HANDBOOK FOR HYDRAULIC MODEL EXPERIMENT ON CHANNEL WORKS

1986

VOLCANIC SABO TECHNICAL CENTRE
JAPAN INTERNATIONAL COOPERATION AGENCY

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PREFACE

For planning and designing the channel works, the flood flow in its volume less than the design-flood discharge should be flowed, and also, the channel works should be economical. The flow accompanied by the movement of sediment is complicated, and there are many unknown points by only hydraulic review on desk. Accordingly, it is necessary and beneficial to make experimental review by manufacturing the model of channel works. Moreover, recently, large-scale channel works have been planned, thereby, the model-experiments as a technique for reviewing the dimensions of channel works have been generalized considerably. However, the procedures and profitability have not yet been well understood. In this text, for the purpose of deepening the understanding of the technics in the field and the diffusion of the model experiments, arrangement has been made on the following problems for planning. That is, how is the model experiment useful? What can be found and understood by performing the model experiment? To what degree is the similarity between the flow in the model-experiments and that in actual rivers? The procedures and the content about how the model-experiments are performed? It is hoped that further effective model-experiments can be performed for planning the channel works.

CHAPTER 1 OUTLINE

1.1 Significance and role of the model experiment

Model experiment means the direct and indirect observation and measurement as well as the analysis of the phenomena caused in the actual river and the phenomena which may occur in future by giving the approximately similar relations between the prototype and the model.

Model experiment is performed for the prepared planning draft in case it was judged to be necessary to review the designing dimensions by experimental methods in view of the importance and the technial aspect of the channel works, therefore, the planning draft ought to be prepared as a rule at the stage of performing the model-experiment.

For the model experiment, the following features can be considered by understanding or grasping the changes in plane movement of flowing water including or containing the sediment or the deformation of river bed (including the local phenomena) quantitatively to some extent.

1) When the local surveyed data would not be obtained enough, it is possible to know the type and cause of the disaster in the river-channel in the present status by the model experiment, thus the basic data can be obtained for preparing the planning draft for channel works.

2) Rational selection of the planning draft can be made to some extents for the best adaptation to the actual river by arranging the merits and demerits after comparative review on some considerable planning drafts.

3) It is possible to review if the planned and designed channel works are safe, or if functions are fully exerted, and comparative review can be easily made for the adjustment or correction of the planned and designed dimensions of the channel works.

1.2 Judging criteria for performing the model experiment

In view of the basic experiments related to the hydraulic model experiments or the channel works plans performed by Public Works Research

Institute of the Ministry of Construction, Japan, when the following contents are included in the designing dimensions of channel works, it is desirable to review the designing dimensions by performing the model experiment.

(1) Case when the width of channel works would be particularly wider or narrower than that executed numerously in the past, or concretely, in getting out of the range of channel width in the following equation (1) showed by ASHIDA.

$$B = (3.5 \sim 7)\,Q^{1/2} \cdots\cdots\cdots\cdots (1)$$

(2) Case having a sharp bend damaged in the past

According to the experimental studies, at the bend having the shape of the following formula (2), local scouring depth at the bend and its downstream are deeper than that of the straight river channel, and it is necessary to take a preventive countermeasure against the local scour.

$$\theta \geqq 30^{\circ},\ R/B < 10 \cdots\cdots\cdots\cdots (2)$$

Also, in case of inserting the reverse curved part of S-shape.

(3) Case with transversal structures such as diversion weir, erosion control dam, and groundsel, and at its front and rear parts, the design longitudinal slope is discontinuous:

(4) Case with the flowing possibility of the entrance of much sediment ($Qs/Q > 5\%$) into the channel works:

(5) Case of the plan of channel works including the sand retarding pond or sand-catching works, or case of plan on channel works having the sediment control function.

(6) Case with the secular variation of the deformation of the channel and the river bed.

(7) Case with big influence by the branch with diversion or confluence in view of the flow regime or the deformation of the river bed.

(8) Case of junction of the design channel works with its downstream-river improvement work having the problem of treatment for junction in view of the hydraulics or execution.

(9) Case of big deviation of the designing draft from the data of the already established channel works all over Japan.

(10) Case of big-scale channel works designed on the desk, needing long-term work with the necessary sequence of priority for execution.

1.3 Contents reviewed by model experiment

Major items reviewed by model-experiments are as follows:

(1) Grasping of the problematic points of the present channel

(2) Review of planning dimensions for channel works

1) Alignment shape

2) Channel width

3) Slope of river bed

4) Sectional shape (single section, compound cross-sections)

5) Need or not of groundsel and bed girdle, its position, interval, direction, and shape.

6) Need or not of revetment works, its height and its foundation

7) Shape of apron-protecting works

From the above items, the major ones are analyzed as follows:

(1) Alignment shape

The bend is liable to be greatly damaged by local scour of the foundation of revetment or revetment-overflow of water. Thus, the alignment is desirable to be straight as much as possible. However, in actual planning for the channel works, it is inevitable to insert some bend.

Local scouring depth or water-level elevating amount at the bend is influenced by the geometric conditions such as channel width, radius of curve and intersection angle, in addition to the conditions such as discharge, grain diameter and slope of river bed. Moreover, water-level elevating amount or the degree of the local scouring depth is different at each position of the bend even at the same bend. Also, by the shape of the bend, the maximum value of the local scouring depth or water level is not necessarily induced at the bend. Furthermore, the change of the height of river bed or water level is different by the following conditions, that is a single curve, a S shaped curve or the provided length of straight section at the interval of the bend.

As in the above, it is difficult to solve or analyze the changes of the river bed, water level, or concentration of flowing water which takes place in the channel of complicated alignment composed of the straight portion and the bend in various shapes.

With the model experiment, it is possible to make quantitative observation and measurement of the deformation of river bed or concentrated degree of flowing water as caused by the influence of the curved alignment, and to arrange the problematic points on the alignment, or to correct the alignment for solving the problematic points. When it is difficult to adjust or correct the alignment, it is possible to review the countermeasures for reducing the local scour or controlling the flowing water by establishing the cross-dyke like a groundsel.

(2) Sectional shape

For the sections of river channel, there are single sections and compound cross-sections, and in some cases, a compromise may be taken between the single section and the compound section.

1) Single section river channel

At the single-section river channel, the problem is the setting of the low-water channel width. The channel width of the river with smaller deformation of river-bed because of less supply of sediment according to a measure of progress of the land-erosion control works at upper-stream can be planned with the standard of

(1)-formula by the study of ASHIDA et al. in application of Regme Theory. In narrow width against discharge, the designed velocity is higher, therefore the safety of river-channel structures becomes a problem because of the lowering of the river bed, and a great deal of construction cost is necessary for the construction of groundsels or increase of excavating volume when intending to keep the stable slope, thus it is beneficial not to narrow the channel width than the value of lower limit of (1)-formula.

According to the result of model experiment, in planning the channel width to make $B/\overline{Hm} < 5$ with $H/d=40$ even at the subcritical flow area of the river, it is impossible to expect the prevention of the lowering of the river bed with groundsels or river-bed girdles even at the straight portion. Moreover, among the already established channel works all over Japan, there are many examples of construction of 3-phase extensive channel works under the condition of $B/\overline{Hm} < 10$, therefore, it is not beneficial to narrow the channel width for the discharge (volume), but if an unreasonable channel width should be planned, it is necessary to review the establishment of extended width section by avoiding the uniform channel width by model experiment under consideration of characteristics of river channel, and also, review is made for the countermeasures-works to reduce the scouring depth or deceleration of flowing water.

On the other hand, in the river of active movement of sediment in the river channel, the buried channel or the sedimentation is liable to cause the decrease in the effective cross sectional area of the river, thus there is a case that it is unreasonable to plan a uniform channel width, or the uniform channel width may expert adverse influrnce on the downstream by increasing the sediment transportation with the destruction of natural control function of the sediment. Thus it is necessary to pay attention to the above fact. In such a case, review should be made on the grasping of the actual status of the deformation of river bed in actual river with the consideration of the sediment transportation as well as the change in the topography of river channel by performing the model experiment.

2) Compound cross-section river channel

The design channel width is decided by the estimated height water discharge, thus in some cases it is too wide for the discharge less than the estimated height water discharge, and whole river bed is not always covered with water, therefore, unstable river channel may be formed because of turbulent flow and drift current in the channel. Accordingly, in the river with bigger coefficient of river-regime, it is necessary to secure the safe channel with for the medium and small freshet, that is, review should be made for compound cross-section river channel to fix the low-water channel.

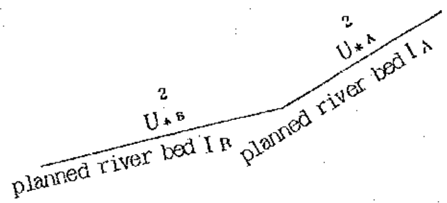
In the compound cross-section river channel, there is a problem how to take the section of low-water channel. Low-water channel section decides the width and the depth of low-water channel. There is a way of consideration that the low-water channel shall possess the section having the flowing capacity with the probability of occurrence 1/1 - 1/5 year. However, for the actual planning, it is necessary to consider that the lowering of the low-water channel bed should not occur, the sedimentation should not occur in low-water channel, also, that the major bed should not be scoured. Therefore, while obtaining various dimensions by hydraulic calculation, it is desirable to review the adequacy of the dimensions of major-bed width and the revetment height, the width and the design discharge of the low-water channel by the model experiment.

When it is not beneficial to construct the revetment of the low-water channel in view of the maintenance of the major bed, the deformation of the river-bed or construction cost, the model eperiment is performed to review the formation of the compound cross-sectional river channel by setting the wing at the groundsel or the river-bed girdle.

(3) Longitudinal slope

One purpose of performing the channel works is to reduce the scouring power of the flowing water by mitigating the slope of the river bed for preventing the production of the sediment. In this sense, the design slope of the river bed should be planned to make the continuous change of the slope from upstream to downstream as a shole. However, bent points surely appear because the design river bed slope is given by a bent curve. As well known, there is a problem of sedimentation in the channel by sudden change of the slope of the river bed, and these phenomenon are the more remarkable with the more sediment discharge and the bigger changing rate of the slope of the river bed. On the changing rate of tractive force, IKEYA suggested the following formula (3).

$$\left.\begin{array}{ll} I_A \geq 1/30, & U_{*A}^2/U_{*B}^2 \leqq 2 \\ I_A < 1/30, & U_{*A}^2/U_{*B}^2 \leqq 1.5 \end{array}\right\} \quad \cdots\cdots\cdots\cdots\cdots\cdots (3)$$



A standard change of the longitudinal slope can be based on the formula (2), but in the model experiment, there is an example of shortage of cross-sectional area because of the sedimentation in the channel in case of $U_{*A}^2/U_{*B}^2 = 1.3(I_A=1/75,\ I_B=1/95)$. Also, it is necessary to decide the changing rate by considering the relations to the sediment yield or the revetment height as well as the executing property. In the model experiment, the proper design slope of the river bed can be determined in relation to the change of water-level and time-series deformation of river bed as well as the changing rate of river-bed slope.

Flood flow may become high densed sand flow by the state of upstream region, or it may be low-densed sand flow. This fact influences greatly the safety of river-channel structures, thus the design slope of the river bed in an unstable river on the supply of the sediment from upstream is reviewed from both phases, that is, one is dynamic equilibrium slope supposing the much supply of the sediment and the other is static equilibrium slope supposing the little supply of the sediment. In setting the design slope of the river bed, damage occurs by the scour of the revetment foundation because of the lowering of the river-bed under less supply of the sediment from upstream. In the river with much supply of the sediment, the design slope of the river bed determined from static equilibrium slope will cause overflow at revetment by the sedimentation in the channel.

If it is possible to set the design slope of the river bed (design river-bed height) in considering the both phases of static and dynamic equilibrium slope, there will be no big problem except the local scour caused by the meandering of flowing water. In actual planning of channel works, even by setting the design river-bed slope by static equilibrium theory, the local scour is caused by meandering of flowing water, thus it is difficult to obtain a stable state by the sectional average primary way of consideration as the static equilibrium, and slope-setting is restricted for the design river bed from the work-cost or existence of the already established river channel structures or on the execution, therefore as the design river bed slope the slope between the static and dynamic equilibrium may be taken, placing the importance to the present river bed slope. In such a case, estimation is made for the deformation of river bed or water-level in case of flood under the design slope and the level of the river bed by the model experiment, and review can be made for the adequacy of the river-bed slope by considering the relation between foundation of groundsel or revetment and scouring depth and the relation between water level and ground height of hinter land. When there is a problem, on the design river bed slope, it is natural to review not only the design slope of the river bed but also channel-width.

Moreover, the design river bed slope may be discontinuous by the presence of land-erosion control dam, diversion weir or groundsel in the design section of channel works. By surveying the defect caused by discontinuance of river-bed slope and its degree, necessary counter-measures can be reviewed.

(4) Revetment level and foundation level

Revetment level can be decided by the calculation of estimated water-depth with hydraulic formula, and it is added with allowance height shown in the Technical Standards for River Engineering and Sabo. However, it is necessary to pay attention to the case of less height of revetment by higher sedimentation than the allowance-height at the inner side of the bend of the river with remarkable deformation of river bed. The experimental value of the highest water level at the bend to show the supercritical flow tends to be greater than the calculated value by the Knapp Formula, and the elevation of water level in case of continuous bends may be induced not only at the outer side of bend but also at the straight part of downstream of bend or inner side.

In the case setting the design bed level, the way of consideration of revetment foundation showed in the Technical Standards for River Engineering and Sabo is based on the performance of depth of embedment over 1m deeper than the design river bed height. Actually, however, local scour is caused by the concentration of flowing water by the formation of alternating bars or influence of the bend alignment, and the design depth of embedment may be in shortage. Moreover, it is uneconomical by too deep depth of embedment at the deposit area of sediment as in the inner side of the bend, or there may be an area without need of the strong envertment, and also, channel-work dose not necessarily need to take the combination system of the envetment work and cross dyke. There may be a case without need of construction of revetment work by proper arrangement of a cross dyke.

As in the above, for the more practical planning of revetment (the necessity of revetment work, allowance height and depth of embedment), it is desirable to review the adequacy of the planning draft by performing some hydraulic model experiments.

(5) Groundsel and river-bed girdle

The interval of groundsel for the mitigation of river-bed slope can be decided by giving the head of the groundsel and the design river-bed slope for the original river-bed slope. In addition, by setting the groundsel, it is intended to reduce the local scope by making conformity of the flow water and by controling the single-raw sand bars by the combined use with river-bed girdle. For groundsel and bed girdle for reducing the local scour and conformity of flow water, the position and direction would be the problem, and there are many cases to adjust and correct the planning draft by the hydraulic model experiment. In order to reduce the local scour caused by the formation of alternating bars, it is recommended to establish the cross dykes at the interval about 2 times of channel width by the experimental study result, while in the relations between the design revetment-depth of embedment and local scouring depth along the revetment, there are some cases to make the interval of cross dyke over 2 times of channel width.

Moreover, there is a remarkable action to affect the center line of downstream with the direction of groundsel, especially, at time of flood, this action is remarkable. If the direction of groundsel is mistaken a little, the revetment of downstream becomes "water-hammer" part, and it is broken, thus it is reported that the direction of the groundsel should be rectangular against the center line of the downstream as a principle. However, at the bend, even if the direction of groundsel is set on the perpendicular line against the direction line of the spillway center of the upstream groundsel on a diagram, it is given by a bent line, in some cases thus no conformity is obtained for the flood, and downstream revetment becomes water-hammer part, also, in many cases, the direction of groundsel is adjusted by the hydraulic model experiment.

Moreover, revetment work may be unnecessary by effective exertion of the function of groundsel by setting the groundsel, while in reverse, in the river of fine particle with mild slope of river bed in sub-critical flow region, it may be better not to set the cross dykes like groundsels.

With model experiment, it is possible to make rational decision of the necessary of cross dyke, proper setting interval, direction and shape.

1.4 Accuracy and applicable limit of the model experiment

Even by giving the similar shape or similar conditions by the model-experiment, it is impossible to give complete similarity dynamically, thus all the phenomena observed by the model experiment would not be similar. In some cases, specific phenomena would be watched thereby, others may be sacrificed. Accordingly, the model-experiment should be done by full reivew of the adequacy of the assumption and boundary condition, and the results should be exactly interpreted by considering various conditions.

In model experiment, hydraulic conditions such as discharge, supplying sand amount, testing materials, water-passing time are given. The yield and wave profile in actual river would be changed continuously on the increase of water, peak and decrease of water. While in the hydraulic model experiment, discharge is changed stepwisely in view of the test instrument or technics to make similarity to the wave profile of flood (Figure 1).

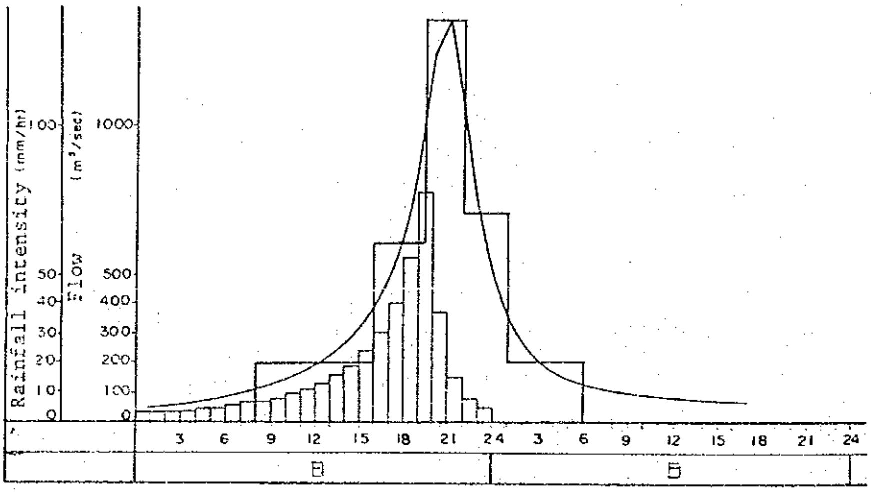


Fig 1 Run off wave profile against rainfall intensity having recurrence interval of 100 years (414 mm/day)

Using test material is geometrically simulated mixing sand in selecting the grain-size accumulation curve which represents the actual river, longitudinal change of the material in actual river is not considered except the case with big change of average grain size. In geometrical simulation of the grain size of test material for the actual river, the minimum method is affected by the minimum dimension of the filter mesh, thus it is impposible to make complete similarity for grain-size accumulation curve in actual river.

Sand is supplied generally from the end of upstream in the model by using the same sand as that of the river material, and its amount in nil in accordance with the state of deformation of river bed at upstream area, or sand is given continuously in accordance with the change of discharge in the continuous time of flood with the sediment discharge go keep the slope of deposited sand at land-erosion control dam on the end of the upstream in the model. On the other hand, the flood stream in the actual river contains low or highly dense sediment by the state of upstream area, thus time-course change is considered on the sediment concentration during the flood.

As in the above, hydraulic conditions of model experiment is given simulated to the supposed state or condition, thereby, all the model-phenomena would not be the same as those of the actual river.

The accuracy in the case applying the measured values in the model experiment is different by the measuring instruments or the reduced scale of the model, thus for obtaining the expected accuracy, full review should be made on the type of measuring instrument or how to give the reduced scale of the model. For instance, supposing that the measuring accuracy of water level is ±2mm, and that the accuracy of ±10cm is requested in actual river, the reduced model scale should be 1/50.

In the model, it is possible to match the meandering state of flowing water to that of the actual river qualitatively, however, it is impossible to simulate the degree of erosion of the bank by the concentrated flowing water as far as the same material as that of the actual river is used in actual state, therefore, the material development is waited for the testing materials in order to elevate the accuracy of the experiment. Moreover, the relation between river width and yield (discharge) by Regime Theory is shown by the above mentioned (1)-formula, but when the flow is free to the lateral direction, the relation between this yield (discharge) and river width is contradictory with the geometrical similarity and Frounde's similarity, thus it is a problem to be solved in future. Also, the local scouring depth by falling water at the erosion-control dam is reported to be less than the depth in model-experiment, then, it is necessary to pay attention to the interpretation of the measuring value in the experiment.

1.5 Procedure for model experiment

The experiment is performed by the following procedure after full understanding of the significance of model test.

1) Grasping of the purpose
2) Collection of necessary data for model test
3) Model design
4) Model manufacture
5) Experiment
6) Analysis of phenomena
7) Conclusion

(1) Firstly, what would be obtained as an answer?

It is necessary to make exact grasping of the purpose by full review of the purpose. The purpose of the ordinary hydraulic model experiment for channel works would be in grasping the problematic points of the current river channel in case of flood and to clarify the arranging plan and its shape of the equipment or facilities adjusted for the problematic points while reviewing the adequacy of the planning draft for the prepared channel works by experimental judgement.

The tester should grasp the proper state of the river as the testing object and make review by full understanding of the preparing course of the planning draft and the problematic points of the planning draft.

(2) After grasping the purpose, necessary data are collected for the manufacture and experiment of the model. The necessary data for model manufacture should include plane view, longitudinal/cross profile drawings, shape of river-channel structures for obtaining geometric similarity or for reviewing the range of model-intake. Model experiment needs the materials of river bed, discharge, sediment discharge time of flood in order to obtain the dynamic similarity. Although actual data on the sediment discharge of many rivers have not been obtained, these data would be necessary for obtaining the highly reliable experimental conclusions and for preparing the rational planning draft for channel works.

(3) In model design, firstly, taking range of model and its reduced scale should be decided, and these deciding factors are similarity, scale of facilities at test site (pumping capacity, area), experimental technics (accuracy of conformity of river bed, selection of grain-size distribution, supplying amount of sand, measuring accuracy) and accuracy of measuring instruments. Moreover, model design is made for necessary structures for the test such as settling basin, etc., test on discharge and value-conversion on model for geometrical simulation to the river channel of actual river.

(4) Model is manufactured by the use of mortar for the planned river channel or the present river channel simulated geometrically in accordance with the Instruction Manual prepared at the stage of model design.

(5) Experiments are those for reviewing the dynamic similarity, for grasping the problematic points at the present river channel, for reviewing the problematic points and adequacy of planning draft, and for reviewing the countermeasures and improvement of necessary facilities for dissolving the problematic points of planning draft.

The verifying experiment is intended to compare the flowing states (deformation of river bed, plane change of flowing water, water level) between model and the actual river, therefore, for proving test, the necessary data are those on actual flood-waveprofile and flow (discharge) (Q-T curve), sediment discharge, longitudinal and lateral (cross) section of river-bed before and after flood, water level in actual results (flood mark), plane-changing diagram of flowing water, and actual disasters. However, there are less data rarely collected in actual rivers, thus the proving test is hardly performed at present.

The test on the present state is mainly intended to grasp the problematic points of the present river channel in view of hydrological sides, and some evaluation can be made for the reproducibility of the flow in the model by comparing it with actual results in the past disasters, yearly changing diagrams of deformation of river-bed, and yearly chaning diagrams of flowing channel readable by airial photos for the tendency of deformation of river bed, shape of river bed, plane-change of flowing water in view of the present experiment.

Complete simulation of the flow in model is impossible, however, it is possible to measure the reliability of the experiment by understanding the degree of reproducibility. If the reproducibility is not obtained, there will be some reasons (e.g. error in the selection of bed material), therefore, by reviewing the reasons, problematic points should be solved.

By the proving test or experiment for present state, review and adjustment in some cases should be made for the adequacy of the planning draft prepared on desk after grasping the problematic points of the present river channel with the review of the reproducibility. Problematic points are adjusted by the review in giving the hydraulic conditions in conformity with the purpose for the adequacy of the various dimensions of the planning draft. As mentioned above the reviewing dimensions for channel works are the alignment shape, groundsel, river-bed girdle, on these shapes and arrangements.

(6) Conclusions can be obtained on various dimensions for planning the channel works by experimental consideration and phenomenal analysis of the arranged measuring results such as water level, changing height of river bed, velocity and flow regime (mainly, local phenomena, traces of timely or plane-changes of river bed or flowing water).

(7) The following pictures show the outlines of measuring states in model-experiments and operating contents for model-manufacture.

1) Outline of model manufacture

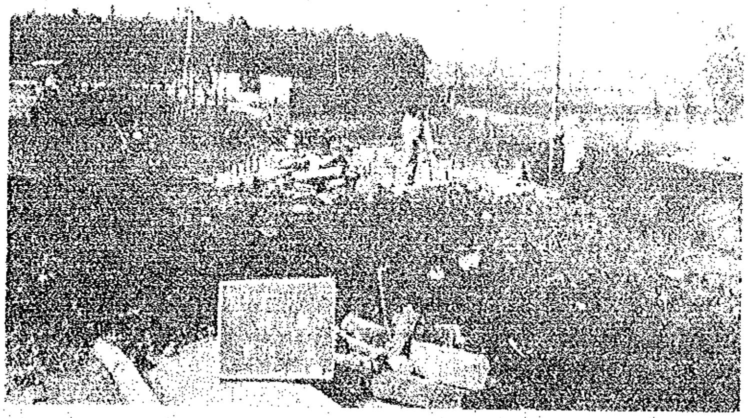


Photo 1: Survey is made for the model-skeleton in dropping the model-taking range at the experimental site. Setting is made for the basic level showing the standard surface. With the formation of cutting and banking in conformity with the standard surface, model-floor surface is manufactured with the land readjustment.

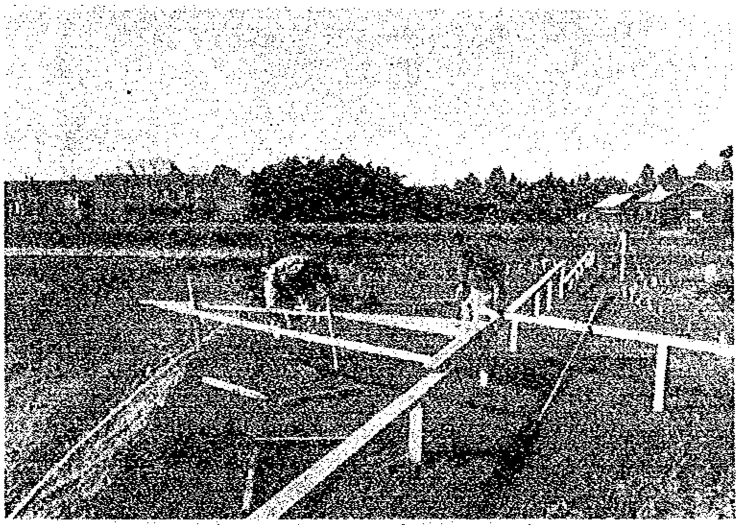


Photo 2: Basic line is set, and distance-marking stake (cross-stake) is set by the method with offset-survey.

Photo 3: Cross-mold plate is manufactured. Cross shape of the scale-reduced actual river is plotted on rawan-plywood, and it is cut along the shape.

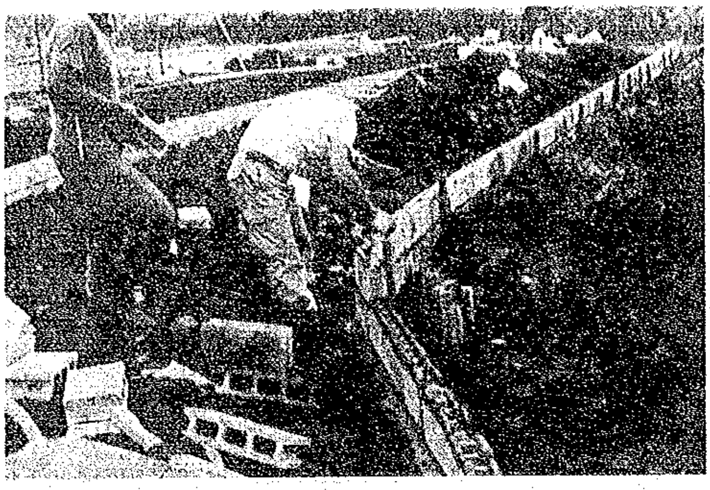


Photo 4: Side wall is manufactured on the inner side of distance-marking stake.

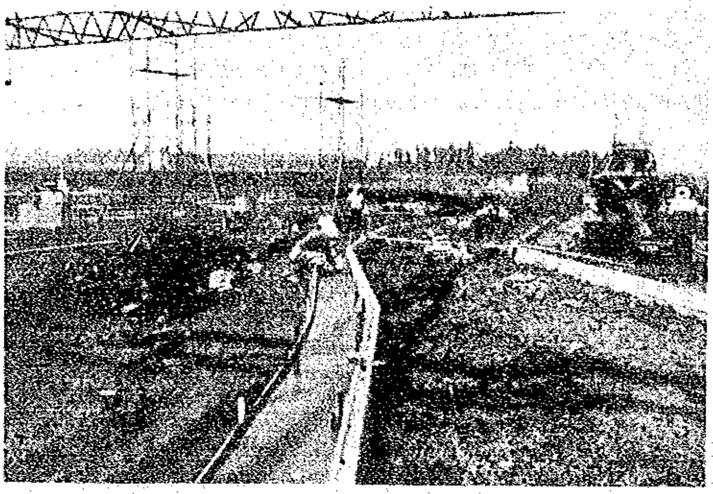


Photo 5: Road for operation is manufactured.

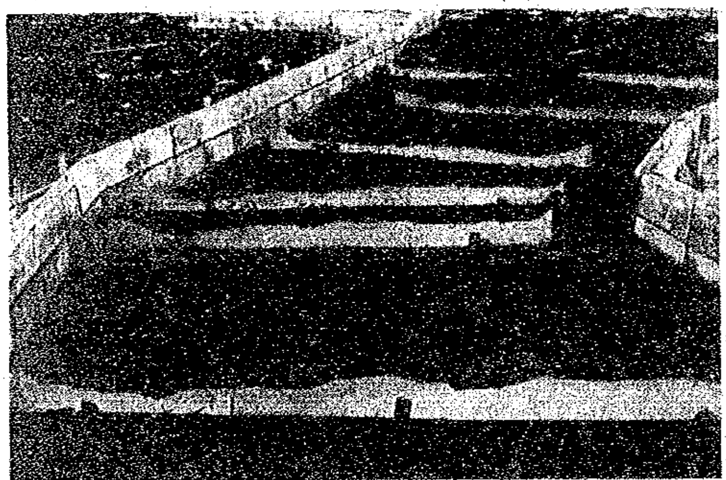


Photo 6: Cross board is matched to the distance stake, and by matching the height of the cross board, install and fix it. Side walls are manufactured on the both side of the cross board.

Photo 7: Gravel is spread in its average thickness 5m between cross-boards, then, it is pressed by a roller.

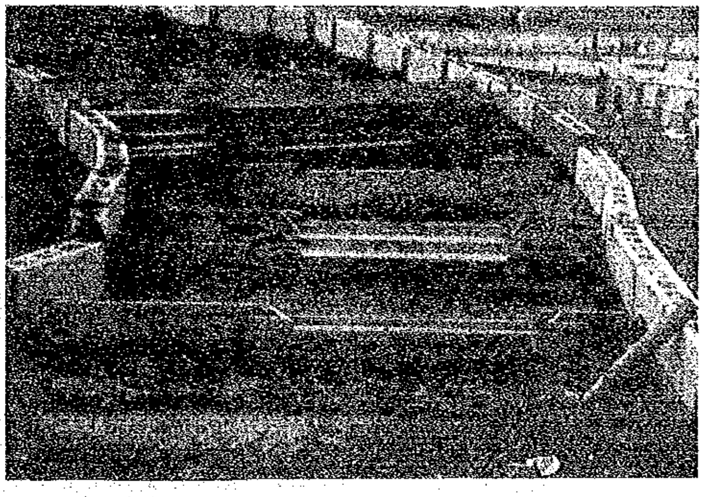


Photo 8: River-channel structures such as a groundsel etc., are installed.

Photo 9: Mortar is used for connecting the cross-boards, and scale-reduced river state of actual river is formed.

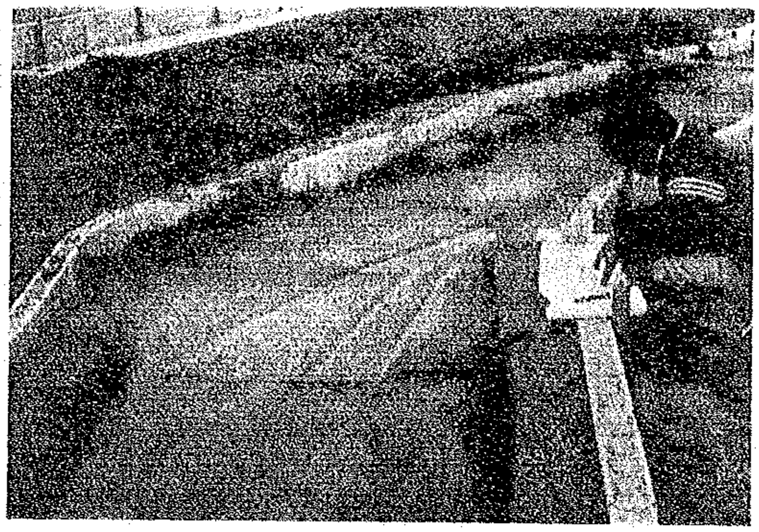


Photo 10: Test is performed to check if micro-topographic shape of river channel is exactly formed.

Photo 11: Water-gauging tank for measuring the flow (discharge)

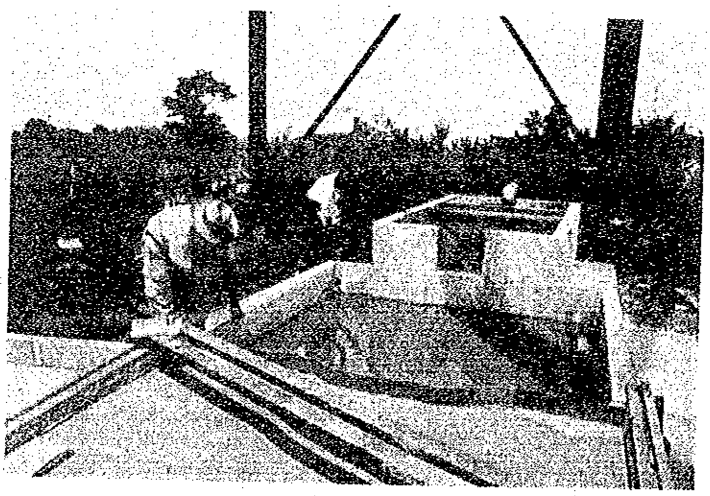


Photo 12: Conformity is made for the flowing water at the gauging weir on the rectifying pond.

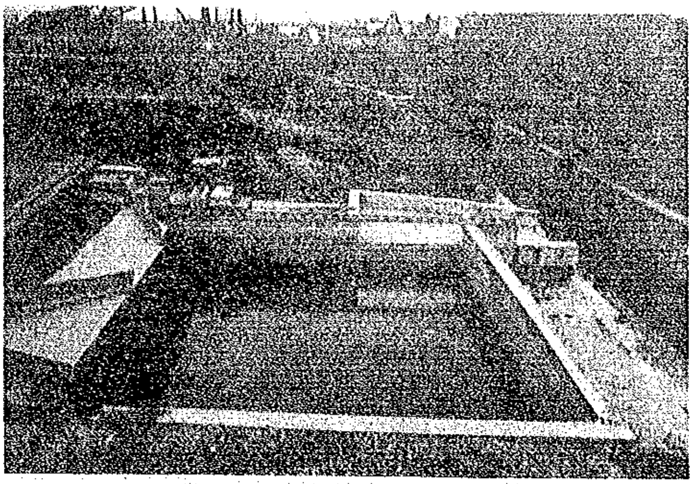


Photo 13: Drainage canal and setting basin for despositing the sediment from the end of the model.

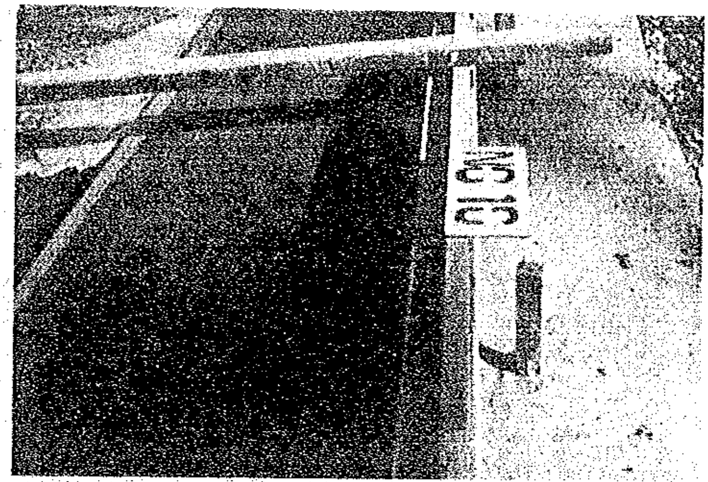


Photo 14: Distance scale (measure) for observing the flow regime on the crown of the side wall. Standard height is set and standard wire is stretched. Also, mark-plate showing the Measuring Line No. is set.

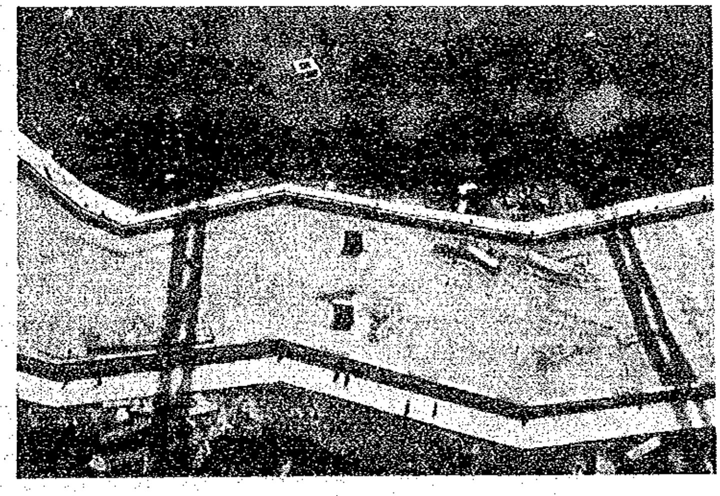


Photo 15: Completed mortar fixed bed

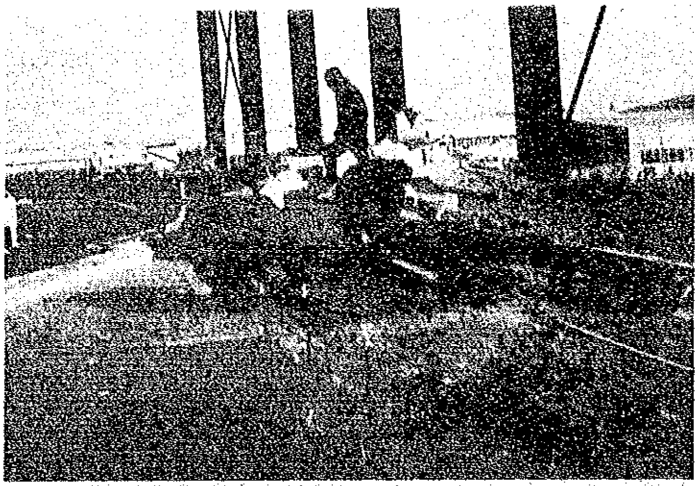


Photo 16: Along the river-bed face finished with mortar, moval bed is formed with the geometrically simulated experimental material.

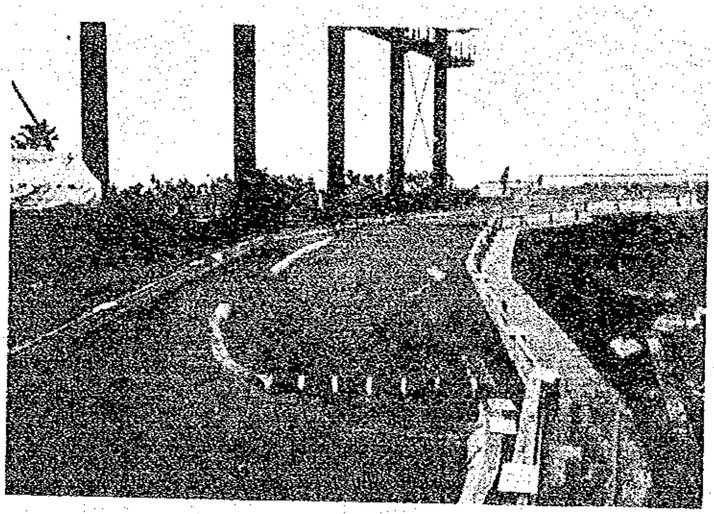


Photo 17: Completed model of moval bed

2) Outline of experiment

Photo 18: While checking the capacity, the specified amount of sediment is supplied from the upstream-end of the model.

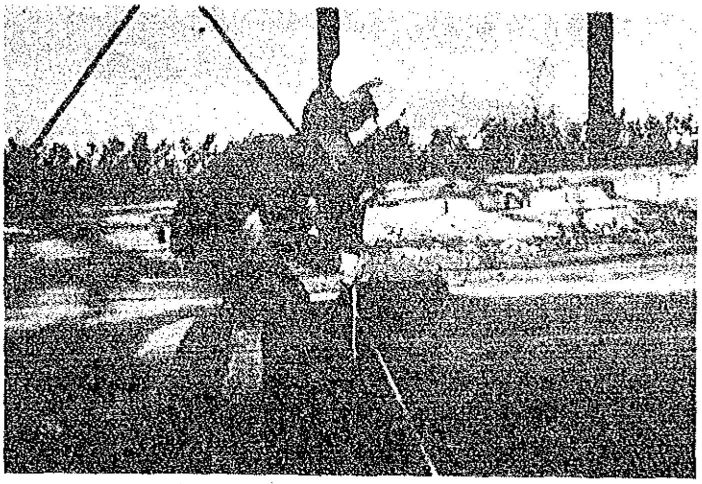


Photo 19: Measurement of water level and height of river bed

Photo 20: Measuring state of flow rate

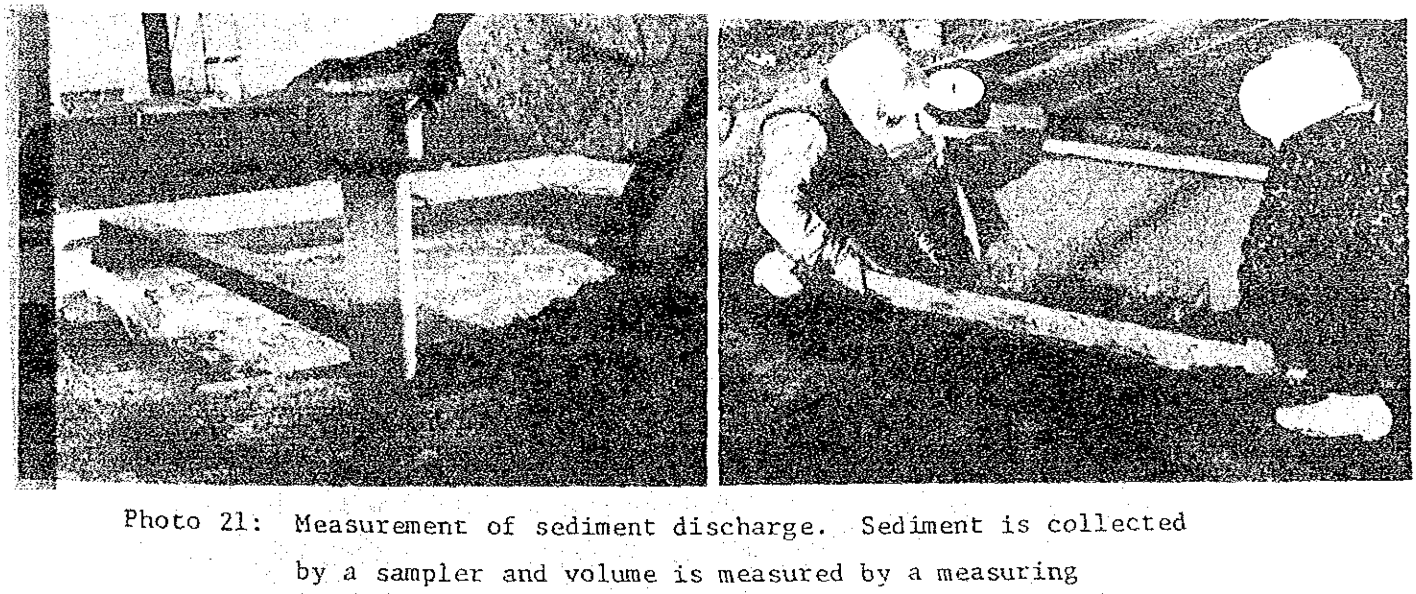


Photo 21: Measurement of sediment discharge. Sediment is collected by a sampler and volume is measured by a measuring cylinder.

CHAPTER 2 Necessary data collection for model experiment

2.1 Necessary data for model manufacture

For manufacturing the model, necessary data are ground plane, cross diagram, longitudinal diagram, drawings for river-channel structures, and aerial photographs. Those diagrams are desirable to be measured at the same time (date) or time stage except the cases of small deformation of river bed or of small changes of channel state. For reviewing the planning draft or test in present state, newer measured results should be used as much as possible. In reproducing the past disaster-phenomena, the measured result before the disaster is necessary since the model should be manufactured for the river state at that time in the past. Also, aerial photos are useful for fixing the difficult part for movement on the model or for producing the moval micro-topography as in the water-route of the river channel by comparing them with the ground plane.

Moreover, cross-sectional survey is performed at a certain interval field investigation should be done in need of the confirmation of the river topography between cross-stakes (surveying stakes), in case of insufficient confirmation of the strength of river-channel structures (e.g. division if the revetment work is vacant rubble work or remodelled rubble work, its obsolete degree), or in need of the confirmation of the exposed state of rock.

(1) Ground plane

This diagram is necessary for manufacturing the model of channel work planned or the present channel of river or for reviewing the taking range of the model, and for alignment planning or the decision of the starting and ending points of channel works.

Aerial photos are used for preparing the ground plane, from which, numerous data and information can be obtained on the shape of alternating bar, meandering of flowing water and land-utilizing form. The map described with contour in its 2m-interval will become the data for estimating the broken point of dykes or innundation area by understanding the old channel, level difference or moving point toward the raised bed river. In addition, the contour, water-route or shape of alternating bar as described in the ground plane will be necessary for manufacturing the model of the present river channel.

Closed-traverse survey or triangulation is necessary for plotting the test result or design dimensions of channel-work decided on the ground plane or elevation of accuracy of plane-survey for the actual river. Moreover, the position of the surveying stakes on the ground plane becomes the standard point for manufacturing the model, thus it should be shown exactly by collation with the stakes on the cross-section diagram.

Ground plane is drawn by the use of aerial photo, therefore plane-shape of older time than that of present channel of river is shown. That is, the actual execution is made for the channel structures which would not exist on the ground plane, or cross dyke is buried in the sediment, thereby, no reading is made by aerial photo, thus, there are different examples on the state of present river channel as compared with that at the time of taking the aerial photo, then, it is necessary to correct the ground plane by actual field investigation for the present river channel, and if it is neglected, not only the planning of channel work but also the result obtained by model-experiment will be meaningless, so pay attention to the fact.

At the time performing the model experiment, plane design would be finished as a rule, thus, it is important to describe the temporary measuring point, center point, alignment shape, channel-width and position of groundsel which are necessary for manufacturing the model on the ground plane.

The reduced scale of ground plane is different by the size or scale of channel work, but it is recommended to be about 1/1000 - 1/2500.

(2) Longitudinal profile

Upon manufacturing the model, longitudinal profile is used for setting the channel structures such as bridge, diversion weir, groundsel and revetment, or for setting the design height of river bed.

Usually, difference is induced on the longitudinal distance at the stage of deciding the temporary alignment shape as compared with that at the stage of survey and investigation for planning the channel work, therefore, it is necessary to correct the longitudinal distance to match the center line of the temporary alignment.

Longitudinal profile should be described with measuring point, interval distance, center-additional distance, curve, previous average level of river bed, deepest river bed height, basic altitude and crown of established and design river-channel structures, altitude of top surface of rock, design level of river bed, design slope of river bed, ground-height of hinter-land at right and left bank of river, design high water level.

Reduced scale of longitudinal profile used for model test is different by the scale or size of channel work, but it is recommended to be longitudinal 1/200 and lateral 1/1000.

(3) Lateral profile

In planning the channel work, lateral profile is used for deciding the design height of river bed or position of structures, and for manufacturing the model for producing the form of river bed of design river channel or present river channel. It is also used as standard (value) for measuring the change of the river bed.

In considering the performance of analysis of the measured results such as the changed amounts of river bed by model experiment, the cross-sectional surveying interval is desirable to be decided by paying attention to the shape of alternating bar which exists in the channel or topological shape or states such as the changes of river width or bending of river channel, and no definite interval will be always obtained, but the standard is 50 - 100m.

The design level of river bed is decided to be lower than the ground level of hinter land, thus the necessary range for cross-sectional surveying width should be the extent to see the topological state of hinder land. Even in model experiment, model-intake range is decided by considering the topological state of hinter land in order to check if there is any danger of flood for the elevation of water level caused by the change in the channel section or elevation or river bed.

Reduced scale of cross-section has difficulty in handling when it is too large, and it disturbs the whole reading of topographic state. Although the reduced scale is different by the surveying width, it is recommended to be longitudinal 1/200 and lateral 1/500.

(4) Drawing of channel structures

For manufacturing the model, the necessary items are various dimensions of land-erosion control dam, groundsel, bed girdle, diversion weir, groyne, revetment, bridge, etc. Extra drawings should be prepared for the structures which are not described in ground planes, longitudinal and cross-sectional profiles. These structures' dimensions can be checked by the ledger or register, however, structures or facilities constructed many years ago may not be described in the ledger, in such a case, field investigation should be done by walking in the river channel. In order to check if the structures are safe or not for the local scour around the structures by model test or for deciding the design level of river bed, it is necessary to check the basic level of the revetment or bridge previously, also, boring survey may be necessary in the case of no description in the ledger about the structures.

(5) In case rock is exposed on the river bed or rock is estimated to be exposed at rather shallow layer on the bed, it is necessary to make the combined description of the estimated rock line on the ground in the longitudinal or cross-sectional profiles.

Without estimation of the average accumulated thickness of gravel in the objective section (interval), the river bed which would not be scoured at the actual river will be scoured in model experiment, thereby, the experimental result will not be useful.

2.2 Necessary data for model experiment

Phenomena in model experiment will be changed by the given experimental conditions (flow, testing time, sediment discharge, testing materials).

Then, these items should be carefully considered. Especially, sediment discharge is uncertain and may greatly affect the test result, therefore, it is important to decide the sediment discharge by observing the progressing degree of land-erosion control work at upstream and yearly deformation of river bed.

As mentioned above, the verifying experiment needs the flow (discharge) of actual result, water level (mark of the water level), deformation of river bed, change of channel, aerial photos before and after disaster, as data, etc., in order to review the similarity and reproducibility, also, it is convenient to prepare the data on yearly deformation of channel or river bed as well as the actual result of survey in the past in performing the test in the present state.

(1) Data on discharge

Design sectional of river channel is decided by the design peak discharge, while in the river of steep slope where the channel works are constructed disaster occurs (Photo 22) numerously at the revertment by the cause of meandering flow which occurs once in a few years because of many changes of flow (discharge) in the steep river. Accordingly, safe channel work should be planned for the design high water discharge or less discharge than it.

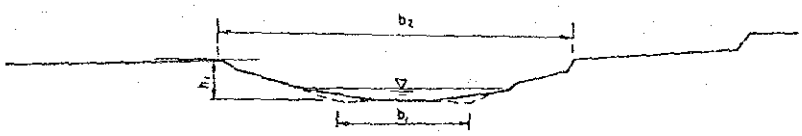


Fig.2 Cross-sectional shape of present river channel

At the model experiment satisfying these conditions, steady flow test is done by flowing the discharge which has high frequency of occurrence of peak flow, and unsteady flow test is performed for the objects of the actually occurred flood waveprofile discharge or the design flood waveprofile discharge, thus these hydrologic data are needed. At the model test of junction treatment, the additional surveying data on freshet time difference will be necessary.

When there are not enough available data for reviewing the discharge with higher frequency, cross-sectional shape of river bed many become the data for judgment, and its sometimes shows compound cross section as showed in Figure 2. Accordingly, the flow (discharge) at the forming time of the low-water channel can be estimated by giving the average slope I of river-bed between the sections and Manning coefficient of roughness "n" by checking the water depth "hl" and the channel width of natural river channel "bl, b2" with cross-sectional profile. Thus it is possible to obtain the reviewing data on the shape of compound section or shape of bed girdle in the planning the channel works.

(2) Sediment discharge at the end of upstream (erosion-control dam) of channel work

Supplying sand amount affects the state of deformation of river bed with the continuous time of flood and the flow (discharge), thus it is necessary to check the sediment discharge at the erosion-control dam at the end of the highest upstream of channel work. (In the planning of channel works, as a rule, in order to induce flowing water to the channel-work, erosion-control dam or big groundsel is constructed at the end of upstream, thereafter, channel work is started.)

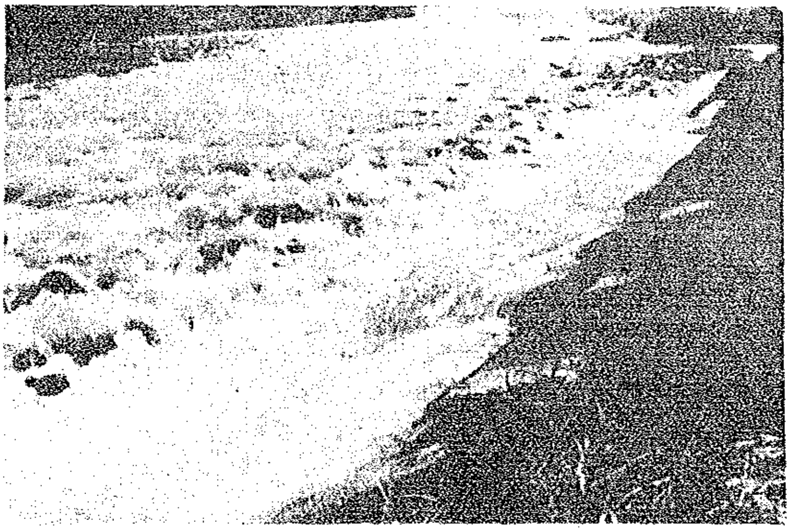


Photo 22: Upset state of revetment by local scour because of the concentrated flowing water along the revetment by the formed single-line.

The sediment discharge at the erosion-control dam is expressed as sum of the traction load discharge suspension load discharge and, but generally, traction load discharge is considered to affect the planning of the channel works. Even in the model experiment, review is made for design dimensions with the object of traction-sand load discharge. The minimum value of the sediment flowing at the erosion-control dam is observed when the dam is not full, and the maximum value is obtained at the state when the slope of sediment of the dam reached the dynamic equilibrium except the abnormal inflow of sediment as in the mud-flow. It is necessary to set the design inflow amount of sediment based on the data by observation of sediment in the actual river, but there are less data of actual survey practically. Thus in the model experiment, model is put up into upstream for the model of channel to cause the fully similar flow at the interval section for observing and measuring the phenomena, thereby the slope of deposited sand at the dam is changed by the experimental purpose, and the amount of sediment to maintain the set slope of sediment is supplied from the end of upstream of the model.

(3) River-bed composing materials and sand-supplying materials

In model experiment, for river-bed-composing materials and sand-supplying materials the grain-size accumulation curve representing the actual river based on the surveyed data are selected, and it is used for the mixed sand simulated geographically. Except the special case that the grain size of the sediment flowing into the channel work is remarakably different from the grain size of river-bed composing materials in the planning section, and also that, a lot of sediment flows into the channel works, thereby, it is judged to influence greatly on the deformation of river bed in the channel work, the same mixing sand is used as with that for composing the material of river bed in model experiment.

(4) Continuous time (period of flood)

The continuous time of flood as well as the discharge and the amount of supplied sediment is releated to the deformation of river bed, thus the actually measured data should be arranged, but if the data are not sufficient, it is necessary to prepare "hydrograph" by statistic processing of rainfall-observed data by the use of the method, e.g. storage function method. The experimental time of constant (steady) flow to flow the discharge having high frequency of occurrence or the peak discharge for a definite time can be decided from a time can be decided from the time for which a tendency of deformation of river bed or meandering state of flowing water becomes constant by the observation of flowing state. While unsteady flow test needs the design hydrograph of the actual river because of the fact that the reduced time by the use of Froude's similarity based on the hydrograph of actual river becomes the experimental time. Model test on junction treatment needs the additional surveying data on freshet-time difference with a branch.

CHAPTER 3 Low of similarity

3.1 Froude's similarity

By solving the basic equation governing the phenomena, model test is intended to know the field phenomena, therefore, review should be made if the basic equation controlling the field phenomena would be the same as that of the model. Moreover, the constant conditions are necessary for the scale-reduction of various physical mass (amount) for the fact that the basic equation on the model corresponding to that of the local state has the same value, and it can be obtained by the basic equation.

The basic equation of unsteady flow governing the flow of model and the actual river is regarded as primary dimensional one, and it is re-written by the use of the Manning coefficient of roughness instead of Cezy's coefficient, and of hydraulic mean depth insteat of water depth, then, the following equation is obtained.

$$\frac{1}{g}\frac{\partial V_P}{\partial t_P} + \frac{\partial h_P}{\partial x_P} - i_P + \frac{\partial}{\partial x_P}\left(\frac{V_P^2}{2g}\right) + \frac{n_P^2 \cdot V_P^2}{h_P^{4/3}} = 0 \quad \cdots\cdots(4)$$

Where, v: Average flow rate, t: time, x: Flow distance, h: Water depth, g: Acceleration of gravity, n: Manning coefficient of roughness, i: River-bed slope.

Even on the model, similar equation can be established.

$$\frac{1}{g}\frac{\partial v_m}{\partial t_m} + \frac{\partial h_m}{\partial x_m} - i_m + \frac{\partial}{\partial x_m}\left(\frac{v_m^2}{2g}\right) + \frac{n_m \cdot v_m^2}{h_m^{4/3}} = 0 \quad \cdots\cdots(5)$$

Where, P: prototype (field), m: Model

For the similarity of the local flow with the model flow, the mutual ratios of each term corresponding between (1)-formula and (2)-formula should be constant. That is.

$$\frac{\frac{1}{g}\frac{\partial v_P}{\partial t_P}}{\frac{1}{g}\frac{\partial v_m}{\partial t_m}} = \frac{\frac{\partial h_P}{\partial x_P}}{\frac{\partial h_m}{\partial x_m}} = \frac{-i_P}{-i_m} = \frac{\frac{\partial}{\partial x_P}\left(\frac{v_P^2}{2g}\right)}{\frac{\partial}{\partial x_m}\left(\frac{v_m^2}{2g}\right)} = \frac{\frac{n_P^2 \; v_P^2}{h_P^{4/3}}}{\frac{n_m^2 \cdot v_m^2}{h_m^{4/3}}} = \text{Const} \quad \cdots\cdots(6)$$

here

$$\frac{v_P}{v_m} = V, \quad \frac{t_P}{t_m} = t, \quad \frac{h_P}{h_m} = h, \quad \frac{x_P}{x_m} = x, \quad \frac{n_P}{n_m} = n, \quad \frac{-i_P}{-i_m} = i$$

then, (4)-formula can be changed into

$$\frac{V}{t} = \frac{h}{x} = i = \frac{V^2}{x} = \frac{n^2 \cdot V^2}{h^{4/3}} = \text{Const} \quad \cdots\cdots (7)$$

thus, by multiplying x/h to each side, the following equation is obtained.

$$\frac{V \cdot x}{t \cdot h} = 1 = \frac{i \cdot x}{h} = \frac{V^2}{h} = \frac{n^2 \cdot V^2 \cdot x}{h^{7/3}} = \text{Const} \quad \cdots\cdots (8)$$

Now, by giving the horizontal reduced scale "x" and vertical reduced scale "h" in (6)-equation, the reduced scale of flow rate can be obtained by the 2nd and 4th terms, as follows:

$$V = \sqrt{h} \quad \cdots\cdots (9)$$

The reduced scale of time can be obtained by 1st and 2nd terms as follows:

$$t = \frac{V \cdot x}{h} = \frac{x}{\sqrt{h}} \quad \cdots\cdots (10)$$

The reduced scale of energy-gradient can be obtained by 2nd and 3rd terms, as follows:

$$i = \frac{h}{x} \quad \cdots\cdots (11)$$

The reduced scale of roughness coefficient can be obtained by the 2nd and 5th terms, as follows:

$$n = \frac{\sqrt{h^{7/3}}}{V \sqrt{x}} = \sqrt{\frac{h^{4/3}}{x}} \quad \cdots\cdots (12)$$

The reduced scale of sectional area and flow (discharge) can be obtained respectively as follows:

$$\left.\begin{aligned} A &= x \cdot h \\ Q &= V \cdot A = x\,h^{\frac{3}{2}} \end{aligned}\right\} \quad \cdots\cdots (13)$$

When the horizontal and vertical reduced scales are the same, x=h, and the reduced scale on each physical amount with the reduced scale of length 1/70 is as shown in Table 1.

Table 1 Reduced rate of various basic dimesions by Froude's similarity

Dimension (Measurement)		Dimension	Reduced rate	
			Ratio	Reduced scale
Geometric measurements	Horizontal (X)	L	Xr	1 : 70
	Vertical (h) (water depth, altitude)	L	hr	1 : 70
	Gradient (h/x)	—	$hr \cdot Xr^{-1}$	1 : 1
	Area (A)	L^2	$hr \cdot Xr$	1 : 4.900
	Volume (Vm)	L^3	$hr \cdot Xr^2$	1 : 343.000
Measurements on flowing water:	Froude's number (Fr)	—	1	1
	Flow rate (V)	LT^{-1}	$hr^{1/2}$	1 : 8.3666
	Discharge (Q)	L^3T^{-1}	$Xr \cdot hr^{3/2}$	1 : 40.996
	Time (T)	T	$Xr \cdot hr^{-1/2}$	1 : 8.3666
	Pressure strength (P)	FL^{-2}	hr	1 : 70
	Coefficient of roughness (n)	$L^{-1/3}T$	$hr^{2/3} \cdot Xr^{-1/2}$	1 : 2.03009
	Discharge coefficient (c)	—	1	1
	Tractive force (Z)	FL^{-2}	hr	1 : 70
	Energy (E)	FL	hr^4	1 : 24.010.000
	Momentum (mv)	FT	$hr^{7/2}$	1 : 2.869.790

3.2 Similarity of deformation of river-bet

Next, review is made on the similarity of deformation of riber bed.

This similarity is based on the kinetic equation and the continuous equation of sediment. Kinetic equation of sediment has not been established yet, but following relation is known to be almost established as sediment discharge formula.

$$\phi = f_B (\tau_{*e} , S_{ec}) \qquad \cdots\cdots (14)$$

here, $\phi = q_B / \sqrt{(\sigma/\rho - 1) g d^3}$, $\tau_{*e} = U_{*e}^2 / (\frac{\sigma}{\rho} - 1) gd$,

e: Effective factor

S_c: Non-dimensional expression of limited tractive force in consideration of effect as steep slope

Thus, the ratios of various values on the model against the trototype can be expressed with the suffix of "r", as follows:

$$\phi_r = \tau_{*er} = S_{*cr} \qquad (15)$$

With the similarity of river-bed shape, $\tau_{*er} = \tau_{*r}$ is considered, thus the formula-(15) becomes as follows:

$$\frac{q_{Br}}{d_r^{3/2}} = \frac{U_{*r}^2}{d_r} = S_{*cr} \qquad (16)$$

On the other hand on the fix bed with the spread sand of representative grain size "d", friction-factor "f" can be expressed as follows, as a result of dimensional analysis.

$$f = \varphi\left(\frac{U_{*d}}{\gamma},\ \frac{U_*^2}{gd},\ \frac{d}{h}\right) \qquad (17)$$

here, γ: Kinematica viscosity

U_*: Friction velocity

In the complete turbulent flow of steep slope, U_*d/γ is not the rulling element, thus the following equation is established.

$$\frac{U_{*r}^2}{d_r} = \frac{d_r}{h_r} = 1 \qquad (18)$$

Thereby, when satisfying the geometric similarity, the 2nd term of (16)-equation becomes "1" from (18)-formula.

$$q_{Br} = d_r^{\frac{3}{2}} \qquad (19)$$

On the other hand, S_{*c} is on the mild slope, and the following equation is obtained.

$$S_{*c} = \frac{U_{*c}^2}{(\sigma/\rho - 1)gd} = f_o\left(\frac{U_{*cd}}{\gamma}\right) \qquad (20)$$

With the bigger Reynolds number on the sand grain, the above S_{*c} shows a constant value, but by the experiment by ASHIDA et al., the following equation is obtained.

$$S_{**} = \frac{U_{*c}^2}{(\sigma/\rho - 1)\, g d} \cdot \frac{1}{(\tan\varphi \cos\Theta - \frac{\frac{\sigma}{\rho}}{\frac{\sigma}{\rho} - 1} \sin\Theta)} = 0.034 \times 10^{0.32(d/h)} \quad \text{...... (21)}$$

Even in such a case, by considering the satisfying case for geometric similarity condition without distortion, $S_{scr}=1$ is clarified, thereby, the formula-(16) can be satisfied.

Moreover, the continuous formula of sediment is as follows:

$$\frac{\partial z}{\partial t} + \frac{1}{(1-\lambda)} \frac{\partial q_B}{\partial x} = 0 \quad \text{...... (22)}$$

Then, the similarity condition is as follows:

$$\frac{z_r}{t_r} = \frac{1}{(1-\lambda)_r} \cdot \frac{q_{B r}}{x_r} \quad \text{...... (23)}$$

$$z_r = h_r = \frac{1}{(1-\lambda)_r} \frac{t_r}{x_r} q_{B r} = \frac{1}{(1-\lambda)_r} \cdot \frac{1}{U_r} \cdot d_r^{\frac{3}{2}}$$

$$= \frac{1}{(1-\lambda)_r} \frac{1}{h_r^{1/2}} d_r^{\frac{3}{2}}$$

$$\therefore h_r^{\frac{3}{2}} = \frac{1}{(1-\lambda)_r} \cdot d_r^{\frac{3}{2}} \quad \text{...... (24)}$$

Accordingly, by the use of geometrically similar river bed material, (24)-formula is naturally satisfied.

As in the above, in considering the similarity on the deformation of river bed and flowing water, the model test on the phenomena given the major influence by the traction load was clarified to give the satisfying results by the experiment in giving the sediment discharge and the flow (discharge) based on Froude's similarity.

3.3 Reproducibility by model experiment

In application of the result of model experiment for actual river, it is necessary to clarify the reliability of test result.

Bed of erosion-control river is steeply sloped, and grain size of the material on river bed is big, thus test is made by the use of geometric similarity and that of Froude's similarity, however, in this text, a concrete example is given on the hydraulic model test of the channel work in DAIYA River as to the similarity in view of the test in the use of Froude's Similarity.

In DAIYA River, before and after the freshet by No.26 Typhoon in September 1966, aerial photos were taken May 1965 in November 1966 and, while survey was done on the deformation of river bed in June 1965 and Cecember 1966. Also, investigation was done on the flood mark in March 1967, and rainfall was observed at the time of freshet by Typhoon No. 26. Figure 3 shows the change of river bed by No. 26 Typhoon based on the shape of river bed of the surveyed section by the survey in June 1965, as compared with the change of river bed of test value given the waveprofile of the actual result in the flood of No.26 Typhoon. In the model test, it is unreasonable to simulate the strength of the alternating bar which is difficult to move by fixation or erosion of a bank by meandering of flowing water, and also, review is not enough on the similarity of the sediment, therefore, it is impossible to simulate the cross-sectional change of river bed completely, however, with regard to the position of scoring or the height of alternating bar, etc., the value of the actual river is rather well matched with the test value on model.

In view of the comparative diagram (Figure 4) of the flow-line between test and aerial photo taken in November 1966, it is clear that the meandering state of flowing water or the point of water hammer is nearly matched with that of the actual river. At the actual river and model test, water-hammer part of a bank is eroded or the revetment is damaged, and also, inundation-occurring point is matched with the result of the model test, thus the reproducibility of the model test is very favorable.

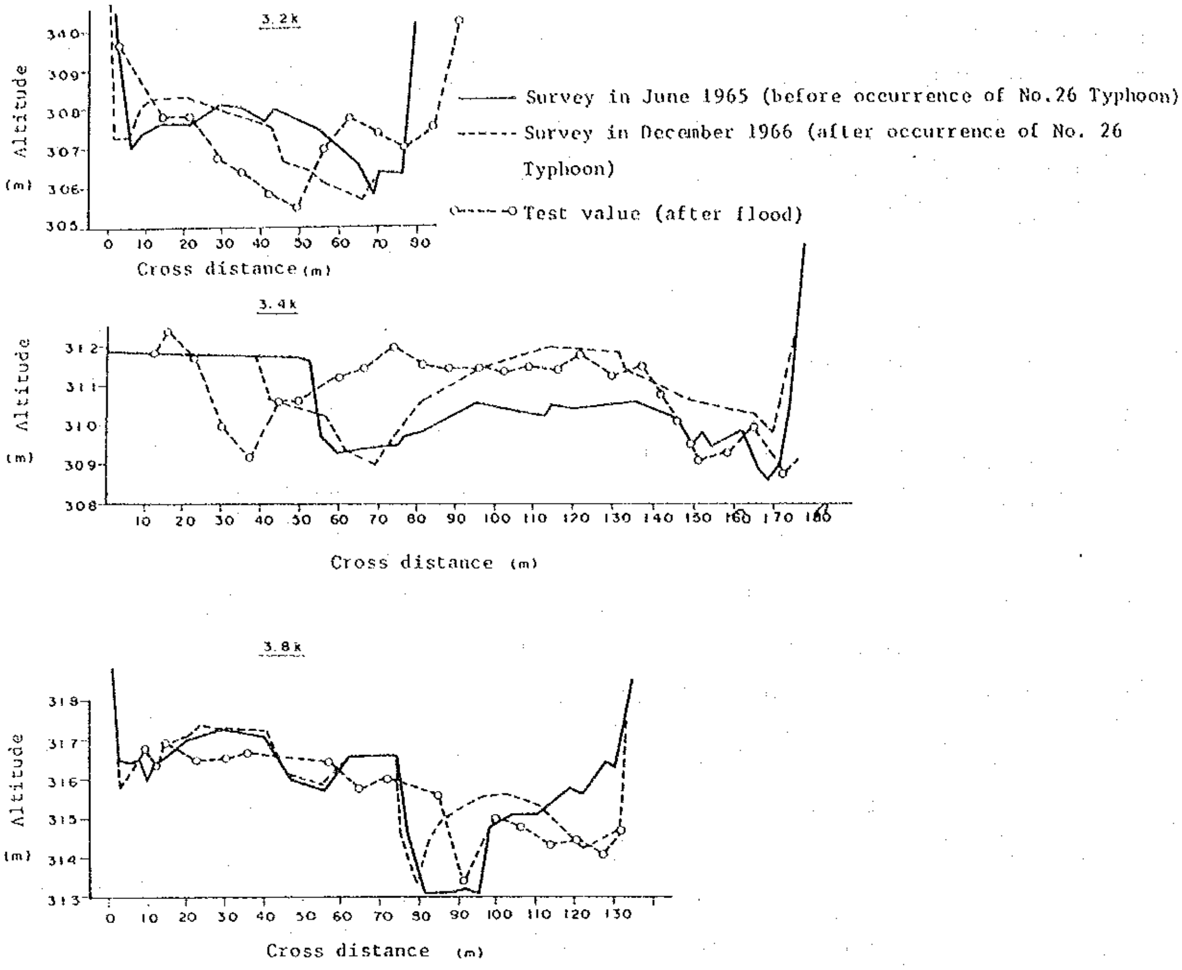


Fig. 3 Review on similarity (cross-sectional change of river bed)

Figure 5 shows the similarity of longitudinal change of average height of river bed between 3.0 - 4.0k. Nearly the same value can be found in comparison of the value after flood with that of model test.

Moreover, comparison was made on the experiment value at the same measuring position with that of flood-mark of the actual river, then, the difference was less than 0.07m in almost points.

At the planning of channel works of DAIYA River, the coefficient of roughness 0.04 was taken, then, the cofficient of roughness was 0.035 - 0.053 as obtained from the result of the model test, and average value was 0.042 which matched the designed value.

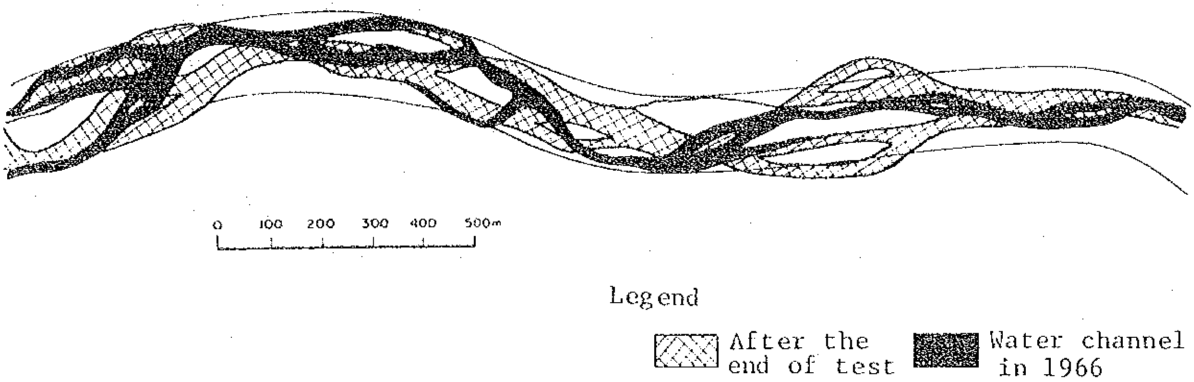


Fig. 4 Review of similarity (comparison of flow-line)

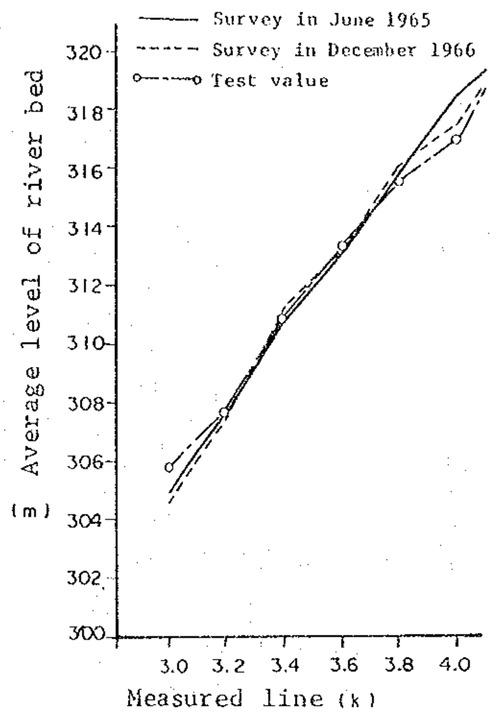


Fig. 5 Review on similarity (comparison on average height of river bed)