SEDIMENT MANAGEMENT AT WATER INTAKES

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INTRODUCTION

Overview

The primary motivation for this study is the need to address the common problem of sediment ingestion with water flow into lateral intakes adjoining alluvial-sediment rivers. This paper is part of a larger study (Barkdoll 1997 and Barkdoll et al. 1997) that examines the flow and ingestion of bed sediment at lateral intakes from loose-bed channels and it evaluates measures for controlling sediment ingestion. The findings of the study apply to lateral intakes in general. However, they are aimed specifically at pump-intake intakes, such as those used for power generation stations. The geometry and outflow conditions of pump-intake intakes make them particularly susceptible to blockage and other problems caused by excessive sediment deposition.

The fact that water often conveys sediment flowing in an alluvial channel is often overlooked by the designers of intakes, especially pump-intake intakes. Consequently, partial or full blockage of intake entrances is not uncommon. In the case of power-generation stations using river water for cooling purposes, sediment blockage can mean an expensive plant derating or, in an extreme situation, plant shut-down to remove (i.e., dredge) sediment from the intake structure. In addition to bearing the cost of clearing the intake of sediment, the electric utility owning the plant may have to purchase power from an outside source. Even without blockage, sediment ingestion and deposition within water intakes may cause accelerated wear of pump impellers and traveling screens and may aggravate biofouling of condenser tubes. Sediment deposited in the intake can also alter the flow patterns within the intake, thereby further skewing velocity distributions and exacerbating resultant pump vibration problems.

Methods of diverting water from a river are numerous and varied. Regardless of the purpose for water (e.g., irrigation, water supply, hydropower, and cooling purposes), interruption of flow will change the river regime locally. It is often the case that the proportion of the total river sediment load removed is greater than the proportion of total river water abstracted (Lindner 1953).

This paper describes the following principal results: 1) establishment of criteria for successful sediment management at lateral intakes; 2) identification of promising new sediment management schemes; and 3) determination of the limiting flow conditions under which submerged vanes, a relatively inexpensive sediment control measure, are effective for preventing sediment ingestion into lateral intakes.

Sediment-Control Measures

Many measures have been developed for controlling (i.e., primarily excluding) sediment entry into intakes. Among them are de-silting sluices and settling basins to remove bed particles at the entrance to intakes. The measures usually are elaborate in design, involving curved channel sediment excluders, vortex tube sediment extractors, side-sluice sediment excluders, tunnel excluders, and approach-flow control (Avery 1989; Cherian et al. 1995). Commensu- rate with their elaborate design are their large size and cost.

Submerged vanes are a promising, partially proven, technique recently developed for sediment control. They are small-aspect ratio plates or foils skewed with respect to the mean flow direction and placed partially buried in the alluvial bed they are intended to modify. Although vanes have been used to control sediment ingestion by intakes (Nakato 1984; Nakato and Nixon 1989; Nakato and Kennedy 1990; Nakato and Einhellig 1989; Ogden and Nakato 1993; Nakato 1992; and Wang et al. 1996), the exact dynamics of their performance and the limits of their use at intakes have not been determined heretofore.

Objectives

This study set out to gain diagnostic understanding of flow and sediment transport at lateral intakes with a view towards identifying relatively inexpensive measures for keeping sediment out of pump-intakes and intakes. The approach taken towards this overall objective entailed several tasks: 1) determination of the dominant features of the three-dimensional flow field at flat-bed intakes, including investigating the effects of flow conditions on these patterns; 2) study of loose-bed intake flow; 3) evaluation of sediment-control measures based on knowledge of the flow field and sediment movement patterns; 4) investigation of rate of sediment ingestion into a lateral intake; 5) development of the promising sediment-control methods screened in step three; 6) comparison of experimental results to field observations; and 7) modification and application of the theory of Wang and Odgaard (1991) to intake flow.

Steps 4 through 6 are described in this paper. See Barkdoll (1997) for details on the other steps.

This study addresses flow and sediment transport at lateral intakes oriented 90° to the main channel. It considers only non-cohesive, uniform bed sediment. Values of the channel width aspect ratio (intake width / main channel width) and flow depth to channel width ratio were kept constant.

EXPERIMENTAL SETUP

Equipment

The experiments were conducted using a recirculating sediment flume, fitted with a lateral intake channel. The flow rates in the main channel and intake channel were regulated using separate pumps. The flows in each channel were measured by means of orifice meters.

The flume channel, which replicated a main channel, is 24 meters long and 1.524 meters wide. The intake channel, the centerline of which was located 15.5 meters from the main channel inlet, was 1.22 meters for flat-bed experiments and 2.44 meters long for all other experiments. The intake width was 0.61 meters. The main channel flow was provided by a 42-horsepower pump connected to a 0.356-m inside-diameter pipe, while the intake flow was pumped using a 3-horsepower pump with 76-mm inside-diameter pipe for fixed-bed flows and a 15-horsepower pump and 152-mm inside diameter pipe for loose-bed flows. Flow was dampened at the main channel inlet by vertical wooden slats and/or a perforated plate. A rubber flap was used to smoothen out free-surface fluctuations.

A precision traverse was mounted on rails that ran along the sides of the main channel. The traverse supported all measuring instruments. A float valve maintained a constant flow depth, and a surge chamber reduced the effects of water hammer caused by float valve operation.

Procedure

Sediment Control. These experiments were conducted in three phases: 1) baseline experiments; 2) screening experiments; and 3) development experiments.

In accordance with the study's diagnostic approach to effective sediment control, the loose-bed experiments were conducted to ascertain the principal causes of sediment ingestion into lateral intakes. The experiments were conducted to determine also how intake blockage by sediment varied with intake flow rate. The main channel flow was kept constant at 0.104 m^3/s for all the phases. The sediment used had a mean diameter of 0.9 mm with a geometric standard deviation of 1.1 and is classified as a coarse sand. This sand was large enough so that the sediment remained as bed load and was small enough to move along the bed at reasonable main channel discharge rates. The mean velocity in the main channel was 1.55 times that for incipient sediment movement, or $U/U_{cr} = 1.55$. The baseline experiments were of loose-bed lateral intake flow with no sediment-control methods. The mean sediment bed level was kept constant at an elevation equal to that of the intake floor. Increasing the bed level would increase sediment ingestion and, conversely, decreasing the bed level would decrease sediment ingestion.

The baseline experiments revealed that a maximum ratio of ingestion rate, g_r, occurred for the intake set-up. The screening experiments were conducted at this condition to ascertain the effectiveness of sediment-control measures. Prior to and during the screening experiments, criteria (presented later) were established for judging acceptable performance of the sediment-control measures investigated. Selected promising control measures were then further developed to identify their most effective configuration.

The sediment transport rate through the intake and the volume of the intake occupied by sediment were measured. To measure the intake sediment transport rate, a sediment-collection strainer was positioned below the intake outlet pipe. The strainer had mesh with holes smaller than the sediment grain size to enable water to pass through to the outlet of the main channel, where it was recirculated as normal. Sediment was collected for a 2-hour period and removed from the strainer and weighed; a 2-hour period corresponded to about the time required for one dune to pass the intake face. The method of weighing was as follows: water in a container was weighed devoid of sediment. The sediment from the strainer was placed in the water and then weighed again. The difference in the two measurements was taken as the weight of the sediment. The transport rate was then calculated as the weight of sediment divided by the time period of sample collection.

Flow patterns generated by the sediment-control measures investigated were observed using neutrally-buoyant dye injected at various locations by means of a dye wand. The patterns helped in identifying sediment-control concepts.

Screening Experiments. The screening experiments were performed under the same main channel flow and sediment conditions used in the baseline experiments. Their purpose was to examine the efficacies of six alternative methods for controlling sediment ingestion into lateral intakes: 1) submerged vanes; 2) skimming wall; 3) intake shuttering; 4) sediment-deflection wall; 5) scouring jet; and 6) scouring piers.

Prior knowledge (Odgaard and Wang 1991) had suggested that one measure, submerged vanes, was especially promising. Vanes, set at a low angle of attack, have been used for controlling channel bathymetry of river bends and, in a more ad-hoc manner, for reducing sediment ingestion into pump intakes. The limit of their effective performance for this latter application has yet to be determined, however.

Development Experiments. Sediment-control measures that showed promising performance during the screening experiments were subjected to further experiments to determine their most effective arrangement that best met the performance criteria presented subsequently.

Submerged vanes and a skimming wall were identified from the screening experiments mentioned above as inexpensive measures worth optimization. Vanes and walls were placed in several configurations. The experimental procedure was identical to that of the baseline and screening experiments. The development experiments are summarized in Tables 2 and 3.

SUCCESSFUL SEDIMENT-CONTROL PERFORMANCE CRITERIA

Criteria for evaluation of the structures, in descending order of importance, are as follows: 1) Minimum intake sediment transport rate. This is considered to be most important because it gives a direct measure of sediment ingestion into the intake and is of prime concern at plant intakes, for example, in order to minimize intake dredging and plant (power station or water supply) shut-downs. 2) Minimum volume of sediment accumulation in intake. This criterion has implications for the asymmetry of the flow in the intake channel. Flow asymmetry has implications for pump vibrations in intakes. 3) Acceptable localized scour of the bed near the intake. Scour is deemed important due to the fact that sufficient scour below the intake sill elevation reduces sediment ingestion. Heretofore, this has been the only criterion used to determine sediment ingestion; e.g., Wang et al. (1996). This study shows that scour is a necessary, but an insufficient, condition for sediment exclusion from intakes. 4) Acceptable scour downstream of the intake. Excessive scour downstream of the intake can cause collapse of any intake structure or sediment-control devices and should be kept to within acceptable limits. 5) Minimum cost. There are many sediment-control measures that are cost prohibitive. Many of these measures are not included here. The goal of this study is to identify inexpensive measures that effectively reduce sediment ingestion.

Criteria 1 through 4 are based on observations of sediment movement in the intake set-up and from preliminary experiments with sediment-control measures. All of them, except Criterion 5, were used to evaluate the performance of sediment-control measures investigated.

RESULTS

Diagnostic examination of the flow field at lateral intakes from flat-bed and loose-bed channels led to concepts for potentially effective measures for controlling sediment ingestion into lateral intakes. Sediment ingestion into the experimental intake used for the present study is described below first for the baseline tests, carried out without sediment-control measures. The screening experiments involving six sediment-control measures are described next. Two promising control measures, identified during the screening experiments, then, are developed further. The developments of those measures also involved modifications to the intake channel entrance geometry to enhance their performance.

Baseline Experiments

Before pursuing effective measures of controlling sediment ingestion into lateral intakes, baseline experiments were performed in which no control was attempted. Sediment transport rate normalized as that in the intake divided by that in the main channel, g_r, and the fraction of the intake occupied by deposited sediment, Vol_r, were measured for a range of specific discharge ratios (intake/main channel values), q_r (specific discharge is volumetric discharge divided by channel width). A discharge ratio causing a severe condition of sediment ingestion into the intake was identified for use in the screening experiments.

Intake Sediment Transport Rate. Data showing the variation with q_r of the normalized sediment transport rate, g_r, are presented as solid circles in Figure 1. With no intake flow ($q_r = 0$), no sediment moved through the intake, though some entered and accumulated in it. The finding by Lindner (1953) (i.e., the proportion of sediment withdrawn into the intake is higher than the proportion of water discharge) is confirmed by this result, as can be seen from the rising section of Figure 1. Values of the proportion of water discharge withdrawn into the intake relative to the main channel, Q_r, are equal to the values of q_r shown divided by 2.5, the aspect ratio of intake to main channel width. An unexpected finding of the experiments was the occurrence of a maximum sediment ingestion rate with q_r. As the intake flow increased, the rate of sediment transport into the intake increases until $q_r = 0.9$. Beyond this value, g_r decreased due to a scouring effect of the main channel flow as it turns sharply into the intake. The turned flow comes back upstream in front of the intake and thereby removes sediment from the intake mouth.

Volume of Sediment Blockage. The volume fraction of sediment deposited within the intake entrance exhibited a different behavior. With no intake flow, a small amount of sediment collects near the corner of the intake in the main channel downstream direction. The sediment enters the intake by virtue of flow eddies generated within the intake entrance and by turbulence in the main channel flow. As q_r increased, more sediment collected, attaining a maximum at q_r approximately equal to 0.4, after which the volume of blockage decreased. With low intake flow, there is insufficient momentum to convect the sediment through the intake, and with high intake flow, cleansing takes place to prevent sediment from entering.

Screening of Sediment-Control Measures

The screening experiments were conducted at the value of q_r (0.91) yielding the highest rate of sediment movement into the intake. This experimental condition was chosen because it provided the most rigorous condition for determining the usefulness of a sediment-control measure. It can be assumed that, if a management scheme was effective at the value of q_r that allows the highest intake sediment transport, then it would be effective at all practical values of q_r.

The two most suitable sediment management schemes were then tested further to find their best arrangement, either in isolation, or in conjunction. The same criteria were used as in the screening tests mentioned above. Once suitable arrangements of the schemes were identified, then these schemes were tested for a range of q_r values.

Besides submerged vanes, the sediment-control measures examined in the screening experiments were identified in the literature on sediment problems at intakes. Table 1 gives the name of the structure, the corresponding concepts involved, and the reference citation.

Sediment-Inflow Criteria. The results of the screening experiments are superimposed onto the baseline results for flow intake from a loose-bed channel. It can be seen that the concepts examined reduced the intake sediment transport rate, with vanes, skimming wall, shuttering, and sediment-deflection wall showing the most efficacy. The scouring jet was only slightly effective, while the scouring piers increased sediment ingestion into the intake.

Sediment-Volume Criteria. There was only minor variation in the volume of sediment collected in the intake between the case with no structure and all of the screening tests, because the value of q_r was not a critical one for sediment volume. The intake velocity at this high value or q_r was capable of convecting any sediment that entered the intake.

Features of Flow and the Sediment Movement Observed. There were three overall dominant causes of sediment entering the intake: 1) persistent sediment deposition at the intake entrance; 2) sediment-lifting vortex at the intake face; and 3) non-uniformity of flow distribution along the intake axis.

These features were usually present. It was found difficult to eliminate all three features simultaneously. The effects on these features of the sediment-control measures are now discussed.

Sediment Management Using Submerged Vanes. For flow at an intake guarded by vanes, a scour trench formed upstream of the intake, and initially the general direction of sediment movement was away from the intake. As the flow approached the intake, however, the flow turned and hit the vanes at a higher angle of attack, causing vigorous scouring by the vanes locally. Strong vertical vortices formed that ingested sediment up and into the intake. This vane-induced vortex ingested sediment into the intake. The flow reversing upstream after striking the main channel wall of the intake downstream of the intake, formed another unsteady vortex. The upstream-moving flow interacted with the flow moving downstream a short distance away from the intake to form the vortex. This second vortex also lifted sediment up and into the intake. The two vortices, one vane-induced, and one flow-induced, were the major sediment ingesting mechanisms for vanes at intakes. Note also that, since there were no vanes downstream of the intake, the bed scoured significantly, as in the case with no sediment-control vanes in place.

This observation underscores an important point embodied in performance criteria number 3; i.e., having sediment scoured to below the intake sill elevation is of itself not a sufficient criteria for determining the effectiveness of a sediment-control measure.

Skimming Wall. With a skimming wall skirting the intake, sediment entered the intake in two places. Some sediment came over the wall at a location just downstream of the intake. The sediment then was carried suspended into the intake. In addition, sediment went around the downstream end of the wall and was convected upstream where it collected between the wall and intake. From this location, an unsteady vortex carried the sediment by bursts up and into the intake. Significant scour of the bed occurred between the wall and the intake.

Only one height of skimming wall was tried (one-third the flow depth above the intake floor elevation). Decreasing the height would allow sediment to flow over the wall at lower intake discharges, and, thereby, reduce the effectiveness of the wall in reducing sediment ingestion into the intake.

Increasing the wall height would cause undesirable hydraulics in the intake, possibly leading to hydraulic jump. Hydraulic jump in the intake would exacerbate pump vibration due to the resulting super-critical flow depth being below the pump bell.

Shuttering. Shuttering over the intake face accelerated the intake velocity so as to increase the flow reversal that cleanses the intake, as observed at high values of q_r with no structures. This scheme is very compact and inexpensive. The flow did indeed cleanse the intake to some extent. However, an unsteady vortex formed immediately downstream of the shutter to lift sediment into the intake. Further engineering would be necessary to perfect this promising idea.

Deflection Wall. The sediment-deflection wall moved bed sediment away from the intake. Some sediment over-topped and out-flanked the wall, however, and came back upstream along the inside of the wall to enter the intake. Sediment that over-topped the wall was convected downstream and away from the intake. Scour in front, and downstream of, the intake was significant in this case.

Scouring Jet. The use of a scouring jet to sluice sediment from the intake face proved ineffective. The jet was placed at different locations in an effort to find an optimal location. At many locations, it ingested sediment up and into the intake, worsening sediment ingestion. The location of the jet shown here was the optimal one and did not reduce the sediment ingestion significantly. The jet caused a second vortex to form that lifted the sediment into the intake. The jet velocity was $1.63U_m$. Jet sluicing might be effective in sluicing sediment from an intake when $q_r = 0$, but it is not effective when $q_r > 0$.

Scouring Piers. The use of scouring piers at the intake entrance caused a significant increase in flow turbulence and, therefore, increased sediment ingestion into the intake; the sediment transport rate actually increased over that with no sediment-control measure. In addition, significant scour occurred at the downstream corner of the intake entrance, which would need scour protection.

Discussion of Screening Experiments. The volume of sediment that collects in an intake and the normalized transport rate through the intake, g_r, clearly depend on the amount of sediment that enters the intake from the main channel. Each intake flow has the potential to store and transport a certain volume of the ingested sediment in and through the intake. If that volume is not able to pass through the intake, however, then the amount of sediment that collects in and transports through the intake is less than the potential value. A sediment-control measure may not necessarily alter the flow pattern in the intake so as to increase or decrease the capacity for sediment collection or transport, but limits the amount of sediment supply. This action should be kept in mind when examining the amount of sediment accumulated in the intake entrance and the rate of transport.

Overall, the screening experiments revealed that the skimming wall, vanes, shuttering, and a sediment-deflection wall hold good promise as effective measures for sediment control at intakes, while jets and scouring piers would not. Of the effective measures, vanes and a skimming wall were pursued further, while shuttering and a sediment-deflection wall are left for further research. Vanes and skimming wall have been used effectively before and represent a compact, relatively inexpensive solution. Shuttering and sediment-deflection wall concepts should not be discarded, but would require extensive testing and engineering before being useful for field applications.

Development Experiments

The vanes and skimming wall were selected from the screening experiments as promising sediment-control measures. A series of experiments were performed to develop optimally effective configurations of these measures. The vanes and skimming wall were used separately and in conjunction with each other. These experiments were conducted at the value of q_r that resulted in the most sediment ingestion. Layouts then were tried at a range of q_r values more commonly found at river-intake situations. Finally, ideas were evaluated resulting from the identification of a non-uniform lateral velocity distribution in the intake mouth.

Vane Configuration Experiments. Table 2 gives the configuration name, concept, and figure number of the further experiments conducted to identify optimal layouts of vanes for reducing sediment into lateral intakes.

The results of the development experiments show (diamonds in Figure 1) that most of the vane configurations reduce sediment inflow into the intake, but do not eliminate it entirely. The only exception is the upstream interception measure with vanes set at β=10° (Figure 2). This measure would be quite expensive, however, and it could cause problems for navigation in the river due to the vanes extending far upstream from, and far out into, the river. Sediment blockage was unaffected because the vanes did not alter the flow pattern within the intake.

The downfall of most of the vane configurations examined was the formation of unsteady vortices in front of the intake. The vortices, which were difficult to eliminate, lifted sediment into the intake, thereby not satisfying performance criterion. Even if no vortices formed by the vanes themselves, the vanes could not prevent the vortex caused by flow turning sharply into the intake near the downstream end of the intake.

Vane/Skimming Wall Combination Tests. A skimming wall was added to work in concert with the vanes. The skimming wall was intended to guide bed sediment past the intake. The main concern of using the wall alone, without the vanes, is that it could be overwhelmed by approaching bed forms. The vanes were intended to keep the sediment scoured down on the outside of the wall, thereby preventing over-topping of the wall. In some configurations, gravel was placed between the skimming wall and the intake to more closely simulate the field condition of needing to backfill the wall to provide scour protection at the downstream corner of the intake entrance. Table 3 gives the name and concept of the experiments with vanes and a skimming wall.

The wall and vanes were unable to prevent sediment inflow into the intake, as can be seen in Figure 3. They reduced the amount of sediment transport from approximately 10 to 70%, but were unable to eliminate it. The main flow feature feeding sediment into the intake was an unsteady vortex located at the intake face. It formed in all of the cases and lifted sediment into the intake. Sediment blockage was not greatly affected.

Discussion of Vane Configurations. Of all of the measures screened, the most promising sediment-control management measure investigated is interception of bed sediment far upstream and gradually leading it away from the intake. However, this measure is possibly expensive and may be overly intrusive into a river channel; this poses a problem, especially for navigable channels. Experiments were conducted to minimize the extent of vanes needed for this measure.

It was assumed that the vanes work well at about 20° and that they can only pass the sediment at an angle of half of their angle of attack. This configuration worked well, passing the sediment from one vane to the next and leading it away from the intake until a point past the dividing stream-plane of the intake. The expense of this configuration arises due to the large number of vanes required. A reduction of the number of vanes required by increasing β to 20° and 40° proved ineffective, even though the angle of attack was increased to the supposed optimal angle of 40° as shown in tests with a single vane. Placing the vanes at a higher angle of β was ineffective, because the vanes were less effective in passing sediment at the increased angle.

Most of the configurations examined reduced sediment ingestion by about 40 to 60%, but none could eliminate it completely. In all the cases investigated, sediment entered the intake at a location where the flow was directed almost parallel with the intake. With no structure, the sediment was conveyed smoothly into the intake along flow lines. If the flow lines were interrupted (e.g., by scouring below the intake sill), then an unsteady vertical vortex formed that lifted sediment into the intake. If the vortex strength was reduced, then the sediment bed rose until the distance to lift the sediment was small enough to allow vortex lifting. The flow and sediment were each composers of the other's behavior, adjusting each other until both flow and sediment entered the intake.

<u>**Experiments at Lower Specific Discharge Ratios**</u>

Because none of the more cost-efficient and compact schemes eliminated sediment ingestion at the worst value of specific discharge (q_r = 0.91), two of the more practical measures were identified and tested to ascertain the limiting value of q_r beyond which they would cease to perform as required. These rates may be more typical of those found in practice, especially at times of maximum sediment movement in the river. High sediment movement corresponds to high main channel discharge and velocity. This would lower the specific discharge ratio.

The ensuing two measures were selected: 1) two and three rows of vanes; and 2) two rows of vanes and a skimming wall.

There was little difference in their performance between two and three rows of vanes, but adding a skimming wall (Figure 3) improved performance by guiding sediment past the intake and by raising the elevation required for sediment over-topping. When sediment did not over-top the skimming wall, no sediment entered the intake. At a specific discharge ratio of about 0.33, sediment over-topped the wall. A dramatic increase occurred at a specific discharge above that, after which the transport rate leveled off. This sudden increase of transport rate at a flow slightly above that for wall over-topping occurred because sediment poured over the wall for a large portion of the wall. The intake velocity was high enough to transport the sediment through the intake. At higher values of specific discharge, however, instead of a further increase in the intake transport rate, a longitudinal vortex formed along the outside of the skimming wall that kept the wall clear of sediment for a large portion. Similar results were obtained for intake sediment volume fraction. There was little difference between two and three rows of vanes, and the wall eliminated sediment collection until a value of q_r of 0.3, after which the value followed the same trend as for the case of no structure.

<u>**Comparison of Experimental and Field Observations**</u>

The results indicate that, when $q_r > 0.3$, vanes and skimming walls cannot keep sediment out of an intake. It is of interest to determine if applications of the vanes and skimming wall in model studies and field applications were performed at velocity ratios above or below the cut-off value.

Evidently, most of the hydraulic model studies and field applications of vanes and skimming walls have been for values of q_r below 0.3. The exceptions are the intakes for Huntley Power Plant and Raritan River Intake. Follow-up studies to each of the field installations show that the vanes and/or skimming wall are performing well for all cases except Huntley. Insufficient information exists on the performance of vanes at the Raritan River intake. This corroborates the findings of the current study and indicates that the vanes and skimming wall do not work well when $q_r > 0.3$. The Yonggwang model study had velocity ratios above the cut-off, but only preliminary tests were done and no field verification is, therefore, possible.

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Table 1 Sediment Control Measures Examined

Name	Concept	Reference
Submerged Vanes	Vortex directs bed load away from intake.	Wang and Odgaard, 1991
Skimming Wall	Sediment guided past intake; clear water allowed in intake.	Nakato, 1992
Intake Shuttering	Increase intake velocity to cleanse sediment from face.	Present study
Sediment Deflection Wall	Guide sediment away from intake and create sediment-guiding vortex.	Carlson and Enger, 1963
Scouring Jet	Scour sediment from intake face.	Present study
Scouring Piers	Scour sediment level below intake sill.	Present study

Table 2 Summary of Development Vane Experiments.

Configuration	Desired Action
Basic Case	Vane-induced vorticity to direct bed-load away.
Near/Far Field	Far-field vanes to act as resistance elements and cause increased velocity and scour at intake. Near-field vanes to keep local sediment out.
High Angle	To use optimal attack angle found in single vane tests.
Turning with Flow	To have vanes at local attack angle.
Fanning Vanes	Increase attack angle downstream to compensate for reduced longitudinal velocity.
Upstream Interception, $=10^{o}$	Intercept sediment far upstream of intake to lead it past the dividing streamline before reaching intake.
Upstream Interception, $=20^{o}$	Intercept sediment upstream of intake to lead it past the dividing streamline before reaching intake.
Upstream Interception, $=40^{o}$	Intercept sediment just upstream of intake to lead it past the dividing streamline before reaching intake.
Shorter Vanes	Reduce vane length while reducing longitudinal spacing to generate more vortices.
Bottom/Surface Vanes, Uniform	To generate higher vorticity by having a surface vane oriented opposite to the bottom vane.
Bottom/Surface Vanes, Turning	Vanes at local angle as flow turns, to generate higher vorticity with two vanes.
Optimal Angle	Vanes at optimal angle to flow everywhere.
Optimal Angle, Reduce Spacing	Reduce longitudinal spacing to reduce vorticity decay prior to next vane downstream.

Table 3 Vane/Skimming Wall Tests

Configuration	Concept
$w_{wd}/b_m = 0.1$, $\partial_y/d = 0.85$, $\partial_x/d = 2.0$, $N = 3$	Wall guides sediment past intake, vanes keep wall clear of sediment. Three rows of vanes keep a wider area clear.
$w_{wd}/b_m = 0.05$, $\partial_y/d = 0.60$, $\partial_x/d = 2.0$, $N = 2$	Closer wall is more compact, 2 rows of vanes is less expensive and may still be effective. Closer vane spacing increases vortex interaction and reduces space.
$w_{wd}/b_m = 0$, $\partial_y/d = 0.85$, $\partial_x/d = 2.0$, $N = 2$	Wall at intake face is less expensive and more compact.
$w_{wd}/b_m = 0.05$, $\partial_y/d = 0.85$, $\partial_x/d = 2.0$, $N = 2$, with gravel fill, optimal angle vanes	Optimal angle vanes may reduce sediment over-topping the wall. Gravel fill is more realistic for field sites.
$w_{wd}/b_m = 0.05$, no vanes	Test the effectiveness of the vanes by having the wall alone.

∂_x = vane spacing in the main channel longitudinal direction;
∂_y = vane spacing in the main channel lateral direction;
N = number of rows of vanes; and,
w_{wd} = distance between the skimming wall and the main channel wall.

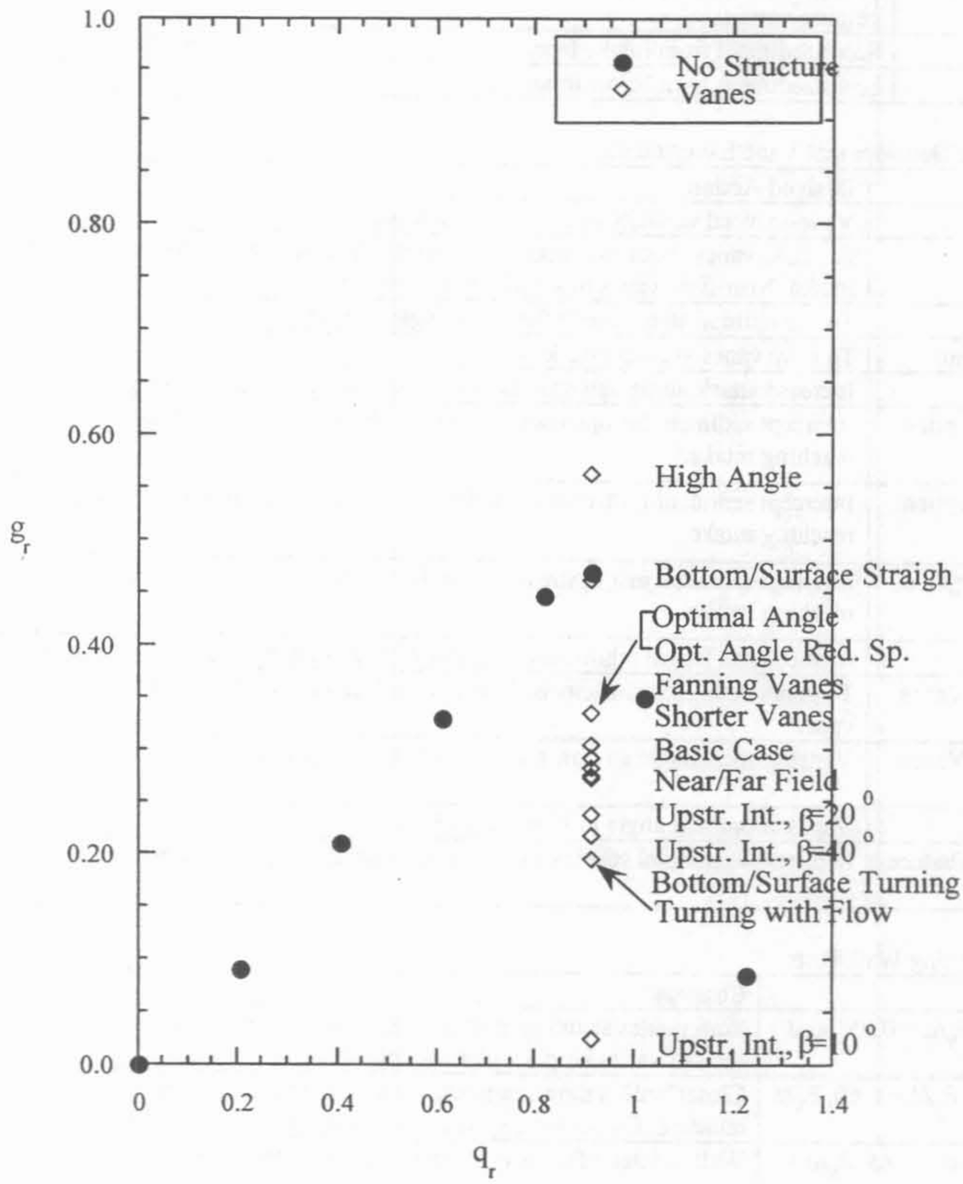

Figure 1. Effect of specific discharge ratio (intake/main channel), q_r, on sediment transport ratio (intake/main channel), g_r, with and without vanes.

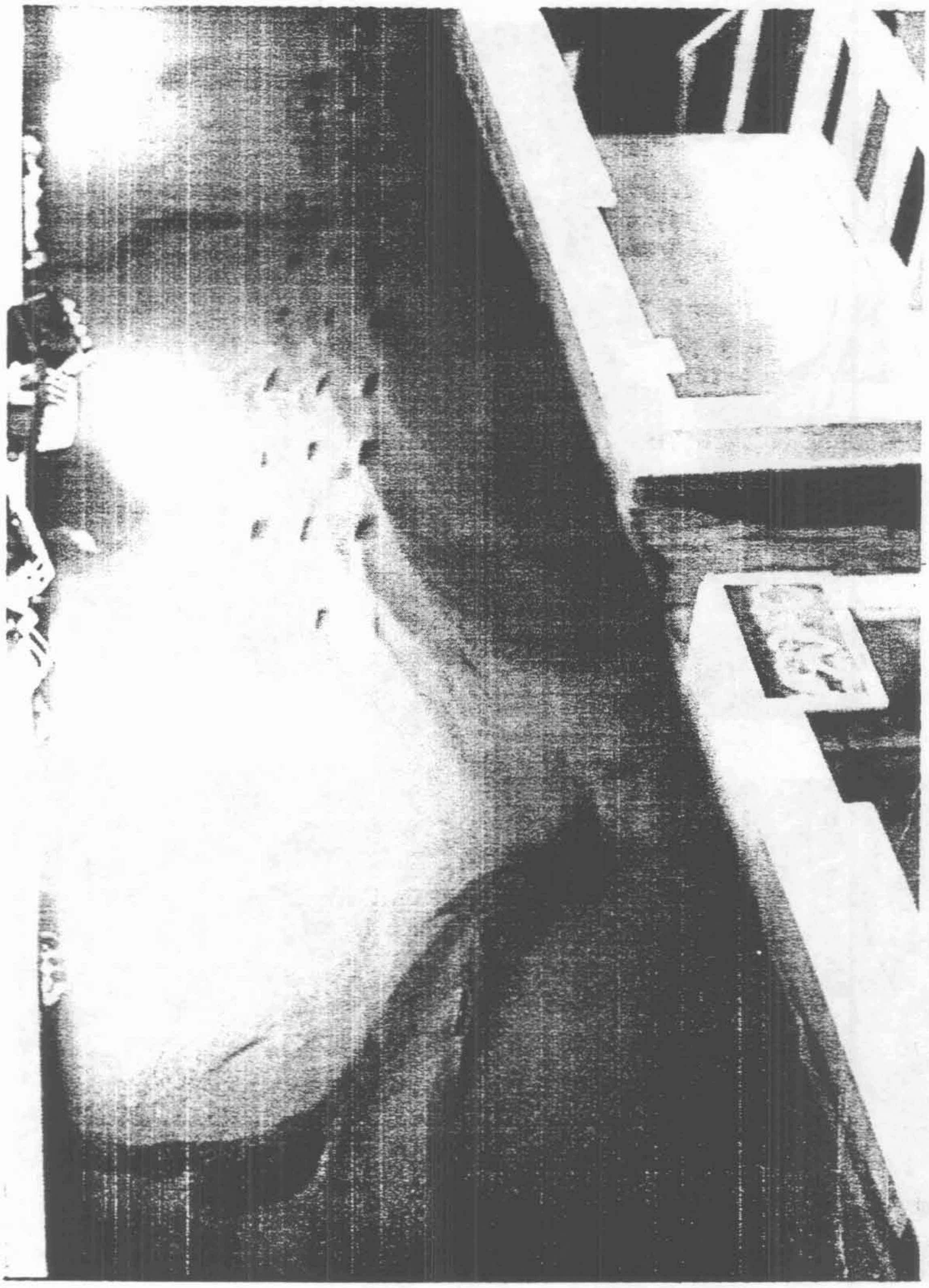

Figure 2. Vanes intercepting sediment upstream and leading it past the intake.

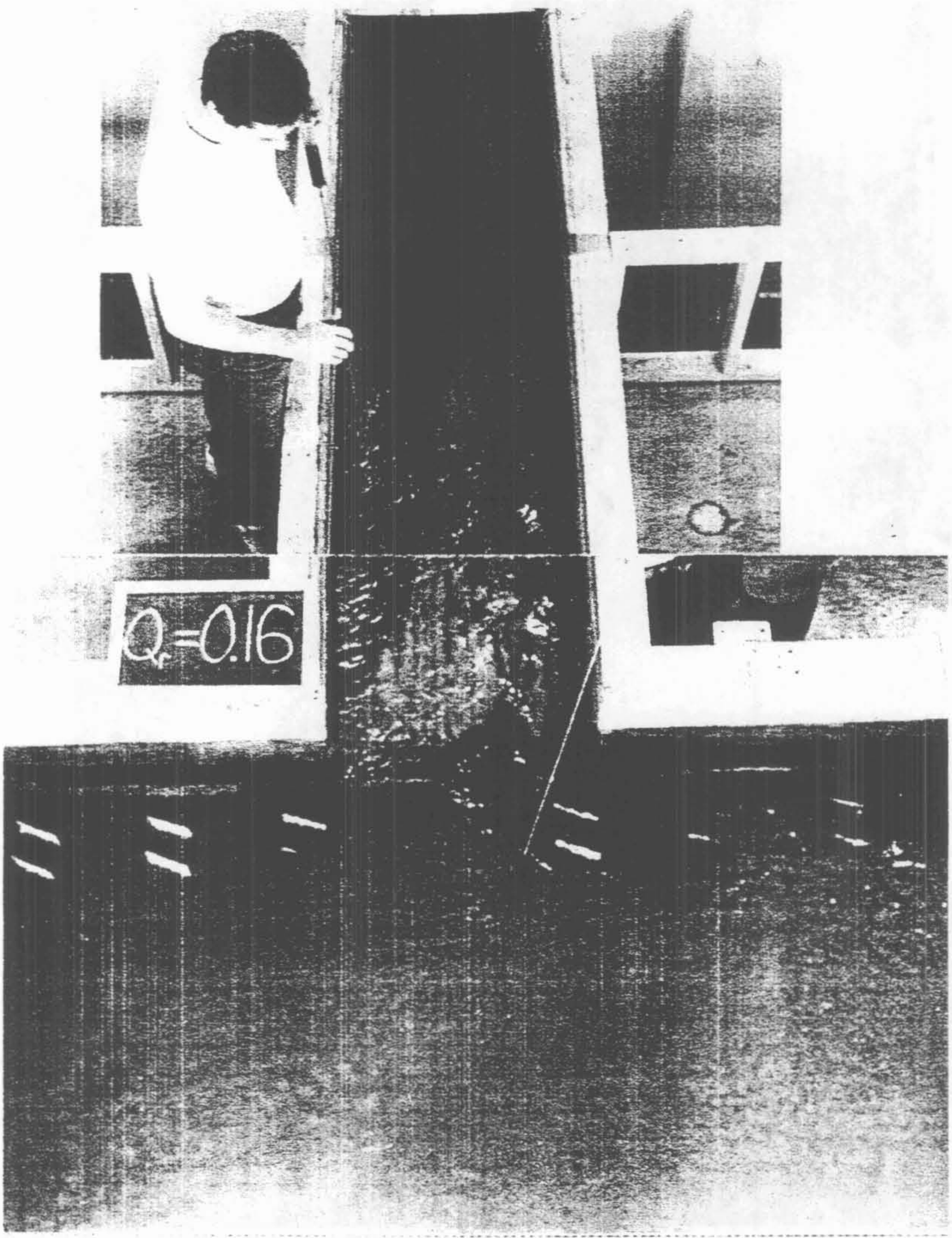

Figure 3. Photograph of vanes and a skimming wall at an intake to exclude sediment.