CHANNEL HYDRAULIC STRUCTURES

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INTRODUCTION

A river should not merely transport flood discharge safely downstream, but also make full use of the river's functions at normal discharge. It is therefore necessary to establish the river engineering technology needed to create channels and hydraulic structures that function as desired at both flood discharge and all other discharge levels. With respect to the latter, various nearly-natural techniques (close-to nature work) have been used in river works. Needless to say, the ability to assure a certain degree of safety even during flooding is a prerequisite for such techniques.

This paper discusses several important issues that we hydraulicians and river engineers must confront for creating safe and nature-rich rivers. In channels where river structures are scheduled to be built, large-scale hydraulic model experiments are often performed because of the complexity of the hydraulic phenomena there, and this paper discusses the possibilities of channel and hydraulic structure design methods that incorporate numerical computation techniques -- a new trend in this field -- and also examines the areas that must be investigated in order to successfully perform design work that is based on such techniques.

EROSION IN NATURAL BANKS

The mechanism of bank erosion caused by flood currents is complicated, and it is believed that this mechanism involves two or more of the following factors: (1) rotational failure; (2) soil mass collapse in upper layers caused by erosion in lower sandy layers (which have a low resistance to erosion) below the water surface; (3) collapse caused by piping effects in high-permeability layers in banks with strata; and (4) erosion caused by shear forces that act solely on the river banks.

What triggers bank damage caused by erosion and collapsing is often strata of different types of soil in which sandy layers with low erosion resistance are situated. And while field surveys have, to a certain extent, revealed the causes of erosion in exposed banks and the mechanism of erosion, this research has not yet reached the stage in which degrees of erosion in exposed banks can be predicted and these predictions used to design cross-sectional profiles and banks to achieve high-safety channels. In short, significant progress has not been made in determining the relationship between hydraulic quantities, channel profile, and bank soil structures that, during flooding, would prevent large-scale damage to exposed banks where no revetments had been constructed. In addition, data and material for reaching conclusions concerning channel design are severely lacking.

In recent years, however, more natural construction techniques have begun to be used in river improvement projects such as these involving small-scale bank erosion, and are now the focus of attention as close-to-nature work. The concept of close-to-nature work also includes using plants growing on the banks (Hemphill and Bramley, 1989). This method, however, is inferior in strength and resistance force to revetments techniques involving concrete and other conventional materials, and as a result forces the engineer to depend also on the erosion resistance force of exposed banks behind a vegetation bank in order to compensate for the latter's lack of strength and resistance force.

Because of this new trend in channel planning, the evaluation of the erosion resistance of natural, exposed banks and revetments using bank vegetation has become an issue attracting much attention.

Much research has been performed on issues concerning bank erosion, and most analysis based on the hydraulic experimental technique primarily involves research on the mechanisms of erosion in banks of non-cohesive soils. However, the natural bank generally has a layered structure consisting of sand, silt, clay and a variety of other types of soil, and, hence, the erosion of non-cohesive soil does not sufficiently reflect the erosion of natural banks. Therefore, it is of the utmost importance that examinations involving bank erosion be performed in the river. Field surveys are being energetically performed, primarily by geologists (Thorne, 1978) and recently by hydraulicians. However, while this research has helped to explain the fundamentals of the phenomenon of erosion, it has not yet reached the stage where it can be used in designing the longitudinal and cross-sectional profile of channels, taking into account soil structures and flood hydraulics.

The process of erosion in natural banks consists of three stages (Fig. 1) : erosion of the lower non-cohesive layers (stage 1), collapse of the overhanging upper cohesive layer (stage 2), and the break-up and transport of the collapsed soil mass (stage 3). As erosion of the sand layer progresses, an overhanging upper layer is formed on the banks. Velocity below this overhang then decreases and the rate of erosion in the sand layer is reduced. The extent of this reduction in erosion rate depends on the length of the overhang, while the maintainable length of the overhang depends, in turn, on the cohesion of the sandy soil layer. The collapsed soil mass settles on the river bed near the bank and, until it is transported away, makes it difficult for further erosion in the sand layer to occur. Hence, the time required for the soil mass to be transported away results in further erosion in the sand layer being postponed (Fukuoka, 1994).

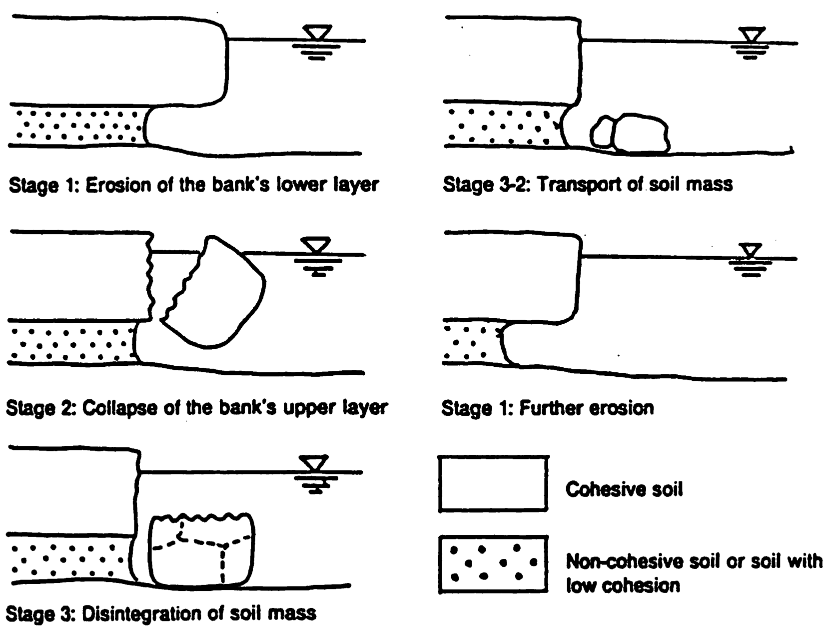

Fig. 1 Erosion process in a natural bank

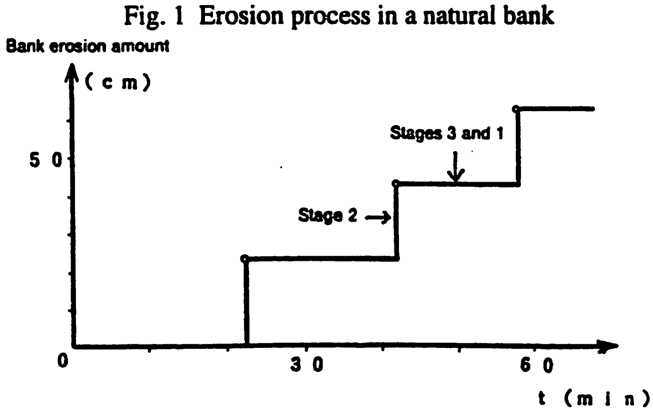

Fig. 2 Changes over time in the amount of bank erosion

Changes over time in the amount of bank erosion measured, shows that collapse (i.e., stage 2) results in the rapid progression of erosion. (Fig. 2)

After determining, in this manner, the mechanism of bank erosion to a certain extent, we should attempt a quantification of the rate of erosion throughout a natural bank. To do this, we shall investigate each stage of bank erosion separately, then integrate the results for each. Essential to a discussion of the rate of erosion in the entire bank is an estimate of the delay in erosion caused by adding cohesive soil to the materials of which the bank is comprised.

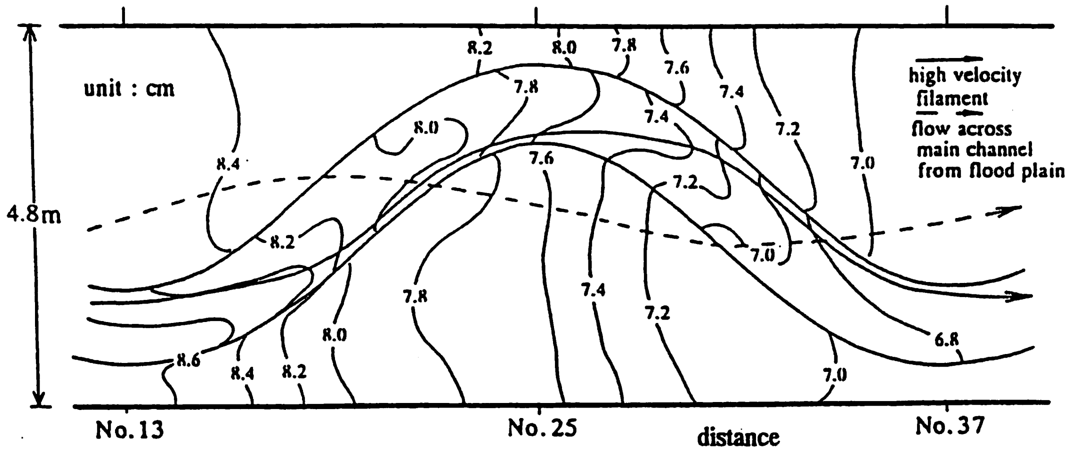

Fig. 3 Water level profile and average flow field in a meandering compound channel

Another important research area of the bank erosion is that of the meandering compound channel. Research in the laboratory experiment of Willetts, Hardwick and Maclean (1990) has shown that in meandering compound channels where a considerable phase difference exists between levee alignment and main channel alignment, and where the width of flood channel changes in the downstream direction, high velocity filaments occur in the shortest distance from the inner bank area to the next inner bank area in the main channel when a flood current is present in the flood channel (Fig. 3), that is, a free vortex-type current occurs in the main channel. This means that the bed is scoured more at the inner bank than at the outer bank when the current runs on the flood plain. Fig. 4 shows the surface velocity distribution calculated from aerial photographs taken at the peak of flooding in the actual river. This reveals that in this river, the high velocity filaments of high flood levels occurred in the shortest distance from the inner bank area of one meander to the inner bank area of the next.

If bed profile had been measured at the peak of flooding, it could be concluded that the scouring occurred at the area of the inner bank due to faster velocity there. However, even in compound channels priority of the bank protection was given to outer bank in the belief that scouring forms at the outer bank side regardless of flood level. However, when a flood current stays in the flood channel for a long period of time, phase differences between the alignments of the main channel and levee can result in scour formation at the inner bank, thus creating the necessity for bank erosion countermeasures for inner banks as well. River structures used as countermeasures to bank erosion, however, are designed mainly to protect the outer bank; they do not take into account flood flow regimes like the aforementioned. Therefore, we must perform research on flow regimes that contain planned or designed structures with the objective of preventing bank erosion and taking into account the channel planar forms and hydrographs during flooding.

VEGETATION REVETMENTS

While it has been common to respond to such channel damage with high-safety concrete revetments and foot protection, this has resulted in a loss of natural river beauty and has negatively affected the overall river environment. While protecting banks is important, what is called for is not a complete dependence on concrete revetments, but rather river improvement and maintenance in which diverse types of revetments are selected in accordance with channel and flood characteristics. The concept of diverse types of revetments means recognizing that for each river, or even within a single river, there can be places where revetments are not needed and exposed banks can remain in their natural state; places where banks can be protected with revetments composed of grass and vegetation; and, finally, places where sturdy protection with concrete revetments is necessary. It is, therefore, necessary to estimate, for each bank protection method, the critical velocity of erosion and allowable amount of erosion for river banks (including exposed banks and natural banks), and, based on these hydraulic conclusions, to design cross-sectional channel profiles and revetments structures that take into account ecological and other factors.

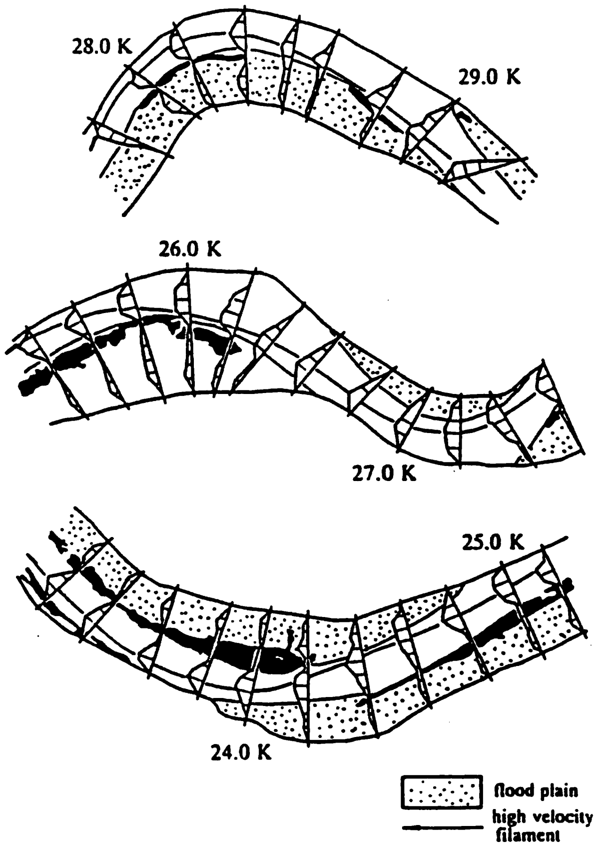

Fig. 4 Surface velocity distribution and high velocity filaments at the peak discharge in the Go River

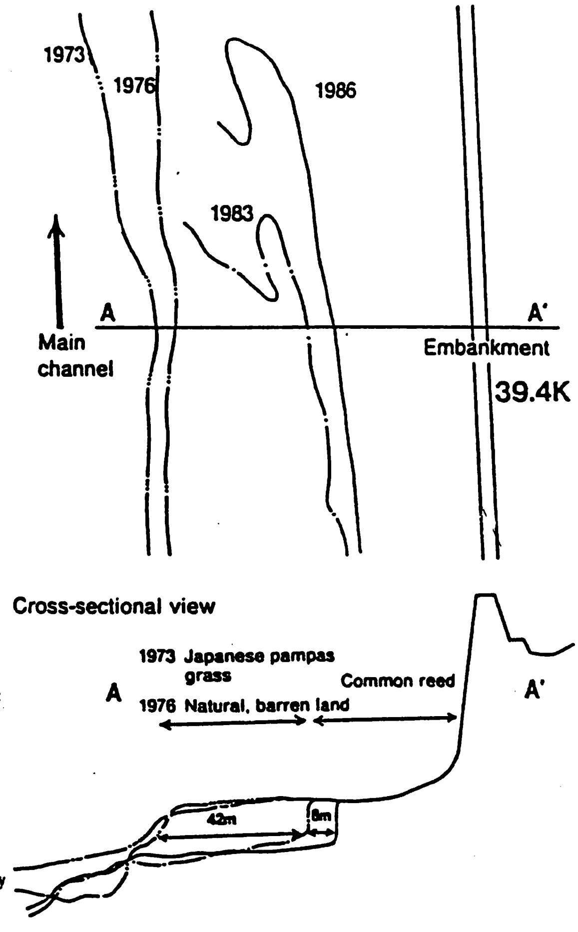

Fig. 5 Changes over time in the state of bank erosion and flood channel vegetation (40 km section of the Tama River)

Figure 5 shows cross-sectional survey diagrams and surveys of flood channel vegetation that show to what extent the right bank of the 39-40 km section of the Tama River was eroded by flooding at that time. Severe flooding occurred here in 1974, 1979 and 1982 (August and September). While pampas grass existed in the flood channel in 1973, severe flooding in 1974 bent large amounts of this pampas grass and caused bank scouring, and by 1976 the flood channel had turned to naturally barren land. Four severe floods attacked the river during the seven years between 1976 and 1983, and although further considerable bank erosion did occur, the speed of bank erosion was significantly reduced around the boundary with the introduction of common reed in the flood channel. In addition, the erosion has not progressed much since 1983, a fact which demonstrates the potential of the common reed as an effective material in bank protection. This demonstrates that river vegetation is of use not only in its role as part of the river environment, but also in the new river technology as a flood-control measure in bank and levee protection (Fukuoka, 1993).

The objective of the bank vegetation study is to examine bank protection methods to achieve harmony between flood control and the environment, and to validate the use of bank vegetation in revetment design. In particular, we will assess the level of erosion resistance of bank soil that forms the erosion-resistance foundation of revetment where bank vegetation is used, and describe the mechanism whereby reeds and other plants growing in flood channels and along the edge of banks control bank erosion; then assess the erosion-resistance force during flooding of banks where these plants grow. Finally, we shall consolidate all this in order to determine, for instance, the allowable critical velocity for making possible the use of vegetation as a bank protection method.

LEVEE-RELATED ISSUES

The devastating earthquake that struck Kobe, Japan, on January 17, 1995 (seismic coefficient, 7; magnitude, 7.2), seriously damaged levees at the mouth (0~3.2 km) of the Yodo River. Liquefaction of the approximately 10-meter-thick sand layer that forms the foundation of this levee caused levee subsidence as great as three meters in some places (Fig. 6). Fortunately, the highest tide level during emergency restoration of the levee was 1.7 meters lower than the top of the damaged section, thus avoiding the intrusion of sea water into Osaka City, which lies nearly at sea level.

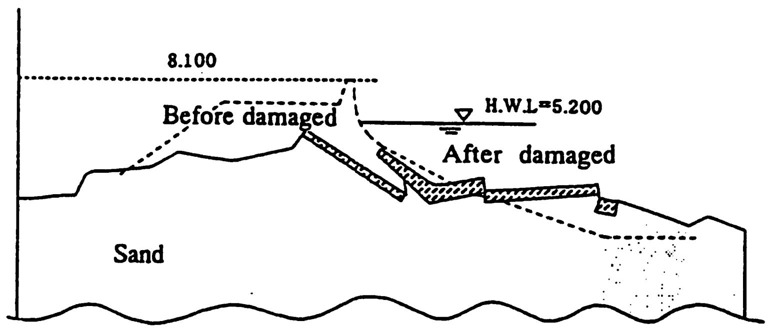

Fig. 6 Levee failure of the Yodo River by the '95 Great Hanshin Earthquake

The most important function of a levee is to prevent the intrusion of river water and sea water into the area beyond during flooding, high tides, and earthquakes. Because the ground around the mouth of a river is generally weak and liquefies readily during an earthquake, levees built on such ground are highly susceptible to seismic force. Although river levee functions can be maintained after earthquake-induced levee damage if restoration is completed before flooding or high tides occur, it is absolutely essential to prevent the inflow of river water or sea water into city areas due to the loss of basic levee functioning after the devastating damage at a major earthquake. In short, the section of the levee a certain distance above the high-tide level must be preserved in the event of damage. To achieve this, it is necessary to consolidate the knowledge and techniques of hydraulics, seismology and soil engineering in order to develop a design theory for levees that takes factors such as seismic force, ground structure and tide height into account, and makes it possible to maintain levee functioning even under crisis circumstances.

APPLICATION OF NUMERICAL CALCULATION FOR HYDRAULIC STRUCTURE DESIGN

Erosion occurs easily on parts of banks that are the attack points of the flow in meandering or curved rivers, creating a higher risk of levee damage. Reducing the curvature of the river is a prerequisite for the prevention of bank erosion in such situations. However, when there are many private residences lying adjacent to a river course, it becomes financially and socially difficult to alter the actual levee alignment and so the use of revetment, spur dikes, vane arrays and other such hydraulic structures as a method of countering bank erosion invariably increases. While decisions involving proper hydraulic structure and its placement are, in many cases, based on a survey of the actual site and hydraulic model experiments, there is a close connection between this structure, placement and channel alignment. It is, therefore, necessary to devise a more rational and relatively easier method.

Judging from an engineering standpoint, methods for determining the flow and bed topography of a river with an arbitrary bank alignment have been developed to a fair degree by two-dimensional or three-dimensional numerical calculations in a case where bank erosion is not large. If, with the aid of these numerical methods, a new mathematical method were found that could represent the flow and bed topography of rivers with hydraulic structures in place, it should become possible to design both river courses and hydraulic structures using the numerical calculation method.

When a structure is placed in a flow, this structure must be incorporated in the calculation as a boundary condition. There are two possible methods for incorporating this boundary condition: The first is used when a computational grid scale is chosen smaller than the scale of the structure and involves representing the shape of the structure with a computational grid; in the second method, used in cases in which the scale of the structure is smaller than the scale of the grid, the structure is incorporated into the grid and the equations are solved so that the kinematic and dynamic boundary conditions around the structure are satisfied inside the grid.

The former method is used for bridge piers and spur dikes that are not submerged, in which case pressure around the structure ceases to show hydrostatic pressure distribution. As the effect of this on bed topography around the structure is particularly great, it is necessary to determine the vertical component of the flow velocity by solving equations of motion for the vertical direction.

The latter method, used for submerged structures such as vane arrays and spur dikes, is effective when the relationship between the surrounding flow and the forces on the structure is known.

SUBMERGED HYDRAULIC STRUCTURES -VANES AND SPUR DIKES

Odgaard and Kennedy (1983) successfully developed the Iowa vane to reduce the erosion of the outer bank in meandering rivers. This research shed new light on the design method of hydraulic structures. Subsequently, a refined vane design method was proposed by Odgaard and Wang (1991).

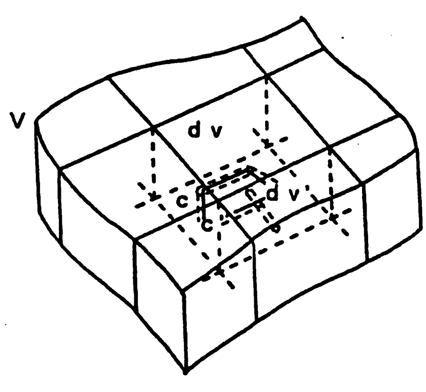

Fig. 7 Determination of the boundary around the structural surface

We shall here briefly describe a more general calculation method for submerged hydraulic structures (Fukuoka 1992). When the structure has been incorporated inside the grid, the boundary is chosen so as to surround the structure inside the grid (Fig. 7) and then integrate the equations of motion thus:

$$\int_c u_j u_k dA_j = -\int_c \frac{p}{\rho} dA_k + \int_c \varepsilon \frac{\partial u_k}{\partial x_j} dA_j - \int_{c'} u_j u_k dA_j - \int_{c'} \frac{p}{\rho} dA_k + \int_{c'} \varepsilon \frac{\partial u_k}{\partial x_j} dA_j \quad (1)$$

where, c = grid boundary and c' = boundary around the structure. Also, the kinematic boundary conditions (i.e., the flux 0 passing through the object) and the dynamic boundary conditions (i.e., F_k, force acting on the object) are determined as follows:

$$\int_{c'} u_j dA_j = 0 \quad (2)$$

$$-\int_{c'} \frac{p}{\rho} dA_j + \int_{c'} \varepsilon \frac{\partial u_k}{\partial x_j} dA_j = -\frac{F_k}{\rho} \quad (3)$$

Substitution of equations (2) and (3) into equation (1) produces equation (4), the basic equation for flow that incorporates the structure:

$$\int_c u_j u_k dA_j = -\int_c \frac{p}{\rho} dA_k + \int_c \varepsilon \frac{\partial u_k}{\partial x_j} dA_j - \frac{F_k}{\rho} \quad (4)$$

It is possible to determine the flow including the structure by digitizing this equation with the finite difference scheme, etc.. The following equation results when equation (4) is rewritten in volumetric integrals and expressed in common form.

$$\int_V u_j \frac{\partial u_k}{\partial x_j} dV = -\int_V \frac{1}{\rho} \frac{\partial p}{\partial x_k} dV + \int_V \varepsilon \frac{\partial^2 u_k}{\partial x_j^2} dV - \int_V \frac{F_k}{\rho} \delta(x - x_i) dV \quad (5)$$

where δ is the delta function.

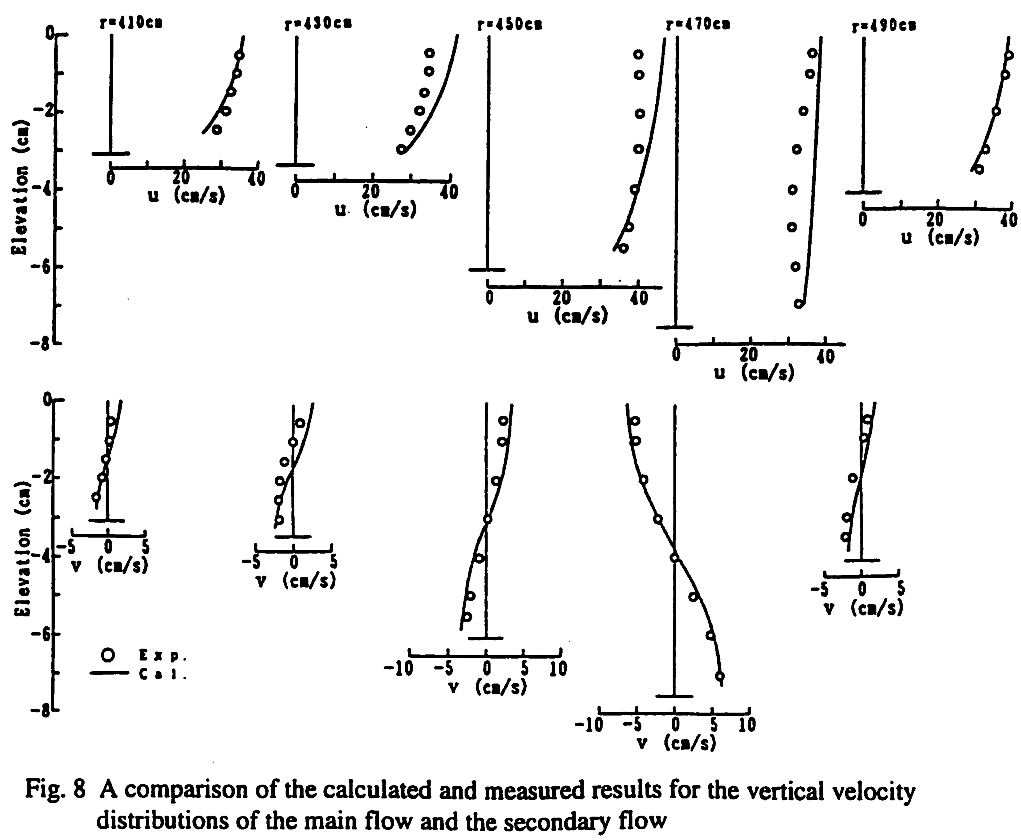

Fig. 8 A comparison of the calculated and measured results for the vertical velocity distributions of the main flow and the secondary flow

It has been proved by laboratory tests that the numerical method using equation (5) explains well flow and bed topography around submerged vanes and spur dikes as seen in Figs 8 through 11 (Fukuoka and Watanabe, 1993). Field tests have also demonstrated that this numerical technique is valid for designing the submerged structures.

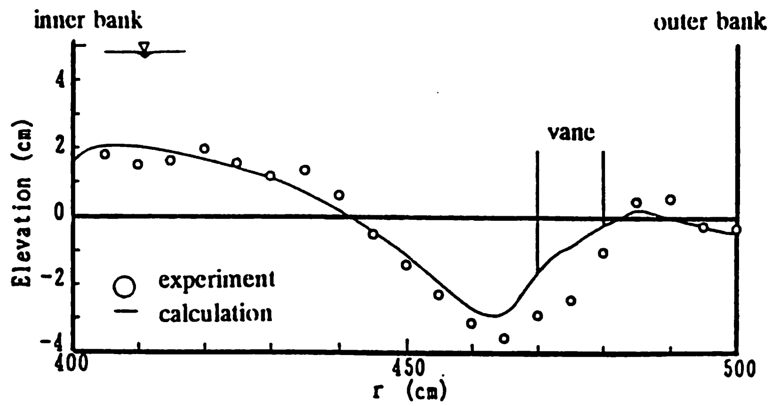

Fig 9. A comparison of the calculated and measured results for transverse bed profiles

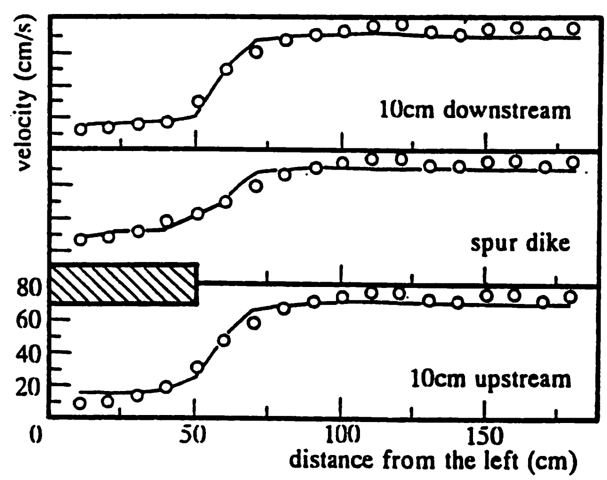

Fig. 10 Longitudinal distributions of depth-averaged velocity

FLOW AND BED SCOURING AROUND BRIDGE PIERS

Local scouring around bridge piers results from local flows that display three-dimensional behavior, and from the resultant sediment transport, which has strong non-equilibrium properties. In constructing a numerical model that describes the phenomenon of local scouring, it is necessary to properly incorporate the physical mechanism behind this phenomenon.

It is felt, however, that even if complicated local flows are not solved in detail, incorporating the principal mechanism of scouring into a model would make it possible to describe, with sufficient accuracy for practical applications, the phenomena of scouring and deposition around bridge piers. This is because as local flows are closely related to bed profile around a bridge pier, the proper expression of scouring and deposition at the bed makes the incompleteness of the solution for the flow separation behind the bridge piers less significant. Sediment transport around a pier is in a non-equilibrium state due to the upstream hysteresis of the flow. We have to, therefore, incorporate an equilibrium sediment discharge equation containing the effects of the bed's local longitudinal and lateral gradients, and also incorporate non-equilibrium properties into the bed load and the pick-up rate of bed sediment. The calculated and measured results for maximum scouring depth and expansion of scour holes are compared in Fig. 12.

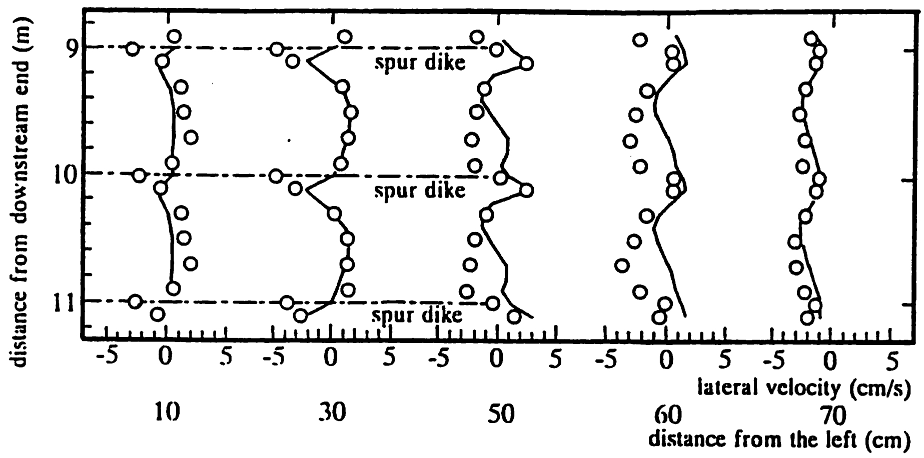

Fig. 11 Longitudinal variations in depth-averaged lateral velocity distribution

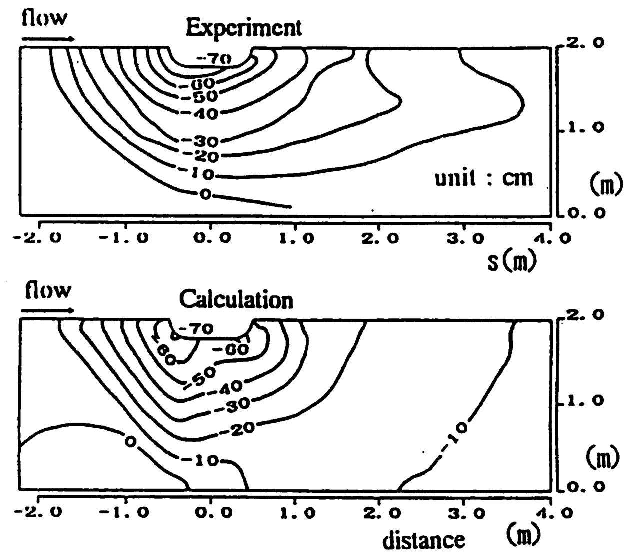

Fig. 12 A comparison of the measured and calculated scour-hole profiles around a bridge pier

CONCLUSION

There are many types of hydraulic structures besides those discussed in this paper. The levee is a familiar hydraulic structure, and while the analysis of seepage flow inside the levee is of particular importance in the design of levees made of earth. However, the main objective of this paper is to clarify the extent to which current numerical models are effective in the prediction of flow and bed topography in river courses in which hydraulic structures have been constructed and the design of hydraulic structures. Therefore, a discussion of the analysis of seepage flow in levees was not included in this paper.

Problems that must be solved hydraulically are generated when drafting plans for hydraulic structures or for longitudinal or cross-sectional aspects of a river course and solutions to many of these problems can be arrived at through the analysis and hydraulic investigation of related material accumulated over the years and through on-site surveying and observation. However, when the phenomena in question are particularly complex or the investigation of a particularly important nature, solutions are searched for through model experiments and hydraulic analysis, with the emphasis placed on large-scale model experiments as the primary problem-solving method. Nevertheless, the physical limitations of equipment and facilities become a problem in satisfying the law of similarity in model experiments to obtain high-precision results; and other problems, such as the significant manpower, time and expense required, also exist.

Progress made in recent years in numerical computation is now making it possible to find practical solutions to many of the hydraulic problems concerning river courses. However, these numerical models cannot be applied with adequate accuracy unless the results of detailed surveying of the site and the results of large-scale hydraulic model experiments are available, and there are many aspects in which research to improve calculation techniques and increase accuracy must rely on accumulated data from surveying and on hydraulic model experiments. Thus, it seems that future solutions to hydraulic problems concerning rivers will have to be found by using site surveys, model experiments and numerical models in such a way that they complement each other.

Furthermore, the planning, design and actual construction of hydraulic structures must be approached not only in terms of hydraulic analysis but also from an environmental perspective. We river engineers and researchers now must not only use concepts grounded in dynamics as a base for design and construction, but are also expected to give adequate consideration to the environment and ecology of rivers and the surrounding areas. This makes it necessary to direct our attention to the accumulation of technology in this field, as well.

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