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Author(s)	Tsubaki, Ryota; Nakayama, Yasuki; Fujita, Ichiro
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The Design Secret of Kyokusui-no-En's Meandering Channel

Tsubaki, R.*[1], and Nakayama, Y,*[2] and Fujita, I.*[3]

*1 Department of Civil Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan.
E-mail: r.tsubaki@gmail.com
*2 Future Technology Research Institute/ Tokai University, 3-56-2 Higashiohizumi, Nerima-ku, Tokyo 178-0063, Japan.
E-mail: y-naka@mug.biglobe.ne.jp
*3 Department of Civil Engineering, Kobe University, Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan.
E-mail: ifujita@kobe-u.ac.jp

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Abstract : The purpose of this study is to investigate the characteristics of the flow through the Jonangu channel which is used for ceremonial game called as 'Kyokusui-no-En' in Japanese. The geometry of the channel is measured, a visualization technique is used to measure the actual flow characteristics, and then a numerical flow model is used to represent the flow including unsteady flow characteristics. Numerical model of drifting cup is introduced to investigate an interaction between flow and motion of the cup. Finally, the intention of the channel design is interpreted from the viewpoint of fluid mechanics using observed and calculated results.

Keywords : Kyokusui-no-en, Large-scale PIV, Shallow water, Numerical model, Irregularly shaped boundary.

1. Introduction

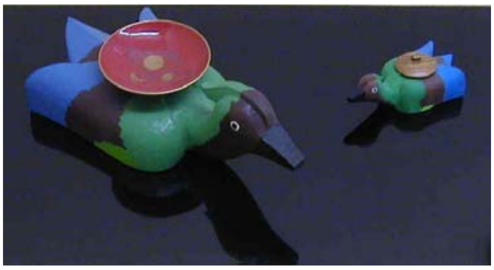
An elegant ceremony, using a meandering channel of water running through a garden, was begun in ancient China. In this ceremony, a cup filled with rice wine is placed into the flow of the channel from the upstream area and released to move freely with the flow. When the cup stops at some point, the person nearest to the cup must promptly make and recite a poem. If this person fails to make a poem, he/she must drink the wine from the drifting cup. In addition to its value as entertainment, this ceremony was used as an experiment to determine who had the most talent at impromptu poetry because at this ceremony it was prohibited to speak in order to ask another person for help. (Imamichi, 2003).

This ceremonial game was introduced into Japan in AD 485 after coming from China by way of Korea. Since then, this style of game has been introduced in many places throughout Japan. The ceremony is referred to as "Kyokusui-no-En (festival on the meandering channel.)" The remains of the channels used for Kyokusui-no-En can be found in eight places in Japan. In five of these places, the channels are still used for the ceremony. The Jonangu (Shrine) in Kyoto, Japan is one of the places where the ceremony is still performed (see Figure 1a.) Chang (2001) pointed out that the styles of the meandering channel for the drifting cup ceremony can be divided into 'the rather natural' and 'the significantly artificial' styles. Japanese channels are good example of the former style and Chinese channels basically represent characteristics of the latter design. In 'the significantly artificial' style, the channel is compactly configured in a limited space by carving stones and the channel is meandered but have a smooth bottom surface and a constant cross-sectional configuration.

Several types of the cups have been used in this ceremony. The cup used in Japan is loaded up on a container imitating a bird shape (see Figure 1b), and then released onto the channel. A famous Chinese poet, Li Bai used birds going up and down as a metaphor of exchanging of wine cups in a banquet. There were instances that releasing a cup directly into the flow and a cup set on square floating boards. Those styles were illustrated in several ancient drawings.

The purpose of this study is to investigate the characteristics of the flow through the Jonangu channel to reveal the intention of the channel in the context of scientific and fluid art (Fujisawa et al., 2007). The geometry of the channel is measured by the authors, a visualization technique is used to measure the actual flow characteristics, and then a numerical flow model is used to represent the flow, including unsteady flow characteristics. Numerical model of the drifting cup is used to investigate an interaction between flow and motion of the cup. Finally, the contributions of each design element of the channel to provide uncertainty of the flow and the cup motion are interpreted from the viewpoint of the fluid mechanics using observed and calculated results.

(a) Persons making poems



(b) Cup with container imitating bird shape (courtesy of Mr. Khoji Shimizu)

Fig. 1. Kyokusui-no-En of Jonangu.

2. Experiment

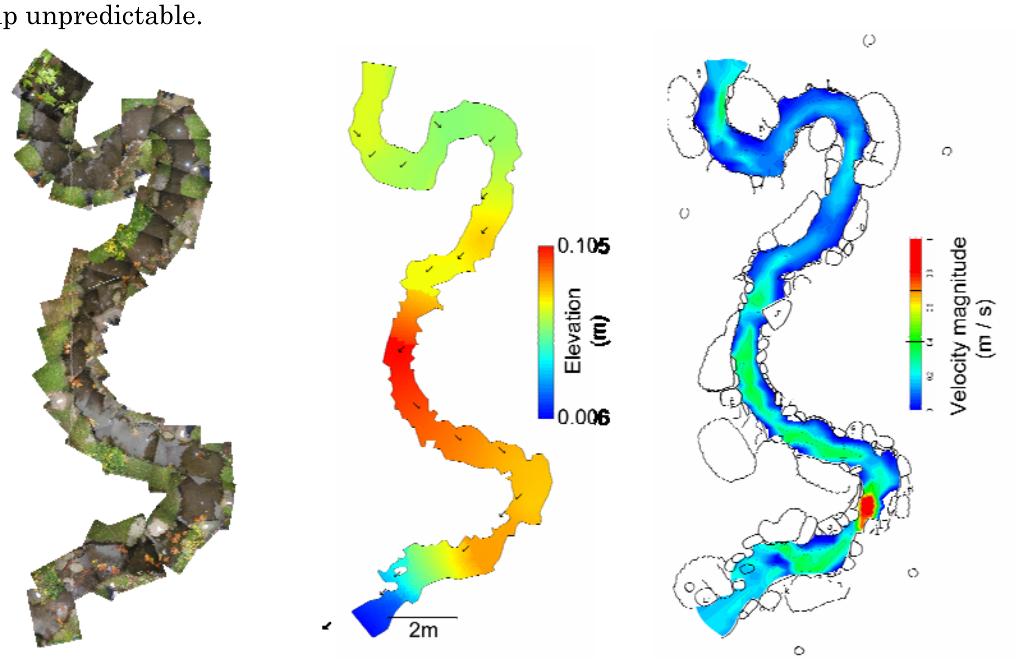
2.1 Aim and method

The configuration of the Jonangu channel is measured by a combination of surveying equipment and photogrammetry (Tsubaki et al., 2007). The channel has beautiful curves and includes cobblestones set along the side banks and hollows in many places (Figure 2). The banks of the channel were made by cobblestones of various sizes (from 5 cm to 100 cm in diameter) and shapes. The bottom of the channel was paved with mortar. The slope of the channel varies depending on the location (Figure 1b).

To investigate the flow characteristics on the meandering channel, a visualization of the surface flow and an image analysis by the Large-Scale Particle Image Velocimetry (LSPIV, Fujita et al., 1998) were performed. Particles of styrene foam, whose diameter is approximately one millimeter and with a specific gravity of 0.8, were used for the tracer in the visualization. Six digital video cameras were used to record flow images, and the whole domain was covered by a total of 13 inclined shooting angles.

2.2 Experimental results and discussion

The velocity magnitude distribution of a surface flow on the channel is shown in Figure 2c. The meandering of the channel and the irregularly-shaped side banks yields separation of flow from side banks, and also induces generation of horizontal vortices. These weak but complex flows hold the cup which passed into the stagnated area for a period. Flows in the stagnated areas showed time-dependent complex patterns (see Figure 3). Due to the high unsteadiness in these areas, groups of small-scale circulations were continuously generated instead of large, dominant ones. The location and the scale of each circulation were unstable, and the arrangement of these vortices varied with time (Khan et al., 2006). The formation of a complex flow in stagnated areas made the path of the drifting cup more complex, the holding time of the cup within the stagnation longer, and the velocity of the cup unpredictable.



(a) Picture of channel **(b) Bed elevation. Arrows in figure show where height is measured** **(c) Time-averaged result contours of velocity magnitude**

Fig. 2. Field measurement results.

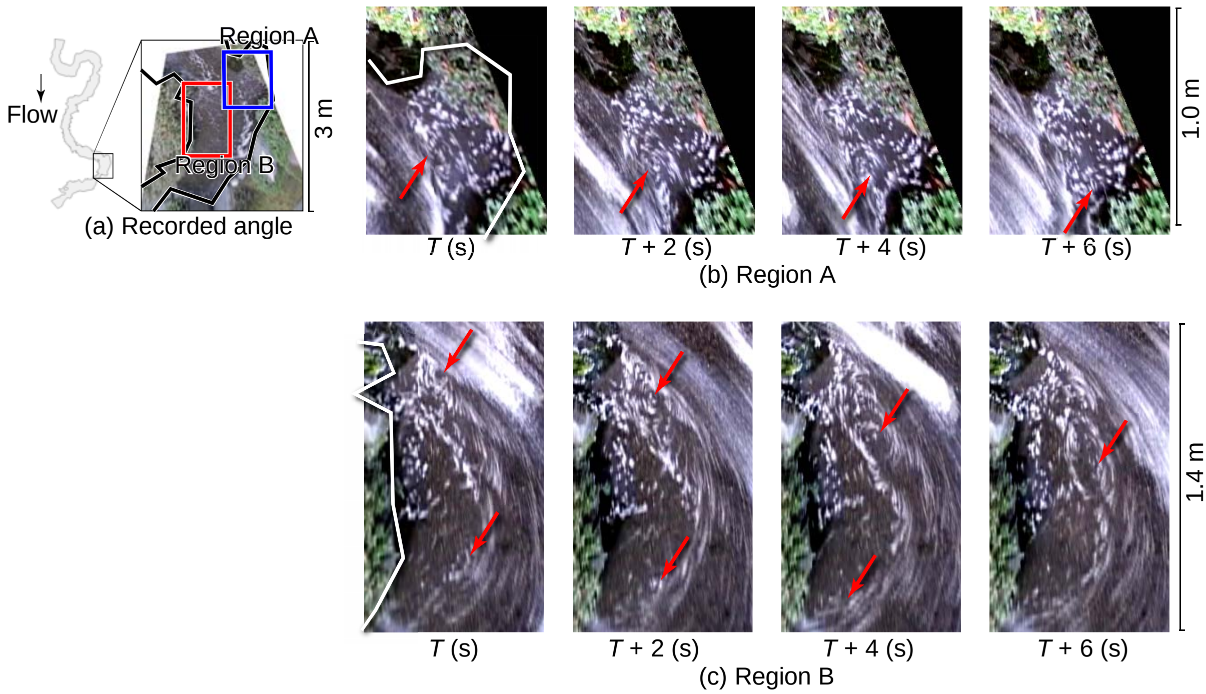


Fig. 3. Instantaneous flow patterns. Paths of tracers are enhanced using a blur filter in the recorded movie. White lines in left figures indicate location of boundary of water surface. Red arrows show center of vortices.

3. Computational model

In the previous section, experimental results were shown and fundamental flow characteristics of the channel were investigated. The measurement was carried out using the actual channel built in the shrine. As a result, experimental set-up e.g. configuration of the camera and light was limited and stable seeding of the tracer was difficult, therefore accuracy of the measurement was insufficient to reveal the unsteady behavior of the flow which is quite an important factor for the ceremony because unpredictability of the route of the cup is the key to the game. In this section, computational flow model is used to understand the unsteady flow structure in the channel.

3.1 Numerical flow model

The numerical simulation is performed to compare the calculated results with the experimental results, and more importantly, to verify the characteristics of the flow. We use a two-dimensional depth-averaged model. The mass and the two components of the momentum conservation equation used in the simulation are as follows:

$$\frac{\partial U}{\partial t} + \frac{\partial E}{\partial x} + \frac{\partial F}{\partial y} + S + \nu \left(\frac{\partial}{\partial x} h \frac{\partial G}{\partial x} + \frac{\partial}{\partial y} h \frac{\partial G}{\partial y} \right) + \frac{\partial H}{\partial x} + \frac{\partial I}{\partial y} = 0 \quad (1)$$

$$U = \begin{pmatrix} h \\ uh \\ vh \end{pmatrix}, \quad E = \begin{pmatrix} uh \\ u^2 h + \frac{1}{2} g h^2 \\ uvh \end{pmatrix}, \quad F = \begin{pmatrix} vh \\ uvh \\ v^2 h + \frac{1}{2} g h^2 \end{pmatrix}, \quad S = \begin{pmatrix} 0 \\ -gh(S_{0x} - S_{fx}) \\ -gh(S_{0y} - S_{fy}) \end{pmatrix}, \quad G = \begin{pmatrix} 0 \\ u \\ v \end{pmatrix} \quad (2)$$

where h is the depth of the water, u and v are the x and the y components of the velocity, respectively, and g is the gravitational acceleration. S_{fx} and S_{fy} are the friction forces of the channel bed. We use a two-dimensional form of Manning's equation for the friction force. A Boussinesq type eddy viscosity is used for the transverse shear. Non-slip condition with a damping function is used for wall boundary to estimates a friction from the side wall. Constant flow-rate is used for the inflow condition and constant water stage is set as the outflow boundary condition. Using these conditions with small disturbance at initial condition, unsteady fluid motion is generated in a self-excited manner.

3.2 Calculated results and discussion

Figure 4 shows time-varying snapshots of velocity vectors and fluctuations of water depth $\hat{h}$ for the region A and B used in Figure 3. Here, for example, $\hat{h} = h - \bar{h}$ where h is the instantaneous water depth and $\bar{h}$ is the time averaged value of water depth. As shown in Figures 4b and 4c, fluctuations in the flow are induced around the shear regions on both banks. These fluctuations are caused by vortices generated due to the separation of flow along the side banks, and become larger within the shear region. Behavior of vortices corresponds well with the visualization result of the actual channel previously shown in Figure 3. The generation and growth of vortices arise continuously at various locations so the periods of fluctuations are not constant.

Generally, fluctuations generated around the cavities have a cycle which consists of the generation of the vortex at upstream separation point coupled with fluctuation of the surface, impinging of grown vortex at a re-attaching point on the down-stream area, and generation of the waves and its propagation to the upstream area. Figure 5 shows distribution of frequency and intensity of product of power spectra of u and h to identify locations of vorticity-surface fluctuation cycle exists (Fouras et al., 2006, Khan et al., 2006). In figure 5, fluctuations having different frequencies, which have harmonic overtones consisting of about 0.054 Hz (f : fundamental tone), 0.108 Hz ($2f$), and 0.162 Hz ($3f$), can be observed in a varied area. These fluctuations propagate to the surrounding area as surface fluctuation, and finally resonate all along the channel. Dominant frequency of fluctuation varies depending on the location, which means that frequency of the flow in front of the poet differs corresponding to the place where he/she is sitting.

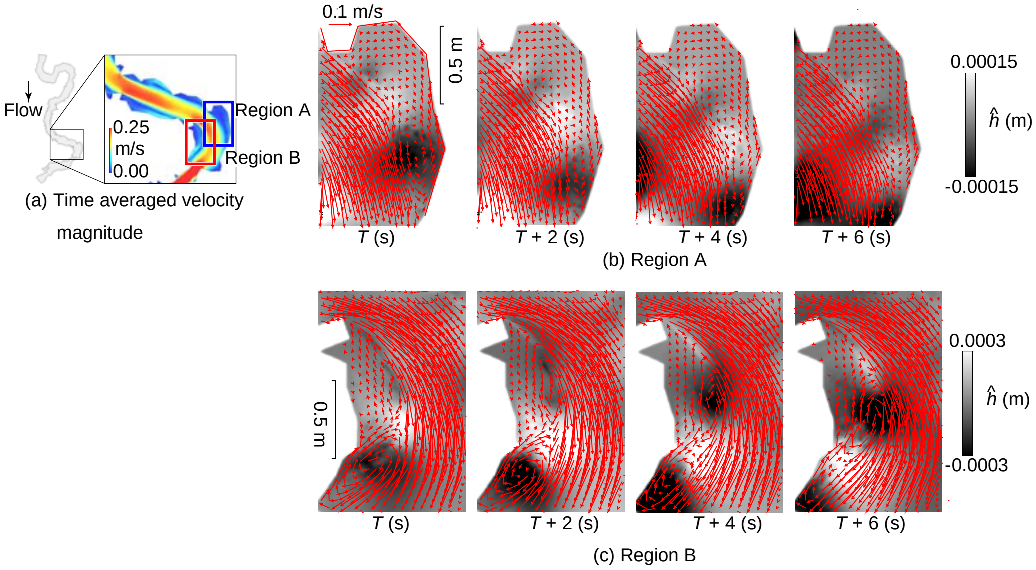


Fig. 4. Snapshot of the contours of fluctuation components. Regions A and B correspond with the regions shown in Figure 2. Back ground contours indicate fluctuation of water depth. Dents of water surface, shown as dark shade in contour, correspond to centers of vortices. Behavior of vortices in calculated result corresponds well to observed result shown in Figure 3b and 3c.

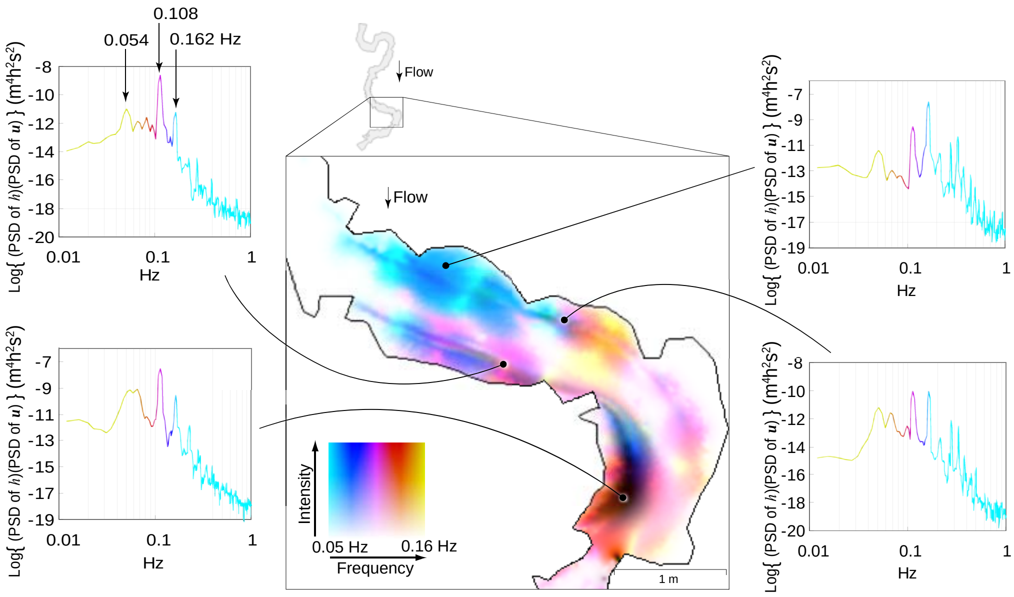


Fig. 5. Frequency and intensity contour of product of power spectral density (PSD) of h and PSD of u obtained by numerical simulation. Color is subtractive color mixture processes of colors, whose hue corresponds to frequency, and color saturation corresponds to intensity of spectrum at each point.

4. Drifting cup on simulated flow

4.1 Drifting cup model

To model a trajectory of the drifting cups with various properties, a point mass model is introduced (Chang, 2001). The drifting cup itself does not have internal force. The main driving force of the drifting cup is the drag from the flow in the channel. Fluid drag F is calculated as

$$F = \frac{1}{2} C_D \rho (U_w - U_c)^2 A \qquad (3)$$

where C_D is drag coefficient, ρ is water density, U_w is water velocity, U_c is the velocity of the cup, A is the area of the cup in a plane normal to the flow. The Reynolds number defined by $Re = (2R\mu\,(U_w - U_c))/\rho$, where R is radius of the cup and μ is the dynamic viscosity which is about $Re \approx 1{\times}10^4$. At this condition C_D can be considered as constant. Buoyancy also drives the cup however gradient of the water surface is not so steep (slope is about 4/10000, see Figure 2b) therefore we neglect the effect of buoyancy for estimating the motion of the cup. Acceleration of the cup is now modeled as:

$$m\alpha = F = \frac{1}{2} C_D \rho (U_w - U_c)^2 A \qquad (4)$$

where m is mass of the cup, $\alpha = \partial U_c / \partial t$ is acceleration. Equation 4 can be expressed as

$$\alpha = \frac{C_D \rho (U_w - U_c)^2 A}{2m} = \beta (U_w - U_c)^2 \qquad (5)$$

where β is a parameter related to the balance between the cup's mass and the drag force from the water.

Another drifting cup model is a no mass model, which does not consider mass of the cup and drag from the water but considers that the cup moves through with exactly the same velocity as that of the water around the cup.

Velocity of the water used in the cup model should be the velocity around the cup, that is, surface velocity of the water, however the velocity calculated in the shallow water equation is a depth averaged one. Therefore, in this study, the depth-averaged velocity u is used as U_w in the cup model because the difference of the property of surface velocity toward the depth-averaged velocity does not have much influence on the motion of the cup under the present quite shallow flow condition (depth/width $\approx$ 0.1). The plane dimension of the cup is neglected so that rotation of the cup, and the lift force from the flow is not represented, however these factors have a limited impact on the trajectories of the cups.

4.2 Result and discussion

By using the above-mentioned cup model, uncertainty of the pathway of the cup can be discussed. Figure 6 shows paths of the cup models with different model parameter β. A pathway of the no mass model remains near the central region of the channel, smoothly moving down the stream without approaching the side bank. The routes calculated using the model considering mass and drag goes along the outer-side bank and frequently are captured within the cavities on the side banks. The results with small β, which means that cup is comparatively heavy but with small drag, shows a route that consist of straight lines and corners. This means that the cup is accelerated around the center of the channel where velocity is comparatively high, and then the accelerated cup goes straight against the outer bank even though the channel is meandering. The results of large β cases resemble the result of no mass case, but even so deviates to the outer side of the curve at the area where the channel bends sharply.

Figure 7 shows the path lines of each cup released at the same point with different release timing. In the case of the no mass model, cups go down the channel comparatively smoothly, however depending on the release timing the cup is captured at a cavity. The trajectories calculated with $\beta = 8$ are more sensitive to the release timing of the cup. The cup is trapped in cavity 1 and/or cavity 2 depending on the release timing, and not being able to move into the downstream area but is kept in the cavities during the drifting cup simulation (260 seconds). The cups with $\beta = 18$ are also trapped around outer bank of the curve. The paths of releases 1 and 3 are trapped and circulate within the cavity 2. The releases 2, 4 and 5 go past the cavity, however they are trapped in the stagnated region along the side bank.

By changing the shape of the cup or controlling the quantity of wine in the cup, probability of trapping in side cavities and time duration to making a poem can be adjusted, thus the difficulty of the game can be controlled by choosing characteristics of the cup. This controllability of the motion of the cup is a unique point 'rather natural' type channel has, because having complex topography of the side bank and having high unsteadiness of the flow are typical characteristics this type of channel has intrinsically.

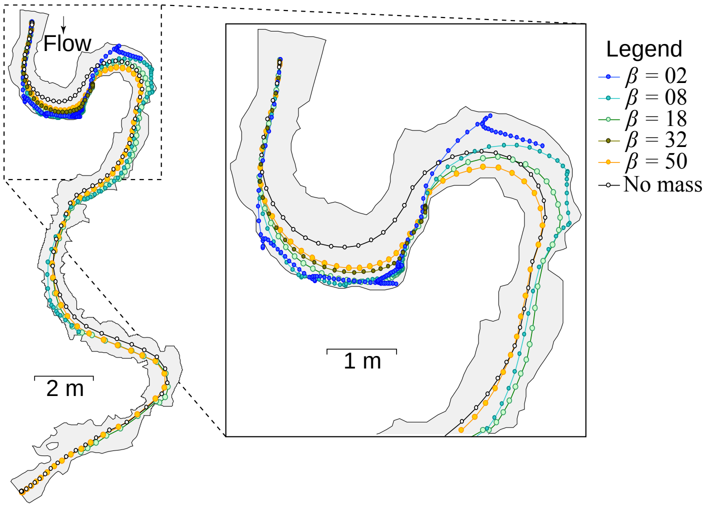


Fig. 6. Paths of the cup models with different parameter β. The interval of the symbols is two seconds. Total duration is 260 second. Difference of β parameter makes distinct routing line of the cup.

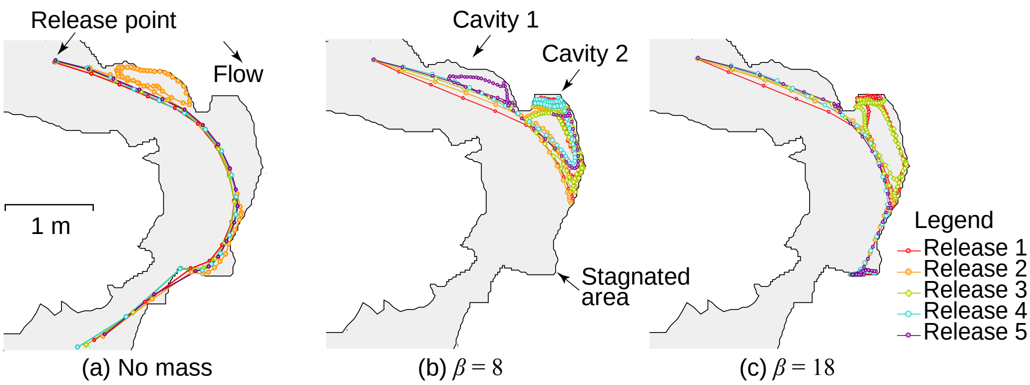


Fig. 7. Paths of the cup models with different release timing. The interval of the symbols is two seconds. Release timing interval is 30 seconds. Even if the cup is released at the same location, difference of release timing causes a different pathway of the cup.

5. Conclusion

Flow characteristics in the channel of Jonangu were investigated. The flow in the field was measured using a visualization technique, and the complex behavior of vortices in stagnated areas along the side banks was observed. To specify the flow structure, a numerical simulation, solving shallow water equations, was performed. From the results, the following findings concerning design components of the channel, and their effects on providing unsteadiness of the flow were revealed. First, irregularly-shaped side banks cause separation of the flow and generation of horizontal vortices. Second, due to the complex horizontal shape of the channel, vortices were generated at varied intervals within the shear region along both side banks, while fluctuations were induced by the vortices propagating along the channel. Third, the comparatively flat and smooth bottom of the channel prevented the dissipation of the generated horizontal vortices and supports the growth of the vortices. Fourth, the fluctuations, consisting of harmonics with a fundamental tone of about 0.054 Hz, resounded throughout the channel, made the path of the drifting cup unpredictable. Finally, the meandering geometry of the channel causes the cup to drift into the cavity on the side bank. This effect is influenced well by the drag/mass balance of the cup.

The attributes of design of 'the rather natural' channel have the above-mentioned effects, which induce significant unpredictability of the path of the cup drifting down the channel. This unpredictability might excite the poets participating the ceremony. Thus, the channel design used in Japan was not only imitating just an appearance of natural river but also representing unpredictability of natural phenomena, and maybe also uncertainty of human life.

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Author Profile

Ryota Tsubaki: He received his Dr.(Eng.) in Civil Engineering from Kobe University, Japan in 2006. He is now working as post doctoral researcher in Nagoya University, Japan. His current research interests are in the areas of environmental fluid flows, numerical simulation of the open-channel flow and inundation flow, and visualization measurement of the motion.

Yasuki Nakayama: He received his Ph.D. in Mechanical Engineering from Waseda University in 1963. He joined National Railway Technical Research Institute and conducted many research projects. After leaving NRRI, he has been a Professor of Tokai University, Japan, responsible for education and research on fluid mechanics. At present, he is serving concurrently as President of Future Technology Research Institute, Japan. His research interest is visualization. He has received a Medal with Purple Ribbon from the Emperor of Japan, and many distinctions and awards for his outstanding research. He has been a Visiting Professor of Southampton University, UK, President of the Visualization Society of Japan, and Director of the Japan Society of Mechanical Engineering. He is now Editor-in-Chief of Journal of Visualization.

Ichiro Fujita: He received his M.. Sc.(Eng.) degree in Civil Engineering in 1979 and Ph.D. degree in 1990 from Kobe University. He worked at Gifu University from 1982 to 1999. He was a visiting associate professor at the Iowa Institute of Hydraulic Research, the University of Iowa from 1995 to 1996. After working at the Research Center for Urban Safety and Security, Kobe University from 1999 to 2003, he has been working at the Department of Civil Engineering, Graduate School of Engineering, Kobe University as a professor. His research interests are image analysis of river flow and open-channel turbulence.