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Research Paper

# A Study on Jobaru River Basin Management by Numerical Simulations of Flooding and Sediment Deposition with Field Survey

K. Ohgushi [1], H. Nakashima [2], T. Hino [3], T. Morita [4] and T. Jansen [5]

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## ABSTRACT

River basin management in Japan in the early modern period can be considered as providing a prototype of possible countermeasures for present-day flood exceeding the design level. The river basin management in the Saga region of Japan was established by Naritomi Hyogo in the early Edo era. This study evaluates characteristics of river basin management in Jobaru River Basin located in the eastern Saga Plain using numerical simulations and geotechnical surveys. A flood flow of Jobaru River was calculated using a 1-D flow numerical simulation. Overflow discharges from Nokoshi, open levee and no-levee intervals are estimated and these discharges are specified as boundary conditions for quasi 3-D inundation flow simulations. 2-D sediment transport by water flow is also simulated. A Geoslicer is used for field surveys that uncover clues of how the sediment has been deposited in the past. The ages of the sampled stratums was measured by using radiocarbon dating methods. The classified sediments columns and estimated ages of the stratum by the radiocarbon dating correspond to the simulated flood flow behavior in the retarding basin after overflow from the Nokoshi and open levee. Moreover, No.1 open levee reproduced by the geotechnical survey's result is used for the flow simulation successfully.

## 1. Introduction

Life and property losses due to flood in Japan have been mitigated by riparian works since the Meiji era, in which flood water is kept in the river channels. However, vulnerability remains against floods that exceed the design level of these engineering works. The river basin management of Japan in the early modern period can be considered as a prototype for possible countermeasures against future floods exceeding the design level. The River Council of Japan reports in 2000 how the traditional flood control technology can be utilized (River Council, MLIT, Japan, 2000). This council also reports in 2000 the effective flood control technology including catchment basin management (River Council, MLIT, Japan, 2000).

The full-scale river basin management in the Saga region of Japan was established by Naritomi Hyogo in the early Edo era. A system of such river basin management

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[1] Professor & IALT member, Graduate School of Science and Engineering, Saga University, Saga 840-8502, JAPAN, ohgushik@cc.saga-u.ac.jp
[2] Engineer, Aira City Hall, Miyajima 25, Aira, Kagoshima Prefecture, 899-5492, JAPAN, n_hiroto_k_s@yahoo.co.jp
[3] Professor & IALT member, Institute of Lowland and Marine Research, Saga University, Saga 840-8502, JAPAN, hino@ilt.saga-u.ac.jp
[4] Researcher & IALT member, ILMR, Saga University, Saga 840-8502, JAPAN, ss5263@cc.saga-u.ac.jp
[5] Lecturer & IALT member, Department of Civil Engineering, Sam Ratulangi University, Manado 95115, INDONESIA, tommijansen@yahoo.com

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can be seen in the Jobaru River basin on the eastern Saga Plain. Jobaru River has many flood control features implemented since the Edo era and after, such as Nokoshi that is a kind of overflow embankment, open levees, etc. These technologies may have potential to be applied as countermeasures against future floods exceeding the design level.

However, there is little research quantitatively evaluating the performance of traditional flood control systems. The bank ground heights and bed levels of the rivers and flow rates including overflow discharge from the river in the past are almost unknown (Nemoto, et al. 2011). In this study, the soil layer under the ground was surveyed using a geotechnical approach. The sediments transported by the flood flow settle and finally accumulated and they keep containing information about past flood behavior. This process was investigated using hydraulic simulation's approach based on the results of the geotechnical investigation.

This study evaluates how the traditional flood control technology functioned in the past and also how this technology can be applied for future flood control given the increasing risk of extreme flood due to climate change and other various effects such as watershed development.

## 2. River basin management in Jobaru River

Jobaru River basin is shown in **Fig.1**. Jobaru River originates from Mt. Seburi and is confluent with Sagae River into Chikugo River that flows into the Ariake Sea. The catchment basin of Jobaru River is about 64.4km$^2$, and its trunk water course is about 31.9km long. Its discharge includes flood storage in a planned dam that is to be constructed in the future. Once the dam contains part of the upstream discharge, the remaining target maximum discharge of the river will become 330m$^3$/s at Hideki-bashi station.

Focusing on the midstream of Jobaru River, there are two no-levee intervals, four open levees, and five Nokoshi as shown in **Fig.1**. These flood control facilities were made to protect downstream villages and towns from inundation (Kishihara, *et al.* 2011).

**Fig.2** shows a lateral section view of a Nokoshi,

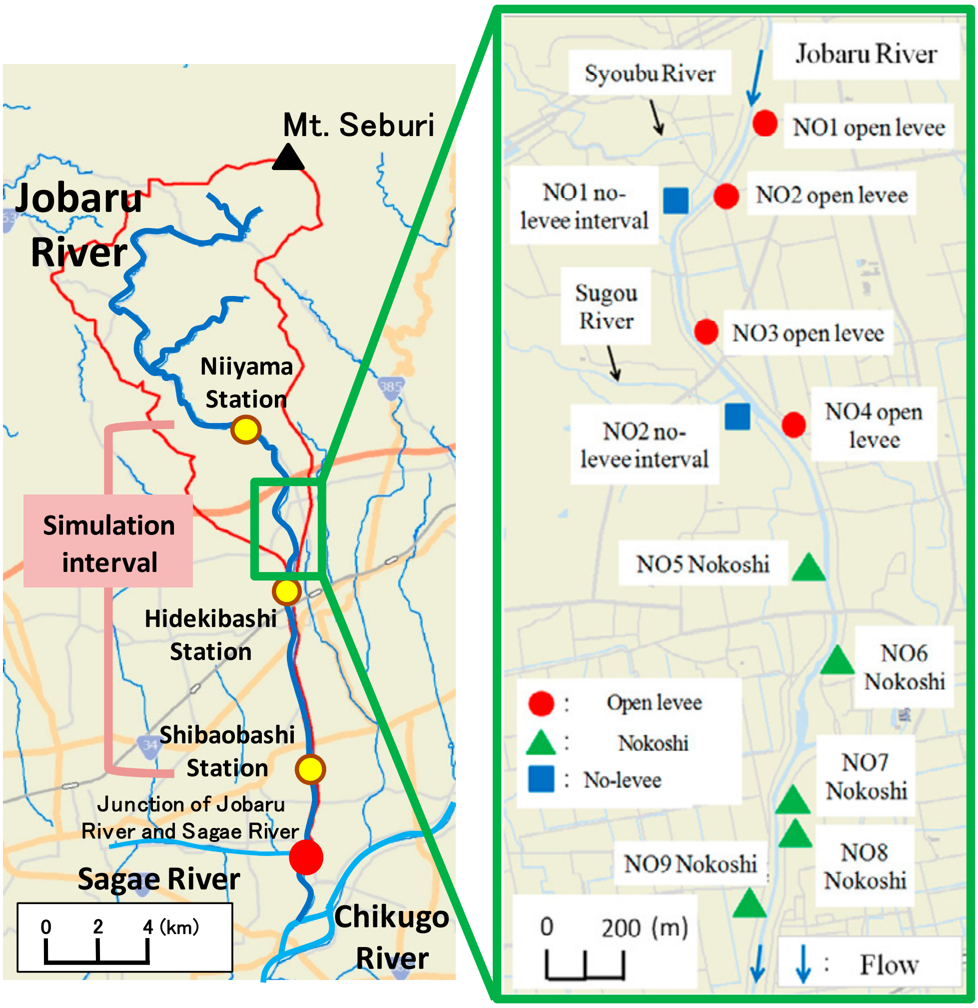

**Fig.1** Plan view of the Jobaru River basin. There are 4 open levees, 2 no-levee intervals and 5 Nokoshi in the midstream of Jobaru River area.

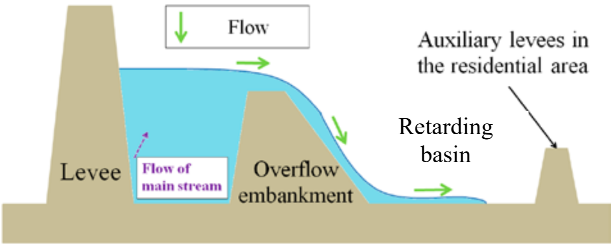

**Fig.2** Cross-sectional view of Nokoshi

**Fig.3** Plan views of Jobaru River before (left) and after (right) the disaster subsidy project

which is one of the discontinuous levee and the flood water overflows it. The overflowing water goes into a retarding basin of the residential area, but is guided by an auxiliary levee for the neighboring village protection. This auxiliary levee is called "Mizuuke-tei" and it functions effectively in conjunction with retarding basins and flood disaster prevention forests.

The open levee is another discontinuous levee which is often used along a steep stream. If the water level outside of the levee reaches the crest level of this levee, the flow behavior becomes that of a continuous water body as one with the water of the main river. Moreover, in the two no-levee intervals, the water is directly stored in the neighborhood retarding basin.

In the Jobaru River basin, after flood disasters in 1949 and 1953, subsidized riparian works were implemented from 1953 to 1961. Plan views of Jobaru River before and after the disaster subsidy project are shown in **Fig.3**. After this project, Jobaru River was widened and the location of Nokoshi and open levees were also changed. Moreover, auxiliary levees in the landside area were almost completely removed for redeployment of arable land. The land use of this watershed has been changed substantially over time. Therefore, Nokoshi and open levees now exist as overflow levees without retarding basins.

## 3. Numerical simulation of flood flow and sediment transport

Flood flows in Jobaru River and overflow discharge from the Nokoshi, open levee and no-levee interval are reproduced using a 1-D open channel flow simulation. The basic equations of this simulation are given in the following.

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad [1]$$

$$\frac{\partial Q}{\partial t}+\frac{\partial (uQ)}{\partial x}+gA\left(\frac{\partial h}{\partial x}-I_0\right)+gAI_f=0 \qquad [2]$$

where $Q$ is river discharge, $A$ is the cross-sectional area of the river, $g$ is the gravity acceleration, $h$ is the total depth, $x$ is the longitudinal distance of the river, $t$ is the time, $I_0$ is the river bed slope and $I_f$ is the friction slope. Flows passing through the Nokoshi and open levee to the retarding basin are presumed as flows of tributaries from the main river channel. These flows are treated to be connected to the main river. The simulation period was set from July 11 to 15, 2010. A maximum discharge in this period was recorded as 318.11m$^3$/s at Hideki-bashi observation station.

2-D sediment transports are calculated from the simulation of the behavior of inundation flow and sediment movement. The basic equations for the quasi 3-D simulation are given in the following.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad [3]$$

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=-g\frac{\partial \eta}{\partial x}+F_u+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial u}{\partial z}\right) \qquad [4]$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial x}+\frac{\partial uv}{\partial y}+\frac{\partial wv}{\partial z}=-g\frac{\partial \eta}{\partial x}+F_v+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial v}{\partial z}\right) \qquad [5]$$

where $x$ , $y$ and $z$ are Cartesian coordinates with horizontal coordinates given by $x$ and $y$ , $\eta$ is the water surface elevation, $d$ is the still water depth, $h=\eta+d$ is the total depth, $u$ , $v$ and $w$ are velocity components in the $x$ , $y$ and $z$ directions, $\nu_t$ is a vertical turbulent viscosity, and $F_u$ , $F_v$ are horizontal stress terms.

The sediment continuity equation is given in the following.

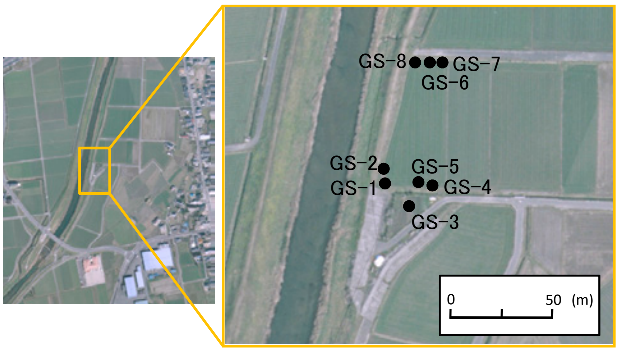

**Fig.4** Study area: No.1 open levee and its surroundings

$$-(1-n)\frac{\partial z}{\partial t}=\frac{\partial S_x}{\partial x}+\frac{\partial S_y}{\partial y} \qquad [6]$$

where $n$ is river bed porosity, $z$ is the level of the river bed and $S_x$ , $S_y$ are total load transport in the $x$ and $y$ directions, respectively.

The total sediment transport formula used is the following equation given by Engelund and Hansen (1967) model.

$$S_{tl}=0.05\frac{C^2}{g}\theta^{\frac{5}{2}}\sqrt{(s-1)gd_{50}^3} \qquad [7]$$

where $S_{tl}$ is the total load, $C$ is the Chezy number, $\theta$ is the Shields parameter, $s$ is the relative density of the sediment and $d_{50}$ is the median particle diameter.

The study areas in the field are shown in **Fig.4** and **Fig.5**, respectively. **Fig.4** shows No.1 open levee and its surroundings. Although an auxiliary levee existed in the past, almost no auxiliary levee can be seen at present. **Fig.5** shows the retarding basin near **No.5** Nokoshi. This area still remains within the system of river basin management including auxiliary levees, retarding basins etc.

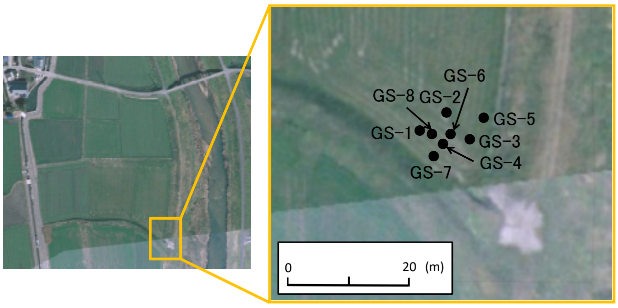

**Fig.5** Study area: the retarding basin near No.5 Nokoshi

An overflow discharge from Nokoshi or open levee is given as a boundary condition for the inundation flow simulation in the retarding basin. The transported sand particle diameter is set to 0.039mm at No.1 open levee, and 0.076mm at No.5 Nokoshi respectively from the results of the in situ geotechnical investigations.

## 4. Geotechnical survey

Eight soil samples were obtained near the open levee and Nokoshi, respectively. This study introduces the soil sampling instrument, referred to as the "Geoslicer", which was developed by Hiroshima University, Japan Nuclear Cycle Development Institute (JAEA at present) and Fukken Co., Ltd. (Nakata and Shimazaki 1997; Haraguchi et al. 1998). As shown in **Fig.6**, a crane truck was used to hoist the Geoslicer which is 0.45m wide and 3.5-4.2m long. The sample tray was first driven by a weighted vibrator (**Fig.7**). Secondly, the shutter plate was driven by the same instrument. After both the sample tray and shutter plate were driven, they are connected together at the top using a pin. Then the Geoslicer and sampled soil were pulled up from the ground without vibrating as not to disturb the sample (Ohgushi and Hino 2013).

**Fig.6** Geotechnical survey using Geoslicer at the retarding basin near No.5 Nokoshi

**Fig.7** A weighted vibrator is used to penetrate the Geoslicer to the ground.

The age of sediment in the sampled stratums was estimated using radioactive carbon dating. This method uses carbon isotope from plant or animal remains to date a sample. The carbon isotope $^{14}$C has a half-life of 5730 years and measuring the proportion of $^{14}$C in a sample gives its age. In the main investigation, wood splinters of several mm in size are targeted for dating. It should be noted that the estimated age is just for the wood splinter, not for the sediment itself. When the sample is taken, the content of an upper stratum may become mixed with a lower stratum and a substance indicating a younger age may become mixed in. However, this risk is minimized for samples taken with the Geoslicer because the width of the sample is large and stratum structure can be easily observed

## 5. Simulation results and discussion

Water level hydrographs obtained from the 1-D numerical simulation and field measurements at Hideki-bashi observation station show that the model well simulates the observed water levels (**Fig.8**). For modelled flood events with much larger discharges, overflow discharges increase. The maximum flood simulated in companion to the July 2010 flood is 1.5 times larger. From the simulations, the No.1 open levee experiences the most overflow among all open levees. The second largest discharge is seen at the No.1 no levee interval. Both the No.1 open levee and the No.1 no levee interval represent almost 90% of all overflow discharges from the discontinuous levees in Jobaru River. The water level changes at Hideki for the case of all discontinuous levees considered is simulated for a flood 1.5 times larger than the flood of July, 2010.

**Fig.9** shows ground height temporal change obtained from the sediment transport numerical simulation at each Geoslicer sampling point near the No.1 open levee. The results show that all points except GS-3 experienced deposition. This tendency of sediment deposition forms a new ground level so that this tendency has influenced the topography and hence the behavior of flood flows.

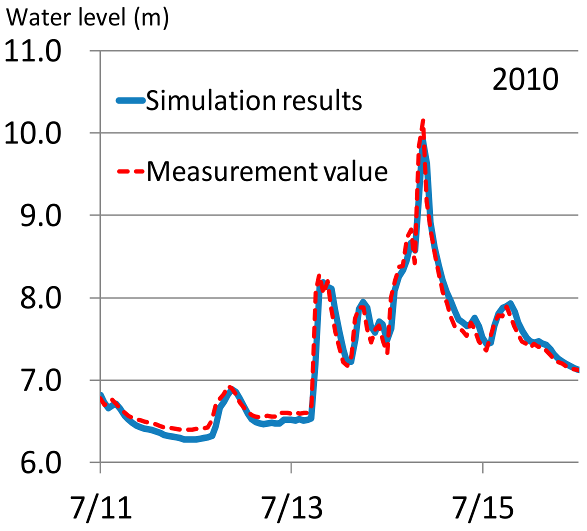

**Fig.8** Comparison of measured value and 1-D numerical simulation result of water levels changes at Hideki-bashi observation station

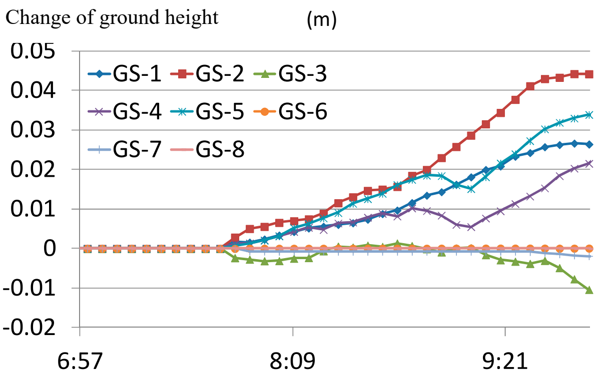

**Fig.9** Ground height temporal change by the numerical simulation at Geoslicer sampling point near the No.1 open levee

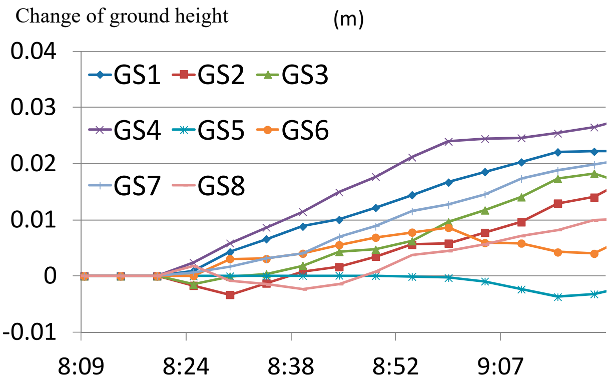

**Fig.10** Ground height temporal change by the numerical simulation at Geoslicer sampling point near the No.5 Nokoshi

**Fig.10** shows ground height temporal change by the same numerical simulation for each Geoslicer sampling point near No.5 Nokoshi. All points except GS-5 experienced deposition during the simulated event. It is considered that the scouring tendency at GS-5 is caused by the distance of the overflow stream from the No.5 Nokoshi.

## 6. Geotechnical survey's results and discussions

Results of the Geoslicer survey at No.1 open levee neighborhood are shown in **Fig.11**, whereas the distribution of wet hinterland sediment at each Geoslicer sampling points is shown in **Fig.12**. Although the soil sampling points are close to each other, the difference can be seen in the layer thickness of wet hinterland sediment, mainly silt with growing plants. The sampling points GS-3, GS-4, GS-5 and GS-7 have a thin wet hinterland sediment layer, mainly silt with growing plants. It is considered that there was previously an embankment layer coinciding with the auxiliary levee for village protection. Furthermore, the piece of wood contained in the upper layer of the embankment gives a date after the river improvement of the beginning of 18th century AD, as estimated by the radiocarbon dating.

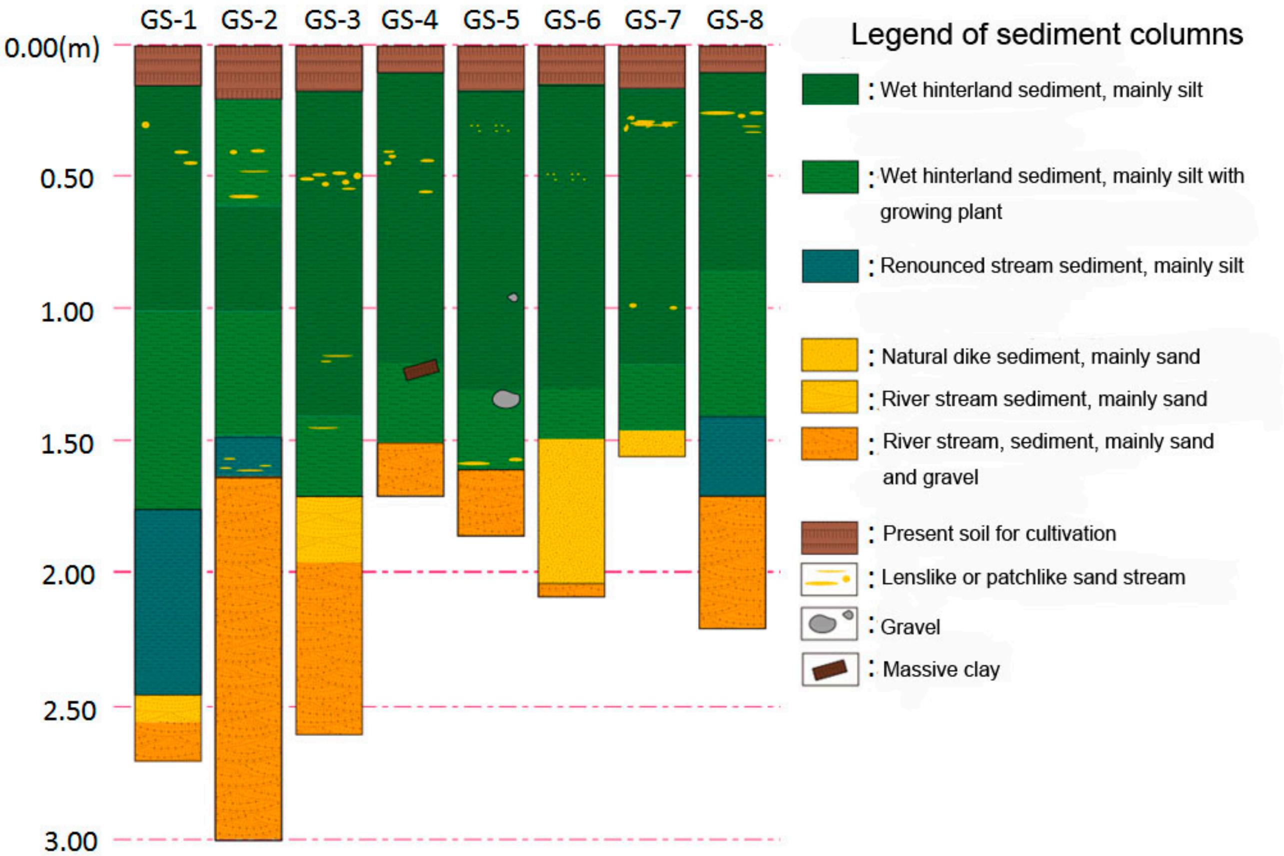

**Fig.11** Sediment columns obtained from observation of soil samples made by the Geoslicer near No.1 open levee.

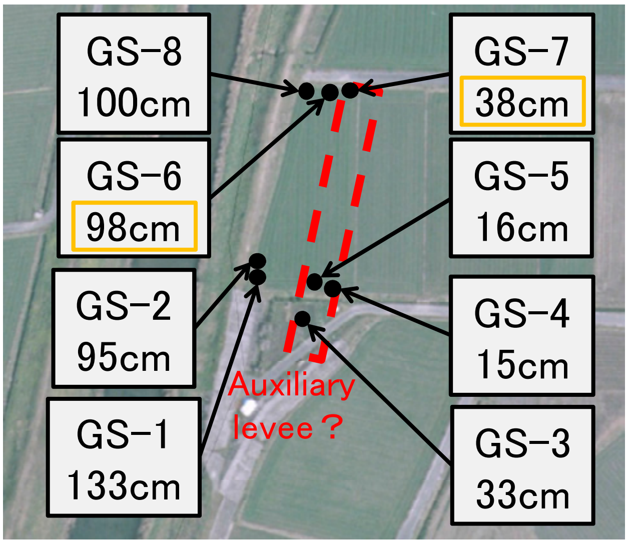

**Fig.12** Layer thickness distribution of wet hinterland sediment layer. The location of auxiliary levee is estimated at No.1 open levee neighborhood basen on the survey results

## 7. Reproduction of the No.1 open levee based on the geotechnical survey and the results of numerical simulation

A numerical simulation of the water flow in the landside area is made based on the results of the geotechnical investigations near No.1 open levee. A reconstructed topography of the open levee is shown in **Fig.13**. A range of auxiliary levees is extended from the present levee to point GS-7. The height of the crest of the open levee is estimated by the altitude of the nearby landside area. Using this reconstructed topography, a water flow simulation including main river flow was performed.

The distribution of flow velocity at flood peak is shown in **Fig.14**. Since the auxiliary levee is present, flooding water is stored to some extent in the retarding basin. Moreover, the inundation flow that passed through the retarding basin flows in a southerly direction.

The inundation flow coming from the auxiliary levee over the land flowing in a downstream direction is considered to return to the main river through another downstream open levee. After the peak flood time, the water goes back into the main river through the open levee as indicated by the arrow in **Fig.15**.

**Fig.16** shows a plan view and cross-sectional view of the flow velocity in Jobaru River and retarding basin. It is considered that the No.1 open levee functions to prevent levee breaching by the main river by the hydrostatic pressure of the water contained in the retarding basin.

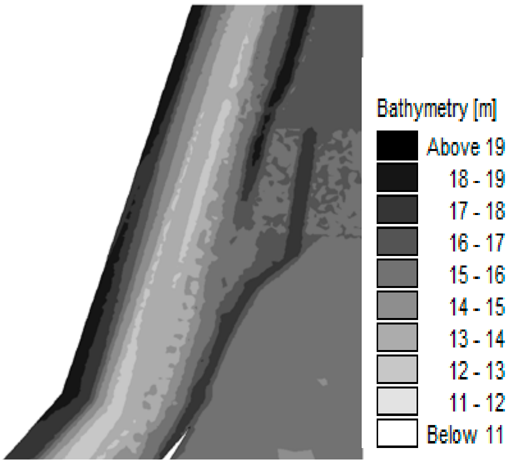

**Fig.13** Reconstructed topography near the No.1 open levee

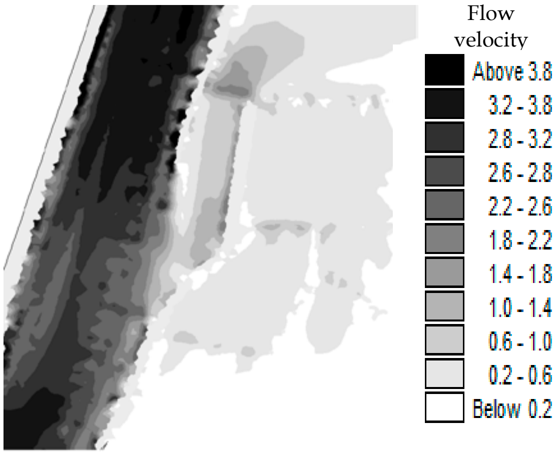

**Fig.14** Distribution of flow velocity near the No.1 open levee at the time of peak flood in Jobaru River

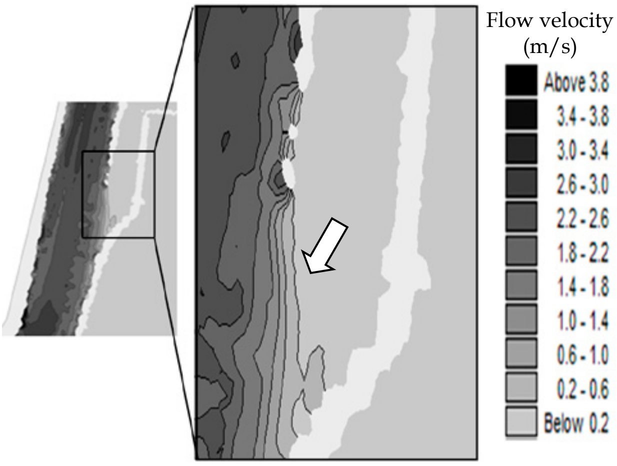

**Fig.15** Distribution of flow velocity after the time of peak flood near the No.1 open levee

## 8. Conclusions

This study validates the function of traditional flood control technology of Jobaru River, Japan using numerical simulations combined with geotechnical surveys. The results are summarized as follows:

1) The sediment transport simulations show that the ground height has changed over time and hence affected the flow in the retarding basin.

2) Geotechnical surveys provide additional information about the sediment deposition in the retarding basin during flooding near an open levee.

3) The open levee functions to weaken the main river power by the presence of auxiliary levee, which acts to protect the main river levee from levee break by the hydrostatic pressure of the water contained in the retarding basin behind the auxiliary levee.

4) In the retarding basin, almost all sample locations were found to have a deposition tendency, except near the Nokoshi or open levees from the results of numerical simulation of sediment transport based on the geotechnical survey.

From the above results, it can be concluded that these traditional flood control technologies have a large applicability against the increasing risk of extreme flood because it utilizes the available space effectively for the flood mitigation and it also utilizes the feature of the water.

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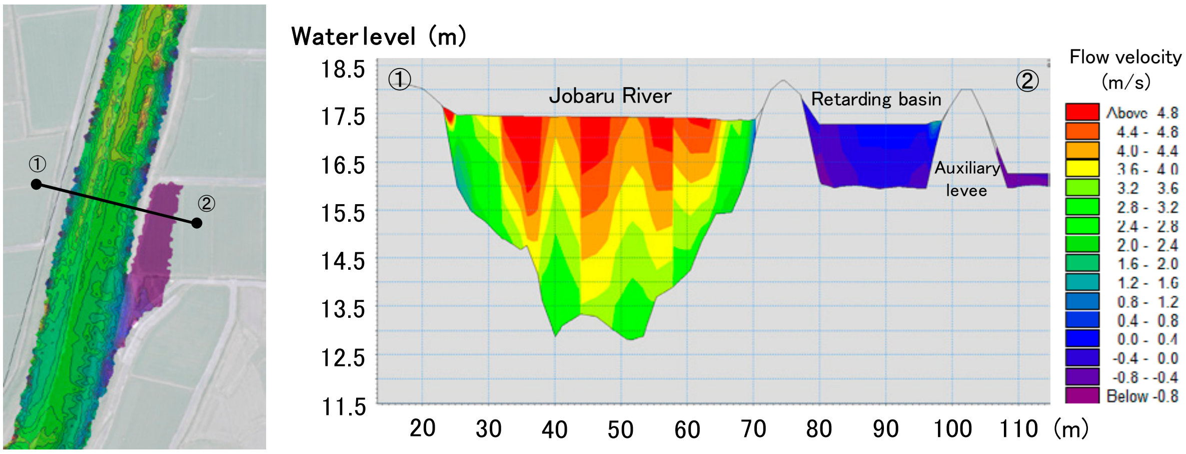

**Fig.16** A plan view (left) and cross-sectional view (right) of the flow velocity distribution at the No.1 open levee. The water returns to Jobaru River from the retarding basin further downstream.

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## Symbols and abbreviations

| | |
|---|---|
| $A$ | Cross-sectional area of the river |
| $C$ | Chézy number |
| $d$ | Still water depth |
| $d_{50}$ | Median particle diameter |
| $F_u$ | Horizontal stress term for x-direction |
| $F_v$ | Horizontal stress term for y-direction |
| $g$ | Gravity acceleration |
| $h$ | Total depth |
| $I_0$ | River bed slope |
| $I_f$ | River friction slope |
| MLIT | Ministry of Land, Infrastructure, Transportation and Tourism of Japan |
| $n$ | River bed porosity |
| $Q$ | River discharge |
| $S_{tl}$ | Total load of the river sediment |
| $S_x$ | Total load transport for x-direction |
| $S_y$ | Total load transport for y-direction |
| $s$ | Relative density of the sediment |
| $t$ | Time |
| $u$ | Velocity component in the x-direction |
| $v$ | Velocity component in the y-direction |
| $w$ | Velocity component in the z-direction |
| $x$ | Longitudinal distance of the river (1-D simulation) |
| $x$ | Horizontal Cartesian coordinate (2-D simulation) |
| $y$ | Horizontal Cartesian coordinate |
| $z$ | Vertical Cartesian coordinate |
| $z$ | Level of the river bed |
| $\eta$ | Water surface elevation |
| $\theta$ | Shields parameter |
| $\nu_t$ | Vertical turbulent viscosity |