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Effect of Installation of Oxidized Slag Boulders on Aquatic Habitat in Artificial Channel

Youichi Yasuda[1], Yoshinori Masaki[2], Tsutomu Wakana[3], Ken Kato[3] & Katsushi Maeda[4]

[1] Department of Civil Engineering, College of Science and Technology, Nihon University, Tokyo, Japan

[2] Daido Steel Corporation, Ltd., Aichi, Japan

[3] Toyota Tsusho Corporation, Aichi, Japan

[4] Aizawa Concrete Corporation, Hokkaido, Japan

Correspondence: Prof. Youichi Yasuda, Civil Engineering Dept., College of Science and Technology, Nihon University, Tower Schola S1010, 1-8-14 Kanda Surugadai, Chiyoda-ku, 101-8308 Tokyo, Japan. E-mail: yasuda.youichi@nihon-u.ac.jp

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Abstract

No previous reports exist of using oxidized slag exceeding 20 cm in size as boulder. In this study, aquatic organisms inhabiting rivers—including river shell, shrimp, other fish, and eels—were released into a channel. Observation periods of one week each were established in September and November. In a rectangular horizontal channel, the consecutively assembled boulders were installed by using approximately 20 cm of oxidized slag and natural stones. As a result, water quality analysis from water samples showed almost no leaching from the slag. Furthermore, no abnormalities were observed in the behavior of aquatic animals. Additionally, the aquatic organisms utilized the spaces between the gravel without distinguishing between the slag and the natural boulders. Measurements of the flow velocity field verified that the flow between boulders was effective for resting and movement behavior.

Keywords: oxidized slag, assembled boulders, aquatic habitat, seepage flow, velocity filed

1. Introduction

River management prioritizing flood control has severely restricted the movement, habitat, spawning, and refuge environments for aquatic organisms, becoming a nationwide problem (Yasuda, 2006). Consequently, the population density of aquatic organisms observed in rivers has decreased, disrupting the structure of the food chain. In gravel-based riverbeds, the formation of riffles and pools, along with flow seeping through or running underground between boulders, enables water temperature regulation, creating favorable habitats and spawning environments. Furthermore, research by Yasuda et al. has shown that environmental improvements using large boulders contribute to pool formation, migration movement (upstream and downstream migration) around river crossing structures, countermeasures against local scouring, and measures against riverbed lowering (Yasuda, Yasuda, & Beretta, 2023; Yasuda, 2025). The application of stones ranging from small pebbles to large boulders is limited in terms of construction feasibility due to transportation costs, stone material expenses, and resource conservation considerations. Concrete artificial rocks or blocks can be used as alternatives to large boulders (Yamato, Noguchi, Sannoh, & Torii, 2004), but their specific gravity compared to natural stone and their uniform block shape result in conditions different from those achieved with gravel placement. Oxidized slag is cited as a material with a high specific gravity comparable to gravel and capable of performing similar functions (Kato, Watanabe, & Imai, 2023). In civil engineering fields, oxidized slag has been effectively utilized as subgrade material confirmed under certain standards (National Institute for Environmental Studies, 2013), but this involves using it in a smaller crushed stone. There are no known examples of its application targeting pieces larger than 0.20 m, which could be treated as gravel. Furthermore, there are no studies examining the impact of oxidized slag placement on aquatic animals such as fish (both juveniles and adults), crustaceans, and river shells. It is also unclear whether slag can be applied in areas inhabited by river fishes, which are sensitive to water quality. For the application of oxidized slag to rivers, it is necessary to quantitatively evaluate the extent of leaching from the slag. It is also crucial to clarify the environmental standards required for oxidized slag application. To clarify the applicability of oxidized slag, this paper used oxidized slag (Kato, Watanabe, & Imai, 2023) with an average size of 0.20–0.25 m. This slag was placed in parallel with natural stones of the same size to form consecutively assembled boulders region approximately 5 m long in an experimental channel. Water flowed through the channel for about one week, and the behavior of aquatic animals and water quality were examined. The study periods were September and November. The first experiment in September targeted swimming fishes, benthic fishes, shrimp, and river shell inhabiting river in residential areas. The second experiment in November focused on mountain river fish, which are sensitive to water quality. The results showed that even in recirculated water, water quality tests revealed almost no leaching from the oxidized slag. Furthermore, in both the September and November experiments, all aquatic animals survived in healthy condition, except for those lost to predation. Additionally, two months passed since the first and second experiments, it was confirmed that even when the oxidized slag was left outdoors, the progression of rust on the metal fragments remaining on its surface was limited.

2. Experimental Setup and Methods

Experiments were conducted using a horizontal channel with rectangular cross section (length 17 m, width 0.80 m, and height at 10 m long section 0.60 m) located within the Environmental Hydraulics Laboratory at Nihon university, Funabashi Campus.

To prevent the painted metal base from affecting the observation of aquatic organisms' behavior within the stone structures, small pebbles (average size 0.53 cm) over a 4.5 m section and crushed stones (average size 1.6 cm) over a 0.45 m downstream section, both approximately 5 cm thick were installed. The stone structures were then placed on top of these layers. Further, stones averaging 9.2 cm in size were installed at the downstream section 0.3 m. Here, average size is defined as the meaning of the long side, short side, and height. Fifty-two pieces of oxidized slag produced at the Chita Plant of Daido Steel Co., Ltd. were used (see Photo 1). The installation status of the slag and natural boulder is shown in Photo 2.

The frequency distribution by size for the oxidized slags and natural stones is shown in Figures 1 and 2, respectively. The average size of the oxidized slag was 0.213 m. The natural boulders were gravel from Gunma Prefecture, with an average size of 0.206 m. To account for aquatic animals' utilization of flow through gaps, the consecutively assembled boulders were installed as approximately four rows of stone placement. Experiments were conducted in September and November. In September, oxidized slag was placed on the left side and natural stones on the right side. In November, natural boulder was placed on the left side and oxidized slag on the right side. This arrangement was made because a pathway runs alongside the channel on the left side in the flow direction. It was done to prevent any misinterpretation regarding the swimming behavior in the oxidized slag placement area and the use of the flow inside slag gaps, which could result from the avoidance behavior of aquatic animals introduced into the channel. In addition, the porosity ratio of both the natural boulder and the oxidized slag is approximately 46%.

The discharge was set to 0.0154 m^3/s to ensure steady flow within the channel, preventing obstruction of aquatic animal movement. To adjust the water level over the stonework so that the installed natural boulder and oxidized slag were nearly submerged, the water depth at the downstream end of the assembled boulders was set to h_d = 0.2595 m.

For the September experiment, water samples were collected and analyzed for 35 water quality parameters, including pH and DO, at three points: before installing oxidized slag in the channel, several days after installation, and at the experiment's end. For the November experiment, a TOADKK DM-32P (see Photo 3) was installed within the blade-shaped weir at the channel's downstream end to measure pH and DO over time.

A two-dimensional electromagnetic current meter with I type probe produced by KENEK CO. Ltd. was employed for velocity measurements (sampling time: 60 sec; sampling frequency: 50 Hz). Point gauges were employed for water depth measurements. Discharge was calculated using a flow formula based on the overflow depth measured at a sharped edge weir with the full width located downstream of the channel.

Regarding aquatic animals, on September 16, 2025, 270 individuals inhabiting the irrigation canal were obtained from the Tochigi Prefectural Fisheries Research Center located in the Kanto area. The species comprised 13 types: 31 Zacco platypus (Oikawa), Pseudogobio esocinus (Kamatsuka), 142 Lake prawn (Sujiebi), 2 Gnathopogon elongatus (Tamoroko), 1 Crucian carps (Funa), 63 Semisulcospira libertina (Kawanina), 7 Nipponocypris temminckii (Kawamuts), 8 Neocaridina (Kawarinumaebi), 1 Stone moroko (Motugo), 1 Big-scaled redfin (Ugui), 1 Barbel steed (Nigoi), and 1 Rhinogobius (Yoshino-bori). Additionally, 11 Eels (young) were obtained from the Hamana Lake Fisheries Cooperative in Shizuoka Prefecture and released at 1:30 PM on the 16th at a point midway between the downstream end of the test channel and the downstream end of the assembled boulders.

Furthermore, on November 22, 2025, 91 Yamame trout (corresponding to 1-pl (juvenile fish)) were obtained from a rearing pond managed by the Ueno Village Fisheries Cooperative Association in Ueno Village, Gunma Prefecture, located in the Kanto area. At 1:30 PM on the 22nd, only the Yamame trout were released into the downstream end of the installation region due to assembled boulders, like the September release. Figure 3 shows the distribution of Yamame by total length. As shown in Figure 3, the individuals targeted were those one-year-old. Note that their weight was 20 g or less. The reason for conducting the release in September was to investigate whether aquatic animals could inhabit the area without disease or mortality even when the water temperature reached 23°C, with the oxidized slag in place. The November release was conducted to examine whether the water-sensitive Yamame trout could inhabit the area without disease or mortality under conditions where the influence of water temperature could be disregarded.

Photo 1. Oxidized Slag Boulders (tested 52 boulders)

Photo 2. Installation of assembled boulders (left side Slag)

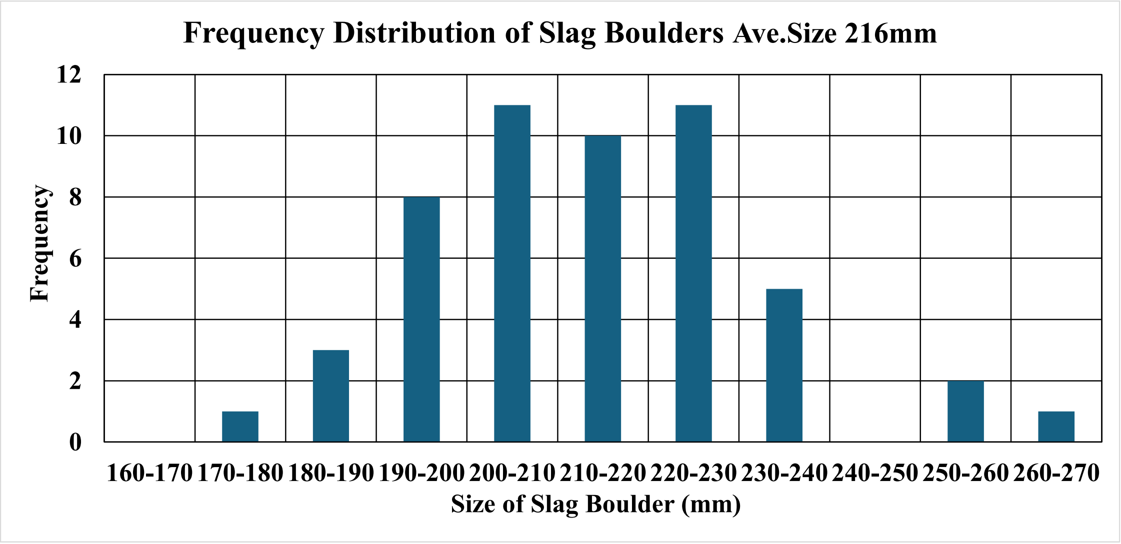

Figure 1. Frequency distribution of size in oxidized slag boulders

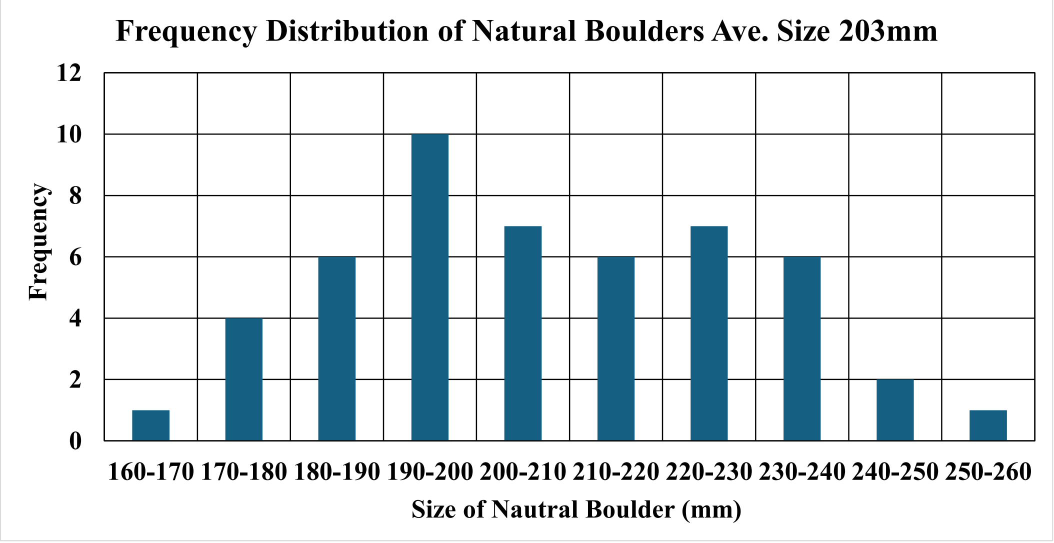

Figure 2. Frequency distribution of size in natural stone boulders

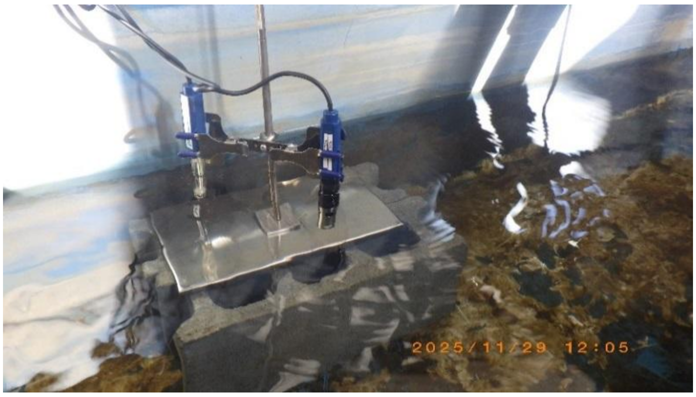

Photo 3. Installation position for pH and DO measurements in sharped edged weir

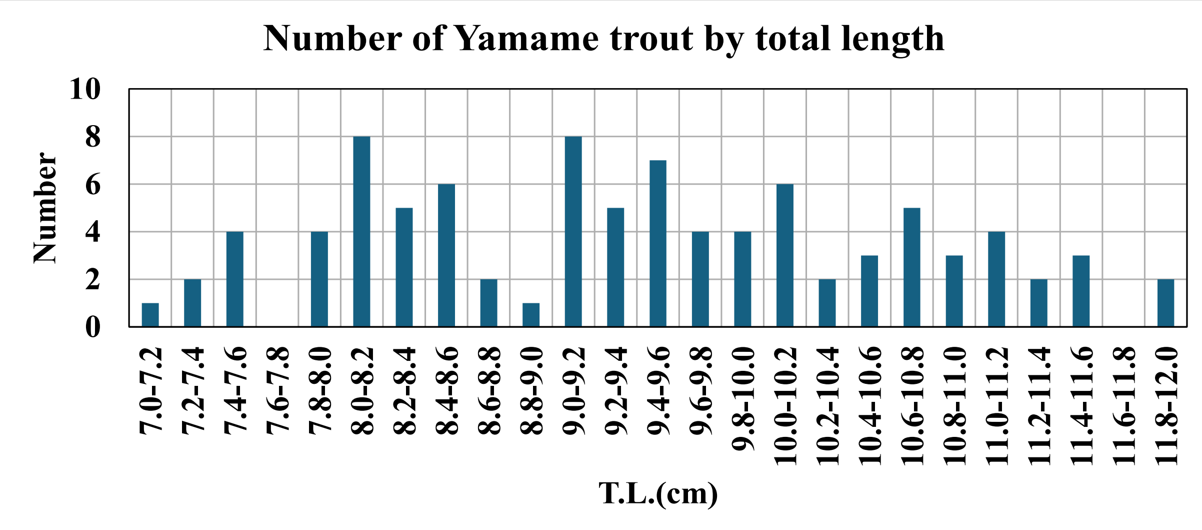

Figure 3. Distribution of Number of Yamame trout per total length

3. Flow Conditions, Water Surface Profile, and Configuration of Assembled Boulders

Photo 4 shows the flow condition passing through the consecutively assembled boulders due to oxidized slag and natural stones. As shown in Photo 4, the water surface exhibits a gradually varying flow profile (H1 curve), with almost no discernible surface irregularities. Furthermore, the flow within the gaps of the assembled boulders is reduced, preventing the scouring of pebbles beneath the assembled boulders and the displacement of aquatic animals.

Figure 4 shows the water surface profile and configuration of assembled boulders on the oxidized slag side, while Figure 5 shows the water surface profile and configuration of assembled boulders on the natural stone side. These figures depict observations recorded in November. As shown in Figures 4 and 5, the configuration of the assembled boulders includes the irregularities of the boulders. Furthermore, the natural stones exhibit a smaller periodicity of irregularities compared to the oxidized slag. This is thought to be due to the shape of the stones. The void ratio is similar for both oxidized slag and natural stones, as their sizes are comparable. The water surface gradient increases slightly downstream from x = 5.30 m. This is thought to result from adjusting the downstream water level to account for the water level above the stonework. In addition, the water depth at the upstream end of the assembled boulders recorded h_u = 0.2995 m.

a) Flow condition at slag boulders side

b) Flow condition at natural boulders side

Photo 4. Flow conditions in consecutively assembled boulders

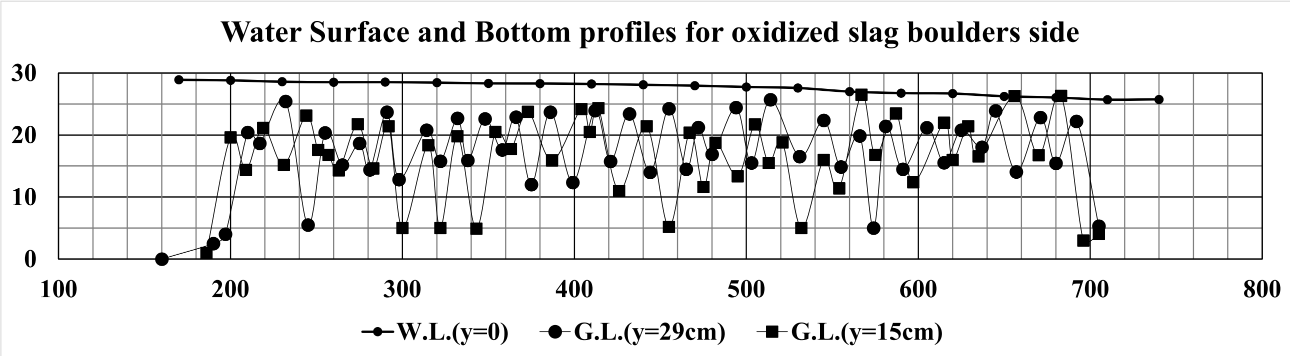

Figure 4. Water surface profile and shape of consecutively assembled boulders for oxidized slag boulders side

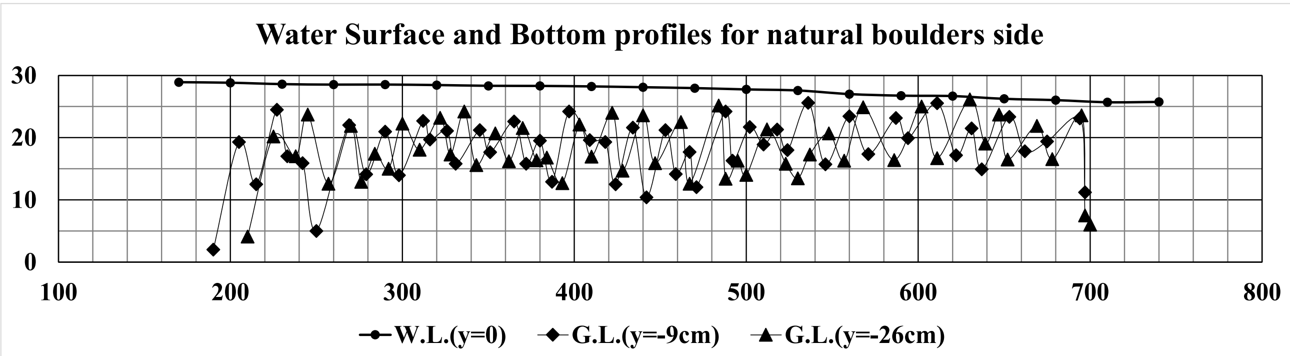

Figure 5. Water surface profile and shape of consecutively assembled boulders for natural boulders side

4. Flow Velocity Distribution in Assembled Boulders

Figure 6 shows an example of the flow velocity distribution in the installation region of assembled boulders. In this figure, u and v represent the time-averaged flow velocities in the x and y directions, respectively, while u' and v' represent the standard deviations (turbulence intensity) of the flow velocities in the x and y directions. The red solid line indicates the crest line of the stone structure. Photo 5 shows the measurement location. As shown in Figure 6, both the time-averaged velocity and standard deviation within the stone structure are small. This suggests the flow condition is suitable for resting space inside boulders for aquatic animals. Furthermore, as the flow between boulders becomes seepage flow, even if the discharge increases, the flow between boulders is reduced, making it suitable as a resting environment. Generally, studies on the flow conditions during flood stages are conducted by changing the model scale. However, the flow inside boulders depends on the configuration of the assembled boulders, the spatial shape, and the spatial volume, making it difficult to explain solely by the effects of simple gravity and viscosity. In the application for prototype, it has been verified that the assembled boulders themselves become a refuge environment in the Sanagouchi River located in Omura City, Nagasaki Prefecture, where the boulders were placed with an average size of 0.40 m (Yasuda, 2025; Yasuda, 2026).

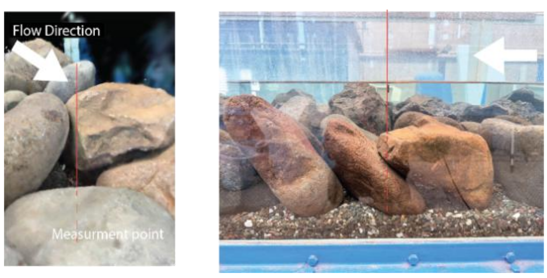

Photo 5. Velocity Measurement position

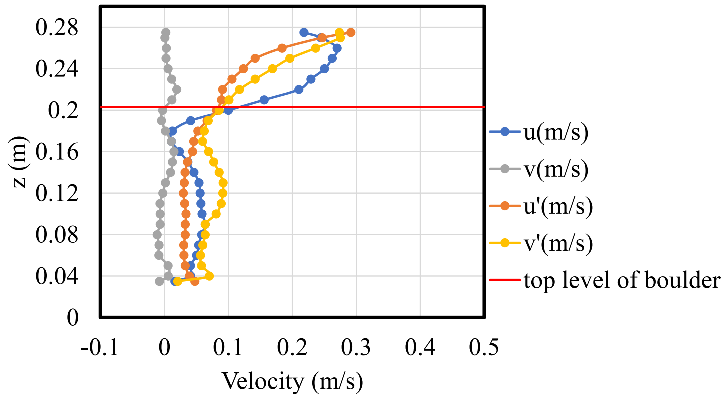

Figure 6. Velocity Distribution in assembled boulders (x=3.5m, y=0.16m)

5. Water Quality Test Results

Table 1 shows the leaching amounts and content of the oxidized slag used here and of washed oxidized slag produced during the same period, as tested in April 2025. Furthermore, Table 2 shows the Environmental Safety Quality Standards (General-Purpose Leaching Standards) presented at the study group on introducing chemical substance evaluation methods for slag materials used as concrete aggregates or for road construction. As shown in the table, the values used are lower than the Environmental Safety Quality Standards. Note that the pH value of 10.3 shown in Table 1, indicating a high alkalinity, reflects the value immediately after washing. Further, in water circulated at over 1000 times the volume of the oxidized slag input, the pH value decreases and approaches a constant value. The laboratory water circulation system pumps water stored in the lower tank, flows it through the upper tank into the channel, and returns it to the lower reservoir.

Water quality analysis results from samples collected on September 13 (pre-experiment), 16 (during experiment), and 20 (end date of the experiment) are shown in Table 3. As shown in Table 3, the pH value increased from 8.2 to 8.3 over time, while the DO value changed from 5.0 to 5.9. The pH value was already on the alkaline side before the experiment. This is likely because frequent experiments using gravel have been conducted in this laboratory, resulting in a higher pH even before slag placement. Furthermore, even after placing the slag and continuing until the experiment's end date, the pH increased by only about 0.1. Since the laboratory uses a recirculating water system, no new water was added. Therefore, leaching from the oxidized slag was considered minimal. Furthermore, the water temperature changed from 22°C to 23°C, indicating a minimal impact on the habitat of the released organisms. The ambient air temperature during the experiment ranged from approximately 28°C to 30°C. Analysis of the 35 parameters shown in Table 3 revealed no adverse effects on the habitat suitability for aquatic organisms inhabiting the Kanto area region (13 species, 281 individuals, and 10 Japanese eels). Professor Nobuhiro Mano (Scholar GPS, 2025), an academic expert specializing in fish diseases, provided the following advice. Based on the analysis results shown in Table 3, the hydrogen ion concentration (pH) is slightly high, and a value around 8 is preferable. Furthermore, when utilizing stream fish, due to the high-water temperature, it is advisable to conduct studies when the temperature is around 8°C to 15°C. Additionally, since the dissolved oxygen (DO) level is somewhat low at around 5, it is preferable to conduct studies under conditions where DO is between 8 and 10.

Table 1. Oxidation Slag Content Test (2025.04 tested by Daido Steel Co., Ltd.).

(a) Dissolution amount

Inspection Subjects	Test Results	Test Methods
Hydrogen ion concentration	10.6 (22 ℃)	Glass electrode method
Cadmium (mg/L)	Less than 0.003	ICP Mass Spectrometry
Hexavalent chromium (mg/L)	Less than 0.04	Jeffnicalbazid Absorbance Spectrophotometric Analysis Method
Total Mercury (mg/L)	Less than 0.0004	Return-Energy Atomization Atomic Absorption Spectroscopy
Selenium (mg/L)	Less than 0.002	ICP Mass Spectrometry
Lead (mg/L)	Less than 0.005	ICP Mass Spectrometry
Arsenic (mg/L)	Less than 0.005	ICP Mass Spectrometry
Fluorine (mg/L)	Less than 0.01	Lanthanum-Alizarin Complexone Compound CFA Method
Boron (mg/L)	0.2	ICP Mass Spectrometry
Oxidation-Reduction Potential	-19 (21 ℃)	

(b) Content

Inspection Subjects	Test Results	Test Methods
Cadmium and its compounds (mg/kg)	Less than 5	ICP Mass Spectrometry
Hexagonal chromium compound (mg/kg)	Less than 5	Jeffnicalbazid Absorbance Spectrophotometric Analysis Method
Total Mercury and its compounds (mg/kg)	Less than 0.1	Return-Energy Atomization Atomic Absorption Spectroscopy
Selenium and its compounds (mg/kg)	Less than 1	ICP Mass Spectrometry
Lead and its compounds (mg/kg)	Less than 10	ICP Mass Spectrometry
Arsenic and its compounds (mg/kg)	Less than 5	ICP Mass Spectrometry
Fluorine and its compounds (mg/kg)	1100	Lanthanum-Alizarin Complexone Compound CFA Method
Boron and its compounds (mg/kg)	270	ICP Mass Spectrometry

Table 2. Environmental Safety and Quality Standards

(a) Dissolution amount

Inspection Subjects	General-purpose leaching standard
Cadmium (mg/L)	Under 0.01
Hexavalent chromium (mg/L)	Under 0.05
Mercury (mg/L)	Under 0.005
Selenium (mg/L)	Under 0.01
Lead (mg/L)	Under 0.01
Arsenic (mg/L)	Under 0.01
Fluorine (mg/L)	Under 0.8
Boron (mg/L)	Under 1

(b) Content

Inspection Subjects	General-purpose leaching standard
Cadmium (mg/kg)	Under 150
Hexavalent chromium (mg/kg)	Under 250
Mercury (mg/kg)	Under 15
Selenium (mg/kg)	Under 150
Lead (mg/kg)	Under 150
Arsenic (mg/kg)	Under 150
Fluorine (mg/kg)	Under 4000
Boron (mg/kg)	Under 4000

Table 3. Analysis of Water Quality in Experiment on Assembled Boulders due to Oxidation Slag (2025.09)

Sampling Date & Time	2025/09/13 AM 10:03	2025/09/16 PM12: 38	2025/09/20 AM9: 37
Hydrogen ion concentration (pH)※	8.2 (22℃)	8.3 (23℃)	8.3 (23℃)
Dissolved Oxygen Content (DO)	5.0	5.5	5.9
Biochemical Oxygen Demand (BOD)	0.7	0.6	Less than 0.5
Suspended Solids (SS)	Less than 1	Less than 1	Less than 1
Coliform Bacteria Count※CFU/100 mL	Less than 20	Less than 20	Less than 20
Zinc	0.11	0.08	0.07
Cadmium and its compounds	Less than 0.0003	Less than 0.0003	Less than 0.0003
Lead and its compounds	Less than 0.005	Less than 0.005	Less than 0.005
Hexagonal chromium compound	Less than 0.01	Less than 0.01	Less than 0.01
Arsenic and its compounds	Less than 0.005	Less than 0.005	Less than 0.005
Mercury, Alkyl mercury compounds, and other mercury compounds	Less than 0.0005	Less than 0.0005	Less than 0.0005
Selenium and its compounds	Less than 0.002	Less than 0.002	Less than 0.002
Boron and its compounds	Less than 0.1	Less than 0.1	Less than 0.1

Fluorine and its compounds	Less than 0.1	Less than 0.1	Less than 0.1
Residual chlorine	Less than 0.05	Less than 0.05	Less than 0.05
Electrical conductivity※mS/m	35	35	36
Chemical Oxygen Demands (COD)	1.5	1.6	1.7
Nitrite Nitrogen Content	Less than 0.2	Less than 0.2	Less than 0.2
Nitrate Nitrogen Content	2.3	2.3	2.2
Ammoniacal Nitrogen Content	Less than 0.7	Less than 0.7	Less than 0.7
Total Nitrogen	2.4	2.4	2.4
Phosphoric Acid Phosphorus	0.02	0.02	0.02
Total Phosphorus	0.023	0.024	0.026
Magnesium ion	7	7	7
Calcium ion	26	26	27
Total Hardness	91	93	95
Sodium ion	26	28	27
Potassium ion	7.0	7.9	7.2
Chloride ion	31	32	33
Sulfate ion	35	35	34
Acid consumption (pH4.8)	73	74	74
Ionic silica	23	23	23
Soluble Iron content	Less than 0.1	Less than 0.1	Less than 0.1
Chromium Content	Less than 0.01	Less than 0.01	Less than 0.01
Total Organic Carbon (TOC)	0.9	0.9	0.9

Photo 6 shows the state of the oxidized slag stored outdoors one month after the first experiment. Due to its outdoor placement, it has been repeatedly exposed to wet and dry conditions from rainfall. As shown in Photo 6, the difference from its state before the first experiment is minimal. After one month following the second experiment, slight rusting became visible. As a countermeasure, it is advisable to avoid oxidized slag where metal fragments are visible on the surface.

Figure 7 shows the time-series changes in pH and DO from November 22 (experiment start date) to November 29 (experiment end date). As shown in Figure 7, the water temperature fluctuated between 15°C and 17°C. The hydrogen ion concentration (pH) remained at approximately 8.2 from the start to the end of the experiment. This indicates no leaching from the slag. Regarding dissolved oxygen (DO), values ranged from 9 to 10. Note that other experiments using different channels were also conducted in the laboratory, so the influence of air bubble entrainment is not solely attributable to this experiment. Based on the measured water temperature, pH, and DO results, it is considered that the results for pH and DO may not affect the habitat selection or movement between gravels by Yamame in this experiment.

Photo 6. Condition of the oxidized slags one month after the first experiment in September

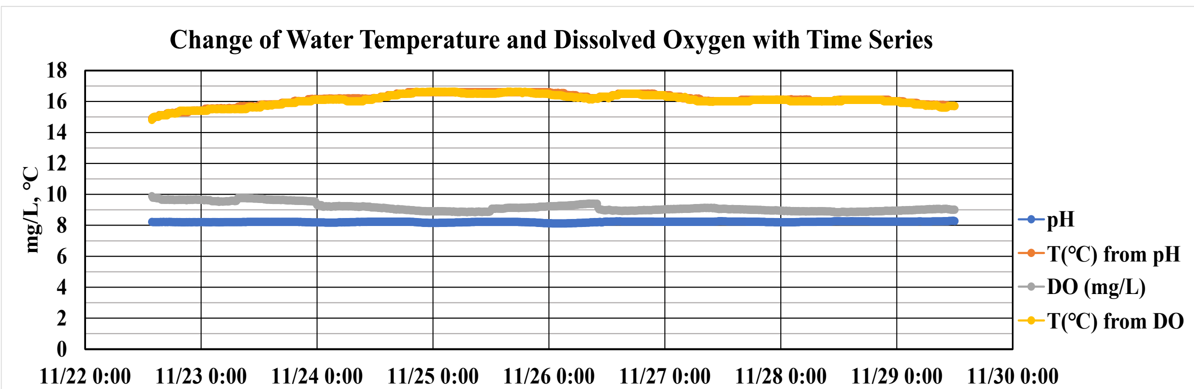

Figure 7. Change of Water Temperature and Dissolved Oxygen with Time Series (2025.11)

6. Observation Results of Released Aquatic Organisms

Photo 7 shows an example of recorded behavior of aquatic organisms released downstream of the assembled boulders in September. Regardless of the assembled boulders, the released aquatic animals utilize the flow between or over boulders to move. Eels hide in the gaps between boulders or among small pebbles during the day. Swimming fish, possibly wary of eels, positioned themselves upstream or downstream of the assembled boulders if less than 10 cm in length. When moving, they traveled through boulder gaps and over boulder surfaces. Freshwater shrimp positioned themselves in boulder gaps unaffected by the current and moved occasionally (Photo 7). Swimming fish around 20 cm in length move through boulder gaps and areas around the assembled boulders. When swimming fish near the assembled boulders sense human presence and retreat, they move toward the natural boulder side rather than the slag side, subsequently also seeking refuge in the boulder on the slag side. This behavior is thought to result from the slag being placed on the passageway side, causing the fish to retreat upon sensing human presence. The impact of the slag's uneven surface appears minimal, as gobies, freshwater shrimp, and freshwater snail (Semisulcospira libertina (Kawanina)) to the slag's surface, crawl along it, or move by hooking their claws. Table 4 shows changes in population size before and after the September experiment for each aquatic organism. As shown in Table 4, on September 20 (the final day), approximately 56 % (84 individuals) of the released Freshwater shrimps were not recovered, suggesting they were likely preyed upon. Goby fish remains alert to eel predation, waiting in boulder gaps within the assembled boulders or near the upstream/downstream edges. Based on the condition of the small fish and Lake prawn that were preyed upon, it is thought that eels were predators. The movement of the eels' habitat suggests they are moving at night.

Photo 8 shows one example of recorded behavior of aquatic organisms released downstream of the assembled boulders in November. At the start of the experiment, the released Yamame cautiously probed between gravels and showed no signs of actively entering the gaps. Subsequently, however, the released Yamame moved using either the gaps between stones or the flow over the gravel, regardless of the stone structure. That is, even when oxidized slag was placed on the passage side, the Yamame remained in the gaps or beside the slag, moved around, or traveled over the top. Furthermore, when there was a sign of human movement in the passage, they tended to become wary and hide within the boulder gaps. Additionally, about 70% of the released fish were observed in the gravel gaps, with the rest mostly found upstream or downstream of the assembled boulders. After the November experiment, all Yamame trout were recovered without any illness or mortality.

a) Eel inside oxidized slag boulders

b) Swimming fishes upstream of boulders

c) Swimming fishes in slag boulders

d) Amur goby inside oxidized slag

Photo 7. Aquatic animals observed in the installation of oxidized slag boulders

Photo 8. Yamame trout observed in the installation of oxidized slag boulders

Table 4. Changes in population size before and after the September experiment for each aquatic organism

No.	Individual Type	Population size of organisms before experiment	Population size of organisms after experiment	Decrease rate
1	Japanese Eels (weight: 150 to 200 g)	11	11	0.0%
2	Zacco platypus (Oikawa)	30	29	3.3%
3	Pseudogobio esocinus (Kamatsuka)	1	1	0.0%
3	Lake prawn (Sujiebi)	142	63	55.6%
4	Gnathopogon elongatus (Tamoroko)	2	2	0.0%
5	Crucian carps (Funa)	2	2	0.0%
6	Semisulcospira libertina (Kawanina)	63	63	0.0%
7	Nipponocypris temminckii (Kawamuts)	7	7	0.0%
8	Neocaridina (Kawarinumaebi)	7	2	71.4%
9	Stone moroko (Motugo)	1	0	100.0%
10	Big-scaled redfin (Ugui)	1	1	0.0%
11	Barbel steed (Nigoi)	1	1	0.0%
12	Rhinogobius (Yoshino-bori)	13	13	0.0%
	Total	281	195	30.6%

This test period is two months long, so it may be necessary to conduct fish-based rearing tests for over six months, performing macroscopic growth analysis and microscopic pathological tissue analysis of reproductive organs such as urinary organs and ovaries. Additionally, since the aquatic resistance period of the oxidized slag is expected to be comparable to that of concrete, there is no risk of it gradually turning sandy. Furthermore, even if concentrations of each item are low, long-term rearing may increase the accumulation of heavy metals and other substances within the fish. Therefore, it is necessary to monitor the long-term progress of the fish used in the trial. Since invertebrates are more susceptible to the negative effects of heavy metals and chemical components, Semisulcospira libertina (Kawanina) and Freshwater shrimp (Sujiebi) were used in this test. Their activity levels were confirmed to be like pre-test levels both during and after the test period.

During the test period and subsequent fish rearing, feed used for freshwater fish was provided at a rate of once every four days. The temperature in the rearing room was maintained below 22°C. Water containing the same components as during the test was taken from the low-level tank, and 90% of the water in the rearing tank was replaced after feeding. Post-test observations showed growth in the Zacco platypus (Oikawa), Nipponocypris temminckii (Kawamuts), and freshwater shrimp. Furthermore, as less than six months had passed since the test, no growth was observed in Japanese Eel (Nihon Unagi), Crucian carps (Funa), Barbel steed (Nigoi), and Big-scaled redfin (Ugui).

7. Discussion on Application

In this experiment, natural stone with an average size of approximately 0.21 m and oxidized slag were utilized. The suitability of the oxidized slag was assessed in a recirculating experimental channel over approximately one week of water flow, evaluating water quality and the presence of 14 aquatic species in terms of their habitat status, movement behavior, avoidance behavior, and predation. The reason for setting the gravel size at approximately 0.2 m was to enable easy manual transport and stonework construction. Furthermore, this size ensures gaps large enough for aquatic organisms, excluding large species, with body lengths of 0.20 m or less to migrate upstream and downstream. This possibility is supported by case studies conducted in urban rivers using natural stone rubble (Yasuda, 2026).

Results from one-week water flow experiments conducted in September and November showed that even when using recirculated water distinct from river and lake water, the pH remained around 8.2 (alkaline). This water met environmental quality standards, with negligible leaching from the slag. There was no bias towards natural stone in the habitat, refuge behavior, or movement patterns of swimming fish, benthic fish, freshwater shrimp, and freshwater shell, confirming the effective utilization of oxidized slag. Furthermore, from a food chain perspective, when 281 individuals of 13 aquatic species were introduced into the watercourse within a limited space, it was confirmed that eels primarily prey on freshwater shrimp. Although artificial feed was used, regular administration confirmed consumption by swimming fish, benthic fish, freshwater shrimp, and shell. These findings suggest that it is worthwhile applying this approach to rivers and lakes and conducting follow-up observations. For applying this method, for example, the process involves crushing and grading the oxidized slag, followed by either a steam steaming process (3 days or more) or washing and outdoor drying (60 days or more). It might be recommended to use oxidized slag that meets environmental standards, with a pH around 8.3 in an aerated environment where the water volume in a test tank is approximately 1000 times (100 kg) the input quantity of slag (test scale: approximately 25mm, 100g) (Agitation period:6 hours). Furthermore, to address the concerns regarding the accumulation of oxidized slag highlighted by the author themselves, consideration must be given to implementing longer-term monitoring.

8. Summary

To investigate whether oxidized slag of boulder size can be utilized for river environment improvement, assembled boulders made of oxidized slag with an average size of 21.6 cm was installed in a channel in the laboratory. For comparison, a stone structure made of natural boulder with an average size of 20.3 cm was installed in parallel. To distinguish between alert and avoidance behaviors triggered by placement along the channel, the positions of the oxidized slag and natural boulder structures were swapped. In September, 281 individuals of 13 fish species were stocked, and a five-day observation period was conducted. The pH remained around 8.3 and the water temperature around 23°C, showing little difference from before the slag was introduced. Water samples collected before the experiment, during the experiment, and on the final day were analyzed. Results indicated potential issues with pH and dissolved oxygen (DO) levels for certain aquatic species, though the impact on the aquatic animals stocked in September was minor. No avoidance behavior by aquatic organisms due to the slag placement was observed; instead, predatory behavior and territorial behavior of swimming fish, typical in rivers, were noted. Although some oxidized slag contained metals and exhibited scattered rust spots on the surface, the spread of rust during the experiment period was minimal. In November, 91 Yamame trout inhabiting mountain streams were released, and a one-week observation period revealed a nearly constant pH of 8.2 and water temperatures fluctuating between 15°C and 17°C. Even when slag was placed farther from the channel, no avoidance behavior by aquatic organisms due to slag placement was observed, consistent with previous results. Based on the two observation periods, all released aquatic animals utilized the spaces between the boulders. Flow velocity measurements in the assembled boulders section confirmed that the time-averaged flow velocity and standard deviation were consistently low. These results indicate that oxidized slag can be applied to flow fields inhabited by aquatic animals when the leaching rate and content meet environmental standards, repeated washing is performed, and the hydrogen ion concentration is maintained around 8.

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