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STUDY ON HYDRAULIC CHARACTERISTICS OF RIFFLES BY A FIELD OBSERVATION

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SYNOPSIS

From the view points of ecology and landscape, it is very important for hydraulic engineers to know the hydraulic characteristics of riffles. For the purpose, we performed a field observation at a riffle of Aki-river in Akiruno city, Tokyo, on 25 August 1995, in which flow velocity, fluctuation of water surface, temperature of water and dissolved oxygen were measured. It is found that organized vortices generated by an interaction between flow and channel-bed gravels are dominant in determining the characteristics of free surface fluctuation at riffles.

INTRODUCTION

There are many garvel-bedded meandering rivers in Japan, where two types of flow field exist in one meander reach: a flow field with shallow water depth and large flow velocity is termed “riffle” and a flow field with deep water depth and small flow velocity is termed “pool”. Recently, it has been known that the riffle and pool system plays an important role as fish habitats. Flow field at riffle and pool system provides not only good habitats but also good landscape and/or soundscape. It is thus required for hydraulic engineers to study the hydraulic and ecological features of the system.

The study on this subject has started recently, and several researchers are working on hydraulic behaviors (Refs.2,3,5) or ecological aspects (Ref.4). For example, Yamada et al.(Ref.5) studied the resistance to flow at chutes-and-pools, employing the Bernoulli theorem. Tsuchiya (Ref.4) measured sound at riffles, and he pointed out that the profile of power spectrum density of sound is in inverse proportion to frequency at high frequency region (between 10 and 20 kHz). As for the ecological aspect, the behavior of fishes has been studied extensively. These results, however, are not yet adequately interpreted in terms of hydraulics.

As a first step to understand the flow field at riffles, it is necessary to get more quantitative data on hydraulic and ecological features of riffles. This is the motivation of the present field measurements.

OUTLINE OF THE FIELD OBSERVATION

Location

The observation was conducted at a riffle of Aki-river in Akiruno city, Tokyo, on 25 August 1995. The observation area locates at 40 m downstream from the East-Akikawa bridge, 60 m downstream from the Takatsuki irrigation dam and about 1.2 km upstream from the confluence of Aki-river and Tama-river (see Fig.1). The riffle extends with a length of about 50 m, consisting of spatial variation of water surface elevation, the longitudinal profile of which is shown in Fig.2. The area A-B in Fig.2 is the start of the riffle, where there are various textures of water surface such as splashing surface and calm one. The area B-C has a steep channel bed, at which the water surface was breaking with entrained air. The area C-D is the end of the riffle, which continues to the subsequent pool. A sub-area for observation was selected in the area A-B so as to measure the various types of free surface. It locates on 16 m downstream from the beginning of the riffle, in which 18 observation points were selected in the transverse direction at an interval of 1 m (for details, see Fig.3). The observation points are labeled as St.1, St.2 ,..St.18 from the left bank, respectively. The longitudinal slope of the channel bed at the observation sub-area was 1/187 (see Fig.2).

Methods

At each observation point described in the above flow velocity and fluctuation of water surface were measured. The velocity was measured by using two types of electromagnetic velocimetry (KENEK Co.,Ltd., model: VM201H, accuracy: ±1 cm/s), in which velocity components of x and y direction, labeled as u and v respectively, were measured by I type probe and those of x and z directions, labeled as u and w, were detected by L type probe. The elevation of measurement of the velocity locates at 10cm below the water surface at each station to measure the flow field near the water surface. The water surface elevation was observed by capacity-type wave gage (KENEK Co.,Ltd., model: CHT4-30, accuracy: ±1mm). Both signals of velocity and water surface variation were sampled with an interval of 20 Hz for 100 seconds. The data were transferred to 5 Hz data by moving-average filtering to remove the noise included in the data which was mainly caused by entrainment of air at high frequency range.

The dissolved oxygen is an important factor for the water quality and the ecosystem in river, and it is much affected by the water temperature. Therefore, the dissolved oxygen and the water temprture were measured. The water temperature and the dissolved oxygen were observed by using eco-probe (TERAL KYOKUTO Co.,Ltd, model: Eco No.43, accuracy: Temp.: ±0.02℃, DO: ±0.1%) at 3 areas, which are area A, area D(the beginning and the end of a riffle shown in Fig.2, respectively) and the observation area for velocity and water surface variation.

Classification of Riffles

Various types of riffles are reported to exist in steep rivers. Scientists basically classify them into Hira-riffle and Haya-riffle. However, there are various flow patterns in Hira-riffle or Haya-riffle, and therefore the classification is crude. More detailed classification on riffles is proposed by fishermen to describe the various local visual patterns of riffles(Ref.1). Referring to the classification made by fishermen, in the present study the following three patterns of riffles are employed:

Chara-riffle (Photo.1) : flow field exists at area with shallow water depth (between about 20 and 40 cm), where the spatial variation of water surface shows a wavy texture. However, water surface does not break.

Zara-riffle (Photo.2) :a flow field almost the same as chara-riffle. Water surface, however, breaks locally with entrainment of air.

Side-riffle : a flow field locates at the side of riffle without spatial variation of water surface.

In the present measurement, the observation areas were classified such that St.1 to St.4 are side-riffle, St.5 to St.12 and from St.17 to St.18 are chara-riffle, and St.13 to St.16 are zara-riffle, respectively.

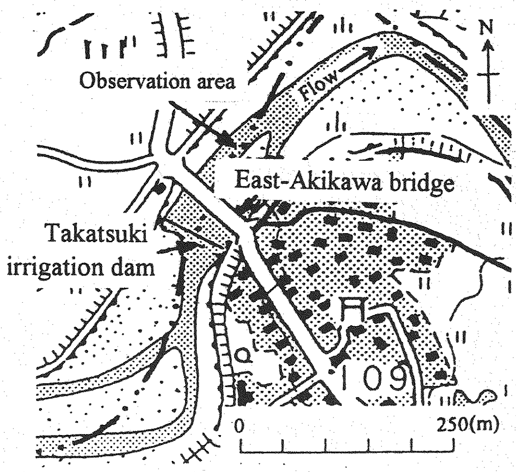
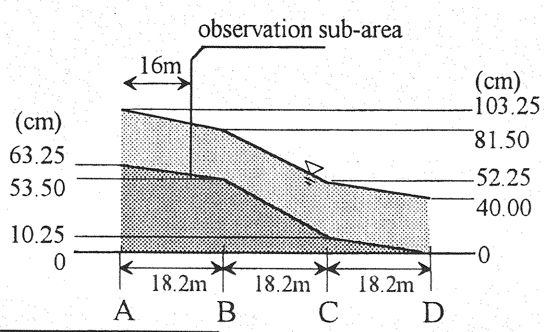


Fig. 1 Location of the observation



Slope of channel bed	1/187	1/42	1/178	1/86 (A-D)
Slope of water surface	1/235	1/39	1/221	1/86 (A-D)

Fig. 2 Sketch of the longitudinal cross-section at the observation area

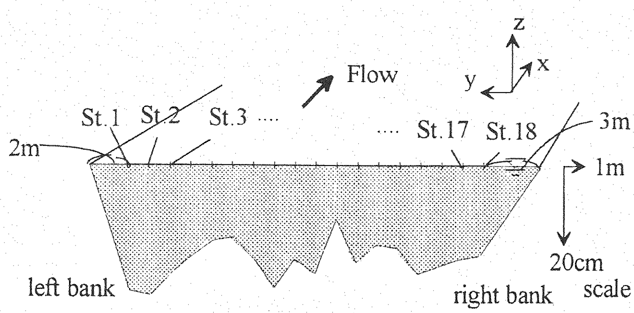


Fig. 3 Sketch of the transverse cross-section at the observation sub-area

Photo.1 An example of chara-riffle

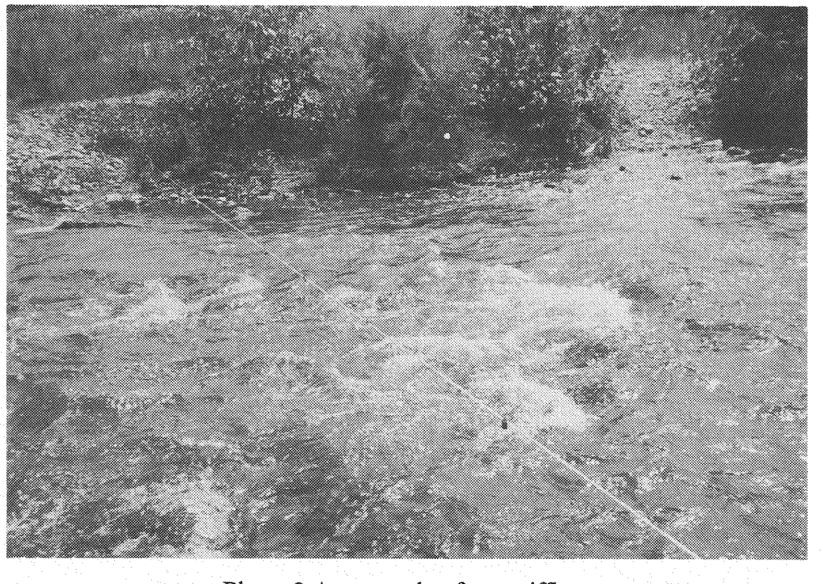


Photo.2 An example of zara-riffle

RESULTS OF OBSREVATION

Temporally-Averaged Flow Fields

The temporally-averaged longitudinal flow velocity, U, is depicted in Fig.4., indicating that the velocities at chara-riffle and zara-riffle are both larger than those at the side-riffle, while there is not any significant difference between chara-riffle and zara-riffle.

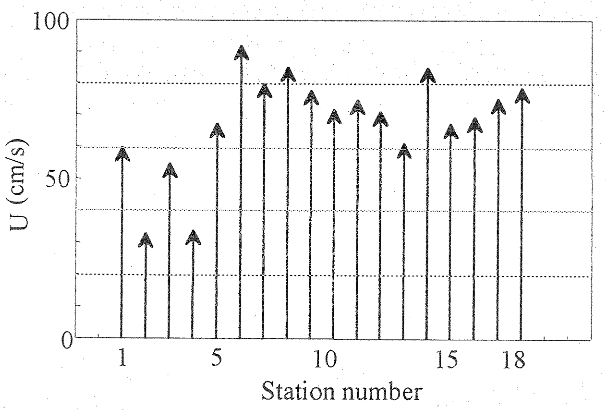


Fig.4 Temporally-averaged longitudinal flow velocity

The R.M.S. of fluctuations of water surface, h', at several points are depicted in Fig.5, which shows that the value is increased in order of side-riffle, chara-riffle and zara-riffle. Water surface fluctuations of riffles were found to consist of both spatial and temporal fluctuations. The definition of the spatial fluctuation is the spatial elevation of the temporally-averaged water surface, and that of the temporal fluctuation is the temporal variation from the temporally-averaged water surface. The spatial fluctuation forms a texture like waves. This wavy texture is observed to be almost stationary. In the present observation, only temporal fluctuations were measured by wave gages, because the measurement of spatial variation requires considerable numbers of wave gages. At zara-riffles, water surface breaks with entrainment of air as described previously, which is induced by hydraulic jump, increasing the R.M.S. of h' compared with the other types of riffles.

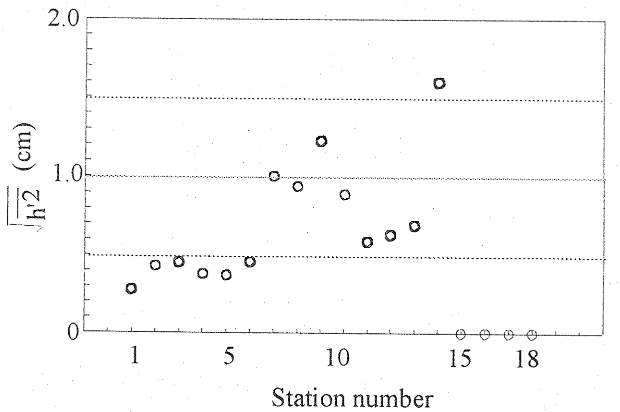


Fig.5 R.M.S. of fluctuation of water surface at several lateral locations

Local Froude numbers, $U/\sqrt{gH}$, are described in Fig.6, in which characteristics length is taken to be the local water depth and the longitudinal flow velocity is a temporally-averaged one at each station. The local water depth was defined such that the distance between the surface of bed gravels and the temporally-averaged water surface at each location. Froude numbers at chara-riffle and zara-riffle are larger than those at side-riffle. Despite the difference of water surface texture between chara-riffle and zara-riffle, there is no significant difference in Froude numbers between them. In open channel flow with flat bed, Froude number determines the type of hydraulic jump, and thus it is expected to be an important factor in determining the type of water surface texture at riffles. However, the local Froude number at riffles is much affected by the bottom geometry associated with large gravels. It is therefore assumed that major factors in determining the water surface texture at riffles are not only spatially-averaged Froude number but also the configuration of channel bed, e.g. size and/or distributions of large gravels.

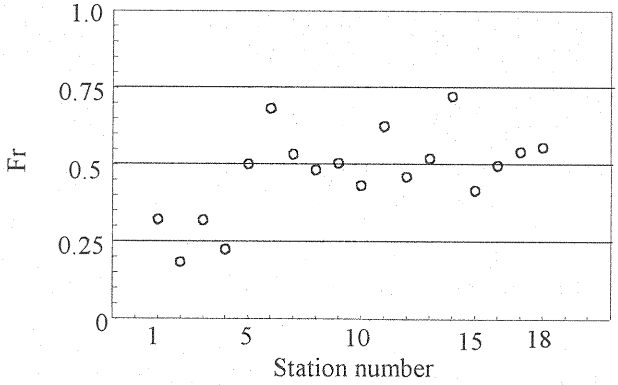


Fig.6 Local Froude number

Fig.7 shows the distribution of diameter of channel bed gravels, $d = d_{90} \sim d_{94}$, measured using photographs taken by a camera submerged in water. The diameters show a considerable scatter for each location. However, there is a tendency that large gravels exist at locations where the velocities are large. The size of these large gravels reaches to about 30%～40% of the local water depth, and therefore the gravels are expected to affect the flow field significantly. For example, the transition from supercritical flow to subcritical flow sometimes occurs behind large size gravels. Therefore, to know the detailed flow fields, the gravels can not be treated as merely roughness but the geometry of channel bed.

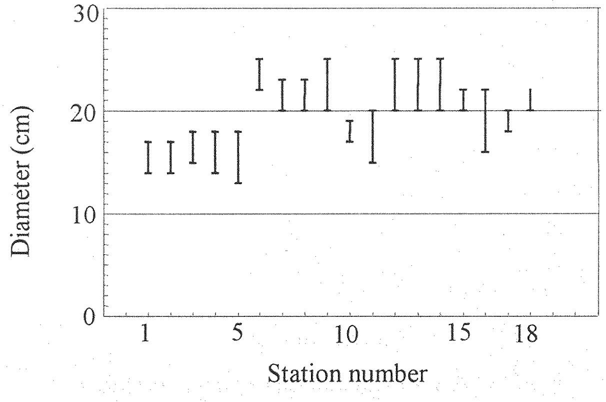


Fig.7 Diameters of channel bed gravels

Dimensionless turbulence energy at each location depicted in Fig.8 shows almost an identical value except at St. 3 and the locations where zara-riffle exist. Upstream of St. 3 by 1m, there was a large gravel which was as large as the water depth, and it generated Karman vortex street. The situation yielded a large fluctuation of velocity at St.3. At zara-riffle, turbulence energy is larger than those of the other riffles, since water surface was breaking to yield intense turbulence.

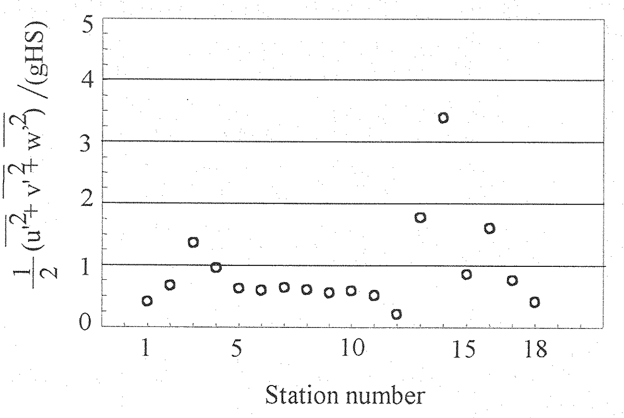


Fig.8 Dimensionless turbulence energy

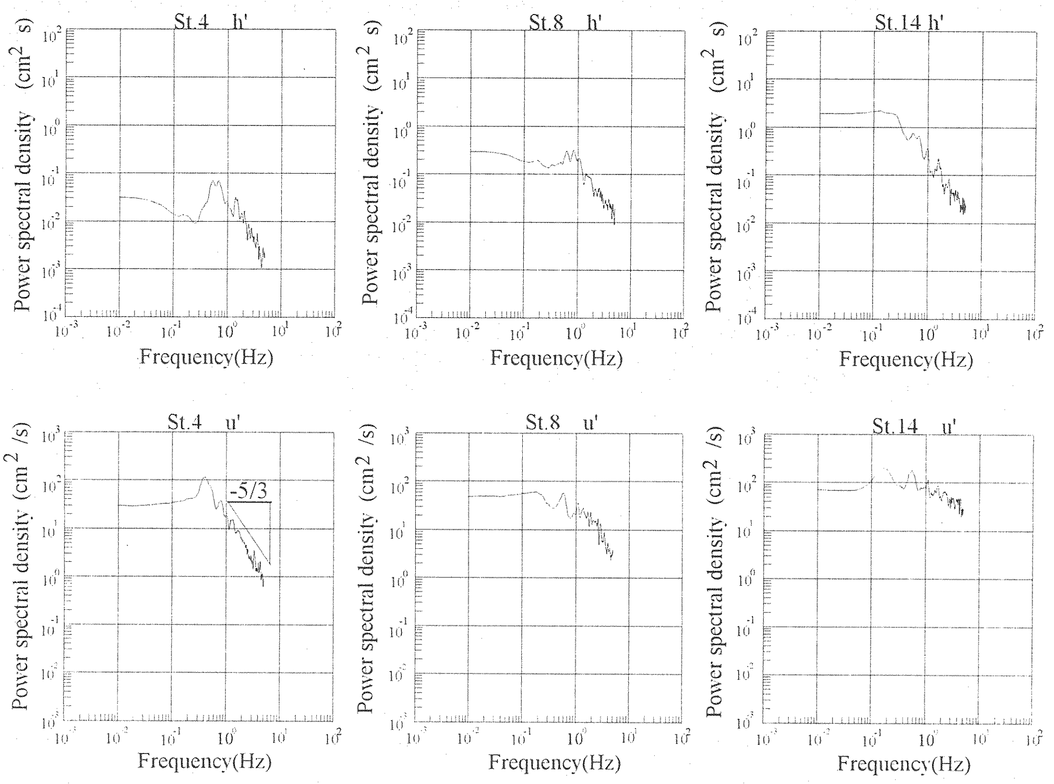
Temporal Fluctuation of Flow Fields

As mentioned in the above, fluctuation of water surface at riffle consists both of spatial and temporal fluctuations. To know the characteristics of temporal fluctuation of free surface, spectral analysis is performed for data obtained in the field.

Figs.9 (a), (b) and (c) show the profiles of power spectral densities of h' and u' at St.4 located at side-riffle, St.8 at chara-riffle and St.14 at zara-riffle, respectively. It is seen that the power spectrum densities of both h' and u' at each riffle are increasing in order of side-riffle, chara-riffle and zara-riffle. The profiles are different for the kind of riffles. At side-riffle, the slope of power spectral density of u' at high frequency range follows with the Kolmogorov -5/3 low well. However, the slope decreases in order of chara-riffle and zara-riffle, the reason for which is probably the generation of turbulence associated with water surface fluctuation and breaking of waves seen at chara-riffle and zara-riffle. Especially, at zara-riffle, entrainment of air induced by hydraulic jump generates turbulence at high frequency range. The location of the peak of the spectrum for water surface fluctuation agrees well with that of velocity at each station, suggesting that the flow velocity fluctuates in accordance with the fluctuation of free surface.

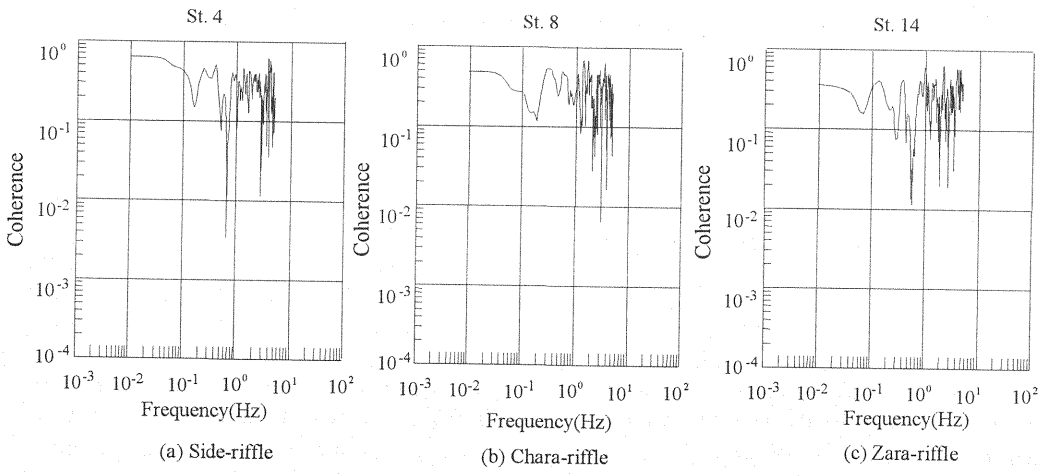
Fig. 10(a), (b) and (c) show the coherence between u' and h'. The coherence is defined such that the square of the cross-correlation coefficient between 2 signals obtained at the same frequency, and it takes value between 0 and 1. The figures show that the coherence takes more than 0.3 for wide frequency range at all stations, indicating that the fluctuation of velocity and that of water surface are correlated each other. The fact suggests that turbulence is closely correlated with free surface fluctuation.

Strouhal numbers, fd /U, estimated from a peak frequency of the power spectrum of longitudinal flow velocity at each station are shown in Fig.11, in which characteristic length is taken to be the diameter of large size gravels, $d = d_{90} \sim d_{94}$, at each station and the longitudinal flow velocity is a temporally-averaged one at each station. The Strouhal numbers take values between 0.1 and 0.2 at every station except for St.2. In calculating the Strouhal number in the present observation, the following difficulties are encountered. First, it was difficult to define



(a) Side-riffle (b) Chara-riffle (c) Zara-riffle

Fig.9 Power spectral densities of fluctuation of water surface, h', and longitudinal flow velocity, u'



(a) Side-riffle (b) Chara-riffle (c) Zara-riffle

Fig.10 Coherence between fluctuation of water surface, h', and longitudinal flow velocity, u' the characteristic velocity, because irregular array of large gravels induced local variation of flow field. Second, the Strouhal number is usually defined for a pair of vortices generated by two-dimensional obstacles. However, in the present case the vortices are shed from three-dimensional obstacles. Despite of these drawbacks, it is still useful to discuss the characteristics of the Strouhal number. The Strouhal number is almost identical regardless of location, indicating that the fluctuation of velocity is induced by the organized vortices shed from channel bed gravels. The good agreement of peak frequency of fluctuation between water surface and velocity suggests that water surface also fluctuates in accordance with the organized vortices.

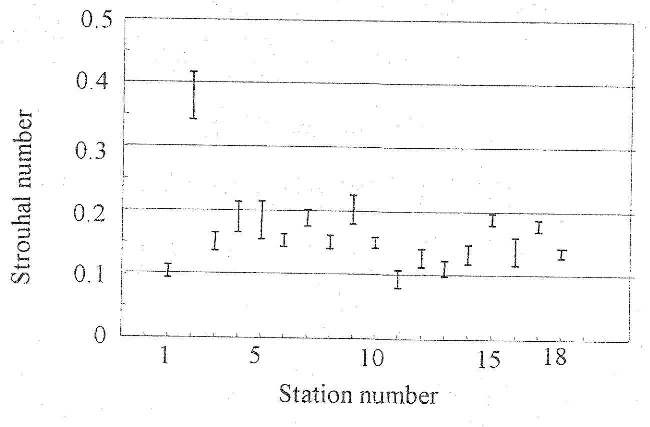


Fig.11 Strouhal number

Water Quality

Water temperature and dissolved oxygen were measured by using eco-probe at 3 areas mentioned in the above, and the results are summarized in Table 1. It is found that the concentration of dissolved oxygen in water increases downstream. The spatial variation of dissolved oxygen is expected to be induced by the followings: reaeration from the water surface, photosynthesis of weed growing on gravels and variation of saturation value of dissolved oxygen in accordance with the variation of water temperature. In this observation there is not any significant difference in the water temperature between the areas, and therefore the effect of the variation of saturation value of dissolved oxygen is negligible, suggesting that the dominant reasons for the increase are the reaeration caused by the entrainment of air at zara-riffle and the photosynthesis.

Table 1 Water temperature and dissolved oxygen

	Water temperature(℃)	Dissolved oxygen (%)
Area A (Beginning of the riffle)	23.68	94.6
Observation area	23.75	96.5
Area D (End of the riffle)	23.82	99.8

CONCLUSIONS

The field observation performed herein has revealed the followings:

1)Fluctuation of water surface is larger at chara-riffle than at side-of-riffle, though the turbulence energy is almost identical. Turbulence energy at zara-riffle is much larger than those of other types of riffles. Turbulence energy where water surface is breaking with entrainment of air becomes very large.

2)Temporal fluctuation of water surface at riffles is much affected by vortices generated by large bed gravels.

3)The dissolved oxygen is increased by the reaeration from water surface and the photosynthesis of weed growing on gravels.

ACKNOWLEDGEMENTS

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APPENDIX-NOTATION

The following symbols are used in this paper:

d	= diameter of large size gravels, $d = d_{90} \sim d_{94}$;
f	= peak frequency of the power spectrum of longitudinal flow velocity;
Fr	= Froude number = $U/\sqrt{gH}$;
g	= gravitational acceleration;
H	= temporally-averaged water depth;
h'	= temporal fluctuation of water surface;
S	= slope of water surface;
St	= Strouhal number = fd /U
U, V, W	= temporally-averaged velocity components along x, y and z, respectively;
u, v, w	= instantaneous velocity components along x, y and z, respectively;
u', v', w'	= temporal fluctuation components of u, v and w along x, y and z, respectively;

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