Number of fish that migrated in upstream tank } n}{\text{Number of fish that used to experiment } N(=20)} \qquad (1)$$

Figure 4 shows migration rates (n/N) in each space of protrusions (d). Migration rate is the maximum in the case d10-15 (d=10mm, θ=15°). Migration rates have decreased with the increase of spaces of protrusions (d). In addition, migration rates have tendency to decrease with the

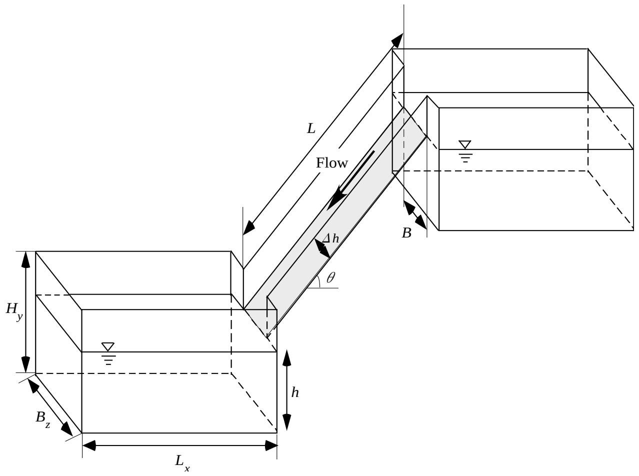


Figure 1. Experimental device

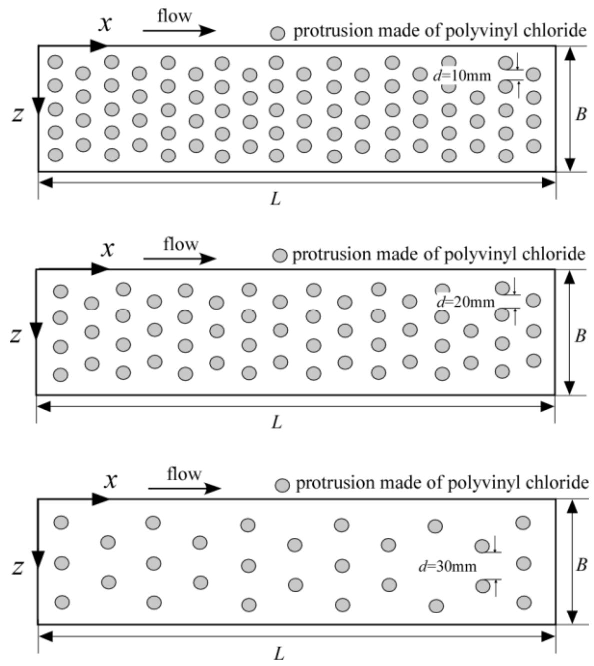


Figure 2. An arrangement of protrusions

Table 1. Experimental case

d (mm)	θ(degree)		
	15°	30°	45°
10	d10-15	d10-30	d10-45
20	d20-15	d20-30	d20-45
30	d30-15	d30-30	d30-45

Figure 3. Young eels used in this experiment

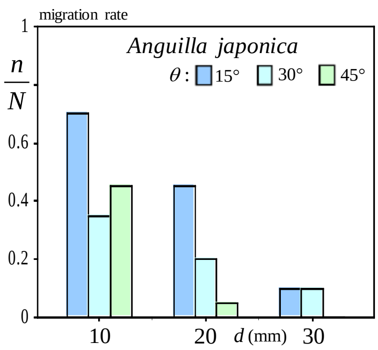


Figure 4. Migration rate

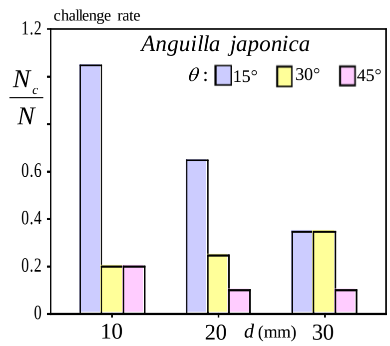
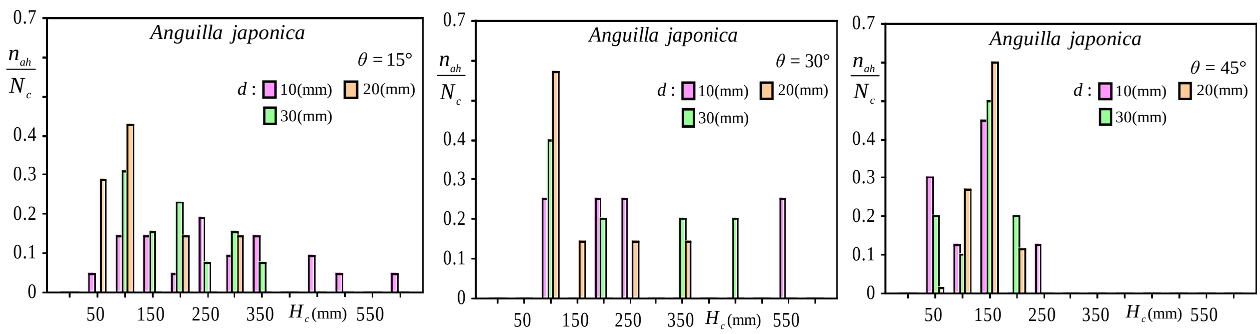


Figure 5. Challenge rate



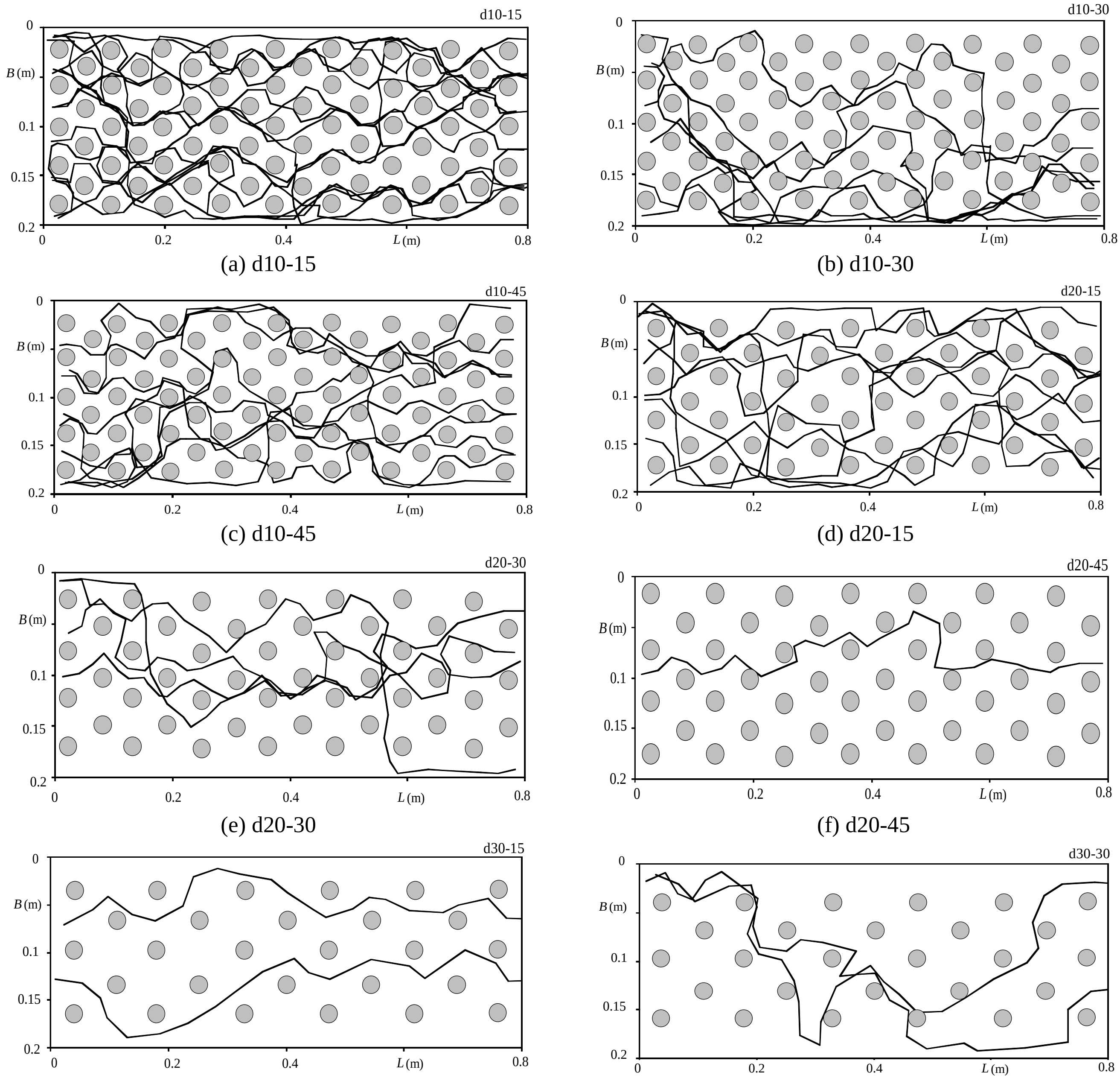
(a) θ=15° (b) θ=30° (c) θ=45°

Figure 6. The Frequency distribution of arrival heights

increase of slopes (θ) in each space of protrusions. Accordingly, it was found that young eels migrate easily in the case that the space of protrusions is d=10mm and the slope is θ=15° in the range of this study.

Challenge rates and arrival heights

The number of eels challenging migration (N_c) is number of *Anguilla japonica* entering this fish ladder from



(a) d10-15 (b) d10-30

(c) d10-45 (d) d20-15

(e) d20-30 (f) d20-45

(g) d30-15 (h) d30-30

Figure 7. Migration routes of *Anguilla japonica*

the downstream tank. Challenge rates of *Anguilla japonica* were calculated as the following equation (2).

Challenge rate

$$= \frac{\text{Number of fish that challenged } N_c}{\text{Number of fish that used to experiment } N(=20)} \qquad (2)$$

Figure 5 shows challenge rates (N_c/N) in each space of protrusions (*d*). Challenge rate was the maximum in the case d10-15 (*d*=10mm, θ=15°). Challenge rates have a tendency to decrease with the decrease of spaces of protrusions (*d*). In addition, challenge rates in smaller slopes are higher than that in larger slopes. Referring to Figure 4, challenge rates are higher than migration rates in all cases. This means that *Anguilla japonica* challenges migration whether they succeed in migrating or not.

Anguilla japonica is distinguished in each slope. The number of their arrival heights in each case is n_{ah}. Besides, arrival heights (H_c) are counted in every 50mm range from the lower ends of slopes in this fish ladder. Figure 6(a)~(c) show frequency distribution of arrival heights (H_c). The Frequencies of arrival heights have dispersion in the minimum slope (θ=15°). This trend is especially remarkable in the case of *d*=10mm. However, it was confirmed that the frequency distribution of arrival heights has a high frequency in low value with the increase of slopes. Therefore, *Anguilla japonica* challenges migration in the highest slope (θ=45°). On the other hand, their arrival heights (H_c) declined in comparison to lower slopes.

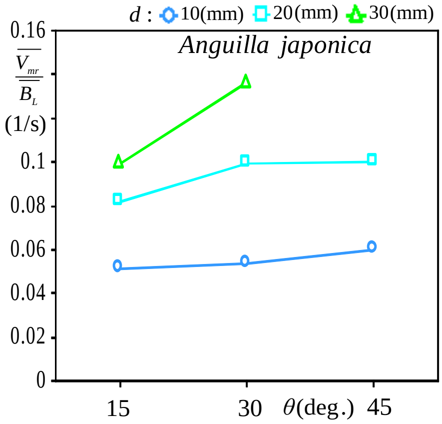


Figure 8. Averaged migrating speed of *Anguilla japonica*

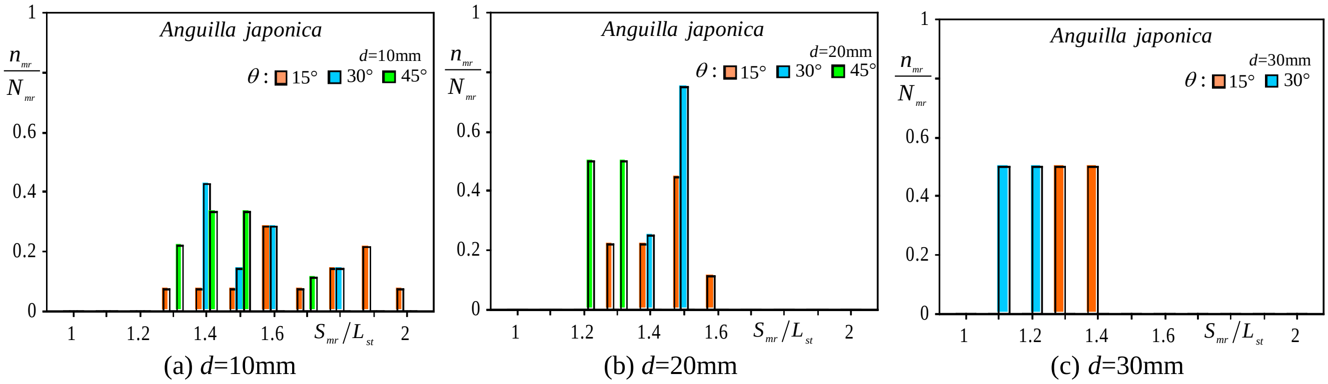


Figure 9. The Frequency distribution of relations between sinuosity of *Anguilla japonica* and slopes

Migration routes of *Anguilla japonica*

Figure 7(a)~(h) show migration routes of *Anguilla japonica* in every cases. It wasn't confirmed that there are a great difference in each case. However, it was found that *Anguilla japonica* migrated while using protrusions by serpentine movement in all cases.

Migrating speed of *Anguilla japonica*

$\overline{V_{mr}}/\overline{B_L}$ is the value that the averaged migrating speed ($\overline{V_{mr}}$) was divided by averaged body length of *Anguilla japonica* ($\overline{B_L}$). Figure 8 shows the averaged migrating speed of *Anguilla japonica* in every slopes. The amount of changes in the case *d*=10mm is small. In addition, the averaged migrating speed ($\overline{V_{mr}}/\overline{B_L}$) has a tendency to increase with the increase of slopes in the same space of protrusions (*d*). Besides, the averaged migrating speed ($\overline{V_{mr}}/\overline{B_L}$) has a tendency to increase with the increase of spaces of protrusions in the same slope of fish ladder for eels (θ). Consequently, it is assumed that the increase of flow velocity has an impact on the increase of migrating speeds with the increase of slopes (θ). In addition, *Anguilla japonica* had difficulty in using protrusions with the increase of spaces of protrusions (*d*).

Sinuosity of *Anguilla japonica*

The length of the straight lines (L_{st}) is the length between entering points of *Anguilla japonica* in the entry of this fish ladder (x=0.8m) and arriving points in the exit (x=0m). The length of actual migrating paths (S_{mr}) is the length of actual migrating routes of *Anguilla japonica*. The sinuosity of *Anguilla japonica* (S_{mr}/L_{st}) is defined as the following equation (3).

$$\text{Sinuosity}=\frac{\text{Length of migrating routes } S_{mr}}{\text{Length of straight lines } L_{st}} \tag{3}$$

Accordingly, it means that the closer the sinuosity (S_{mr}/L_{st}) is 1, the less serpentine *Anguilla japonica* becomes and the more linear they migrate.

Figure 9(a)~(c) show the frequency distribution of relations between sinuosity of *Anguilla japonica* and slopes in every spaces of protrusions. The dispersion of sinuosities (S_{mr}/L_{st}) has been decreasing with the increase of slopes (θ) in all cases. Furthermore, the sinuosity has a tendency to be small. Therefore, it was found that *Anguilla japonica* migrated in the condition that they hardly bend their body with the increase of slopes (θ). Considering Figure 8, it became the clear that the sinuosity (S_{mr}/L_{st}) has decreased and the averaged migrating speed ($\overline{V_{mr}}/\overline{B_L}$) has increased with the increase of slopes (θ).

CONCLUSION

In this study, an investigation on migration rates of young eels (*Anguilla japonica*) was conducted under the condition that slopes of fish ladder for eels and spaces of protrusions are changed. As a result, it was found that following.

(1) *Anguilla japonica* migrates easily in the case that spaces of protrusions is d=10mm and the slope is θ=15° in the range of this experimental cases.
(2) Challenge rates have decreased with the increase of slopes of fish ladder for eels (θ) and spaces of protrusions (d).
(3) *Anguilla japonica* migrated while using protrusions by serpentine movement in all cases.
(4) It was confirmed that the sinuosity (S_{mr}/L_{st}) has decreased and the averaged migrating speed ($\overline{V_{mr}}/\overline{B_L}$) has increased with the increase of slopes (θ).

This experiment of fish ladder for eels was conducted in a constant quantity of flow. It is necessary to investigate the quantity of flow, the diameter of protrusions, shapes and materials to realize appropriate fish ladder for eels in the future.

NOMENCLATURE

L length, m
B width, m
H height, m
Δh height of side wall, m
Q quantity of flow, ml/s
h depth of water, m
d space between protrusions and others, mm
θ slope of fish ladder for eels, degree
$\overline{B_L}$ averaged body length, mm
N number of fish that used to experiment (=20)
n number of fish that migrated in upstream tank
S actual migrating path length of *Anguilla japonica*

Subscripts

x x direction or downflow direction
y y direction
z z direction or transverse direction
c challenge to migration
st straight line
mr migrating route of *Anguilla japonica*

ACKNOWLEDGEMENTS

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 eels treated in this paper.

REFERENCES

(1) Tsukamoto, K., Chow, S., Otake, T., Kurogi, H., Mochioka, N., Miller, M.J., Aoyama, J., Kimura, S., Watanabe, S., Yoshinaga, T., Shinoda, A., Kuroki, M., Oya, M., Watanabe, T., Hata, K., Ijiri, S., Kazeto, Y., Nomura, K. and Tanaka, H. (2011): “Oceanic spawning ecology of freshwater eels in the western North Pacific”. *Nature Communications*, Vol. 2, pp. 1-9.
(2) Santos, J.M., Rivaes, R., Oliveira, J. and Ferreira, T. (2016): “Improving yellow eel upstream movements with fish lifts”. *Journal of Ecohydraulics*, Vol. 1, pp. 50-61.
(3) Clay, C.H. (1994): *Design of fishways and other fish facilities*, CRC Press, pp. 121-127.
(4) Solomon, D.J. and Beach, M.H. (2004): “Fish pass design for eel and elver (*Anguilla anguilla*)”. *R&D Technical Report W2-070/TR1*, Environment Agency, pp. 1-5.
(5) Legault, A. (1992): “Étude de quelques facteurs de sèlectivitè de passes à anguilles”. *Bull. Fr. Pêche Piscic*, Vol. 325, pp. 83-91.