DEBRIS CONTROL AT HYDRAULIC STRUCTURES IN SELECTED AREAS OF EUROPE

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SUMMARY

This interim report contains a review of methods for managing floating debris that have been tested, and employed, at hydraulic structures in Europe. The information is taken from papers, site observations and discussions with researchers and engineers at three major European hydraulic research centres: Delft Hydraulics, The Netherlands, The Hydraulics Institute of the Technical University of Munich, Germany, and; the Institute of Hydraulics, Hydrology and Glaciology at the Technical University of Zurich, Switzerland.

The interim report is divided into four sections covering different types of structure and the various solutions employed. Chapter one examines run-of-river debris detention and diversion devices. Chapter two discusses debris clogging problems at spillways and assess optimum spillway design with regard to passing debris. Chapter three describes the problem of debris collection at a run-of-river hydro-electric power station due hydraulics and flow phenomena, and examines the solutions tested to alleviate the problem. Chapter four reviews trashrack design criteria, raking equipment and rack vibration problems.

The purpose of the European element of this project, together with an ongoing investigation of debris management at US structures, is the assessment of the major debris management systems that have been employed at hydraulic structures. This will allow the development of a set of well informed best-practice guidelines for floating debris management.

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FIELD TRIP ITINERARY

The information contained within this interim report was collected on a 9 day European research trip, between 11th and 20th October 1995, by Mr N. Wallerstein.

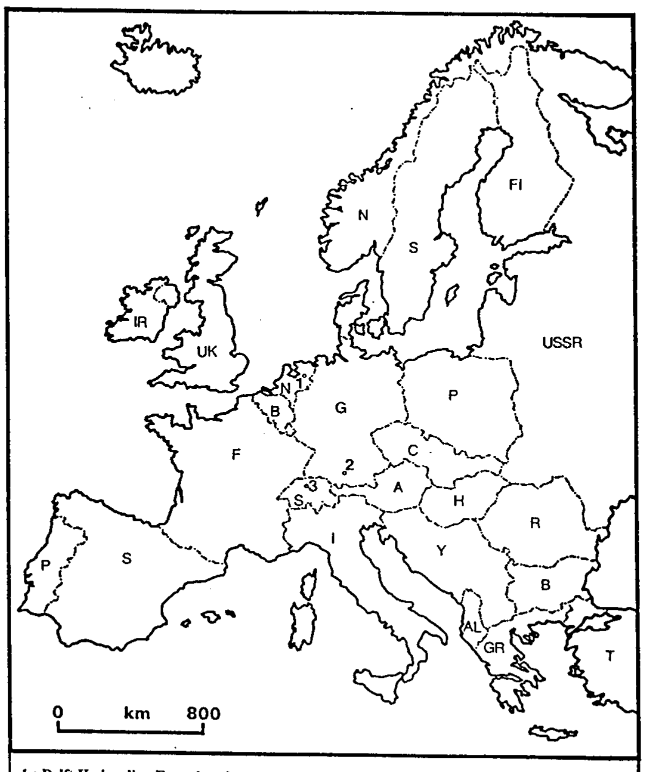
Itinerary:

Thursday 12th October : Delft Hydraulics, The Netherlands : Discussions with Dr J. J. van der Zwaard, Henk Verheij and Herman Barneveld at the Rivers, navigation and structures division.

Monday 16th October : Hydraulics Laboratory of the Technical University of Munich, Obernach, Germany : Discussions with Professor J. Knauss, director.

Wednesday 18th October : Institute of Hydraulics, Hydrology and Glaciology, Technical University of Zurich, Switzerland : Discussions with Dr. A. Chervet.

Location Map :



1 : Delft Hydraulics, Emmeloord
2 : Hydraulics Laboratory, Technical, University of Munich, Obernach
3 : Hydraulics, Hydrology, Glaciology Institute, University of Zurich, Zurich

UK : United Kingdom	IR : Republic of Ireland	N : The Netherlands
B : Belgium	F : France	G : Fed Rep of Germany
S : Switzerland	P : Poland	C : Czech Republic
SP : Spain	P : Portugal	I : Italy
A : Austria	H : Hungary	R : Romania
Y : former Yugoslavia	B : Bulgaria	AL : Albania
GR : Greece	T : Turkey	

1 INTRODUCTION

Floating debris build-up is a continual problem at locks, dams, bridges and water intakes and also causes disruption of many water based activities. for example, operation of a gated spillway can be impaired by debris caught on a gate sill, dam gates can become stuck partly open due to debris intrusion, resulting in severe downstream bed scour, and locks can be partially blocked, disrupting navigation.

In order to develop improved and more cost-effective debris control systems it would be beneficial to have a sound understanding of debris dynamics within the relevant catchment area, upstream of that structure. Basin-wide studies can help engineers to make more informed decisions on debris management and to design better measures for counteracting debris damage and disruption at structures. This is a topic of on-going research at the University of Nottingham (Wallerstein & Thorne 1994, and Wallerstein & Thorne 1995). However, some debris will always arrive at structures and a wide variety of structural and non-structural approaches to dealing with debris are currently employed. Such systems involve considerable capital cost., difficult and expensive maintenance procedures and they may themselves impair the efficient operation of the structure it was designed to protect. Trashracks, for example, at hydro-electric power plant intakes will cause head loss so that bar spacing requirements to prevent debris entry into the turbines must be balanced against the loss of potential energy for power generation.

It is apparent that considerable scope exists for a review of the various debris management systems employed at different hydraulic structures, particularly in European waterways where there are some sophisticated solutions that could be usefully applied within the USA. This interim report, therefore, contains a compilation of findings from a two week field visit to some structures and three major hydraulic research centres in Europe. These were; Delft Hydraulics in the Netherlands, The Hydraulics Laboratory at the Technical University of Munich, Germany and, The Institute of Hydraulics, Hydrology and Glaciology at the Technical University of Zurich, Switzerland. The report is divided into four sections, dealing with debris detention and diversion solutions at run-of-river structures, debris problem and solutions at spillways, debris collection at run-of-river powerplants and a review of dam outlet trashrack design, raking mechanisms and vibration problems. This review along with a forthcoming investigation of debris management at US structures will provide the information necessary for an accurate assessment of all the major debris management systems that have been employed at hydraulic structures enabling the subsequent production of a set of well informed best practice guidelines for every type of structure where floating debris problems are encountered.

1 RUN-OF-RIVER DEBRIS RETENTION AND DIVERSION STRUCTURES

1.1 "Treibholzfange" Debris Detention device.

The following information has been obtained from discussions with Dr J. Knauss at the Institute of Hydraulics, Technical University of Munich, and from a compilation of research papers by Dr Knauss (Knauss, 1985).

Woody debris input into river channels in the Bavarian Alps is mainly due to landsliding on steep slopes during saturated storm conditions. The problem is being exacerbated because many coniferous trees in the region are sick or dying due to air pollution. Another factor is that in the past villages would manage their own particular rivers for water supply, power etc., and kept them largely free of excess sediment and debris. A shift in the social conditions and management practice has resulted in neglect of many of the upland catchments leading to excess debris in the channel and on the adjacent slopes. In the past downed trees were also utilised for fire wood, but this practice is also declining. The problem of excessive debris flows in these river during extreme events is therefore likely to increase in the future.

In 1990 an extreme flood event (estimated 1000 yr. event) in the Lainbach and Arzbach river catchments in the Bavaria Alps resulted in the transport of a large quantity of woody debris which became trapped at a number of bridges in a region where the channel gradient changes from that of a steep mountain stream to alluvial floodplain. As a consequence, four bridges were damaged and the flow under these bridges was constricted, causing overbank flow and extensive flooding of residential areas.

To prevent any repeat of this problem it was decided to install debris retention devices in the upper reaches of the Lainbach and Arzbach catchments to protect the integrity of bridges and reduce the potential for overbank flows in downstream areas. A number of physical model tests were carried out at the Hydraulics Laboratory. It was found that the best method for retaining debris, while allowing the downstream movement of water and sediment, was to use circular posts set into the channel bed, with a post spacing set to the minimum length of debris that it was desired to trap. A number of different post configurations were tested in a rectangular perspex flume to determine the best alignment for retaining the imposed debris load and for passing the designed discharge with minimum backwater effect (figure 1.1). It was found that alignment 2 (a downstream pointing "V") was the configuration with the best debris retention capacity and which had the least backwater effect when the device was filled with debris. Configuration 1 was found to be unsatisfactory because debris tended to be pushed up over the barrier, while the smaller barrier length than in configuration 2 meant that the flow had less area to pass through the structure so that the backwater effects were greater. Configurations 3 and 4 created less backwater effect than 1 but slightly more than configuration 2.

Scale models of the structures at their proposed prototype locations were then constructed, (figures 1.2). The debris retention structures have an upstream catchment area of 19 km^2 in the Lainbach and 14 km^2 in the Arzbach. The models were tested with a variety of scaled debris sizes, a range of discharges (Q max. = 125 cumecs in Arzbach, and 200 cumecs in Lainbach), and a simulated sediment transport load. Both models were found to perform satisfactorily. Plates 1 and 2 show the scale models.

The Lainbach device has a double row of posts, but this was later found to be unnecessary and the Arzbach device, therefore, only has a single row. Post dimensions are 0.66m diameter and 4 m high above the channel bed and each post consists of a steel sleave with concrete core. Each post is set into a concrete foundation which is supported on pilings sunk 4.4m into the ground. The posts are set into the middle of a basin built with massive close fitting stone blocks on both the bed and banks to prevent scour. Figure 1.3 shows the constructional details of the posts and foundations. The device on the Arzbach also has an energy dissipation pool downstream of the posts (see figure 1.4). Both structures will be cleaned periodically of debris and sediment although the Arzbach device has a central in-cut low flow channel designed to flush accumulated sediment downstream at low flow to avoid starving the downstream areas of the sediment load necessary to prevent channel degradation.

The prototype on the Lainbach was completed in 1993 and was, at the time when visited (October 1995), being cleaned of a large sediment bar deposit which had accumulated upstream of the posts. The device on the Arzbach is currently under construction. The estimated cost of the device on the Lainbach, without maintenance costs, is DM 2 million ($1.5 million). Plates 3 and 4 show the prototype device on the Lainbach.

Figure 1.1 Tested flume post alignments. Modified from Knuass (1985).

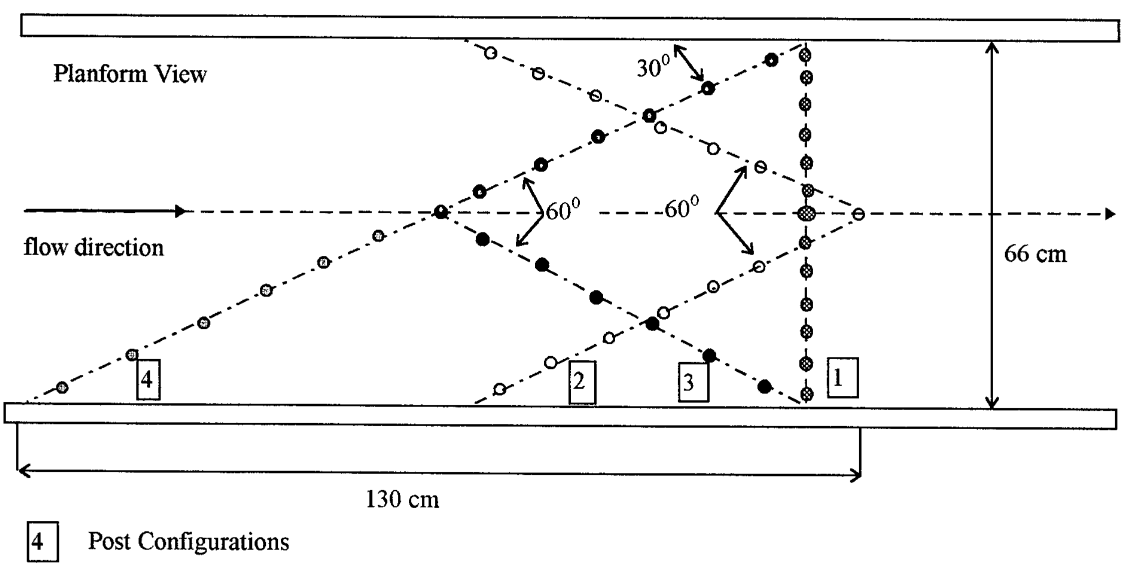


Plate 1 : Physical model of the Lainbach "Treibholzfang" with debris and sediment load. View downstream.

Plate 2 : Physical model of the Arzbach "Treibholzfang" Note the central low flow channel and stilling basin. View upstream.

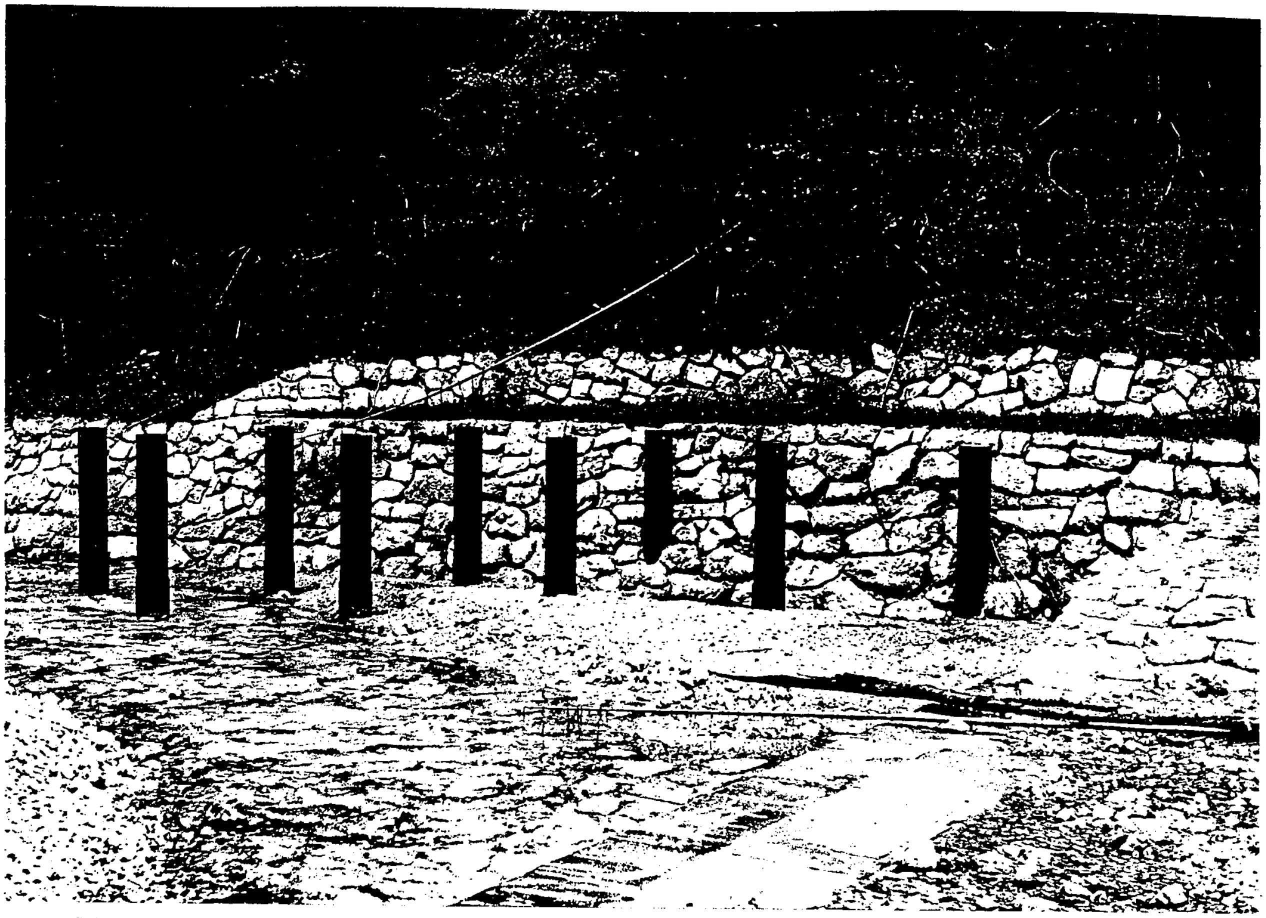


Plate 3 : Treiboholzfang device on the river Lainbach. View downstream.

Plate 4: Treibholzfang on the river Lainbach. Sediment removal operation. View upstream.

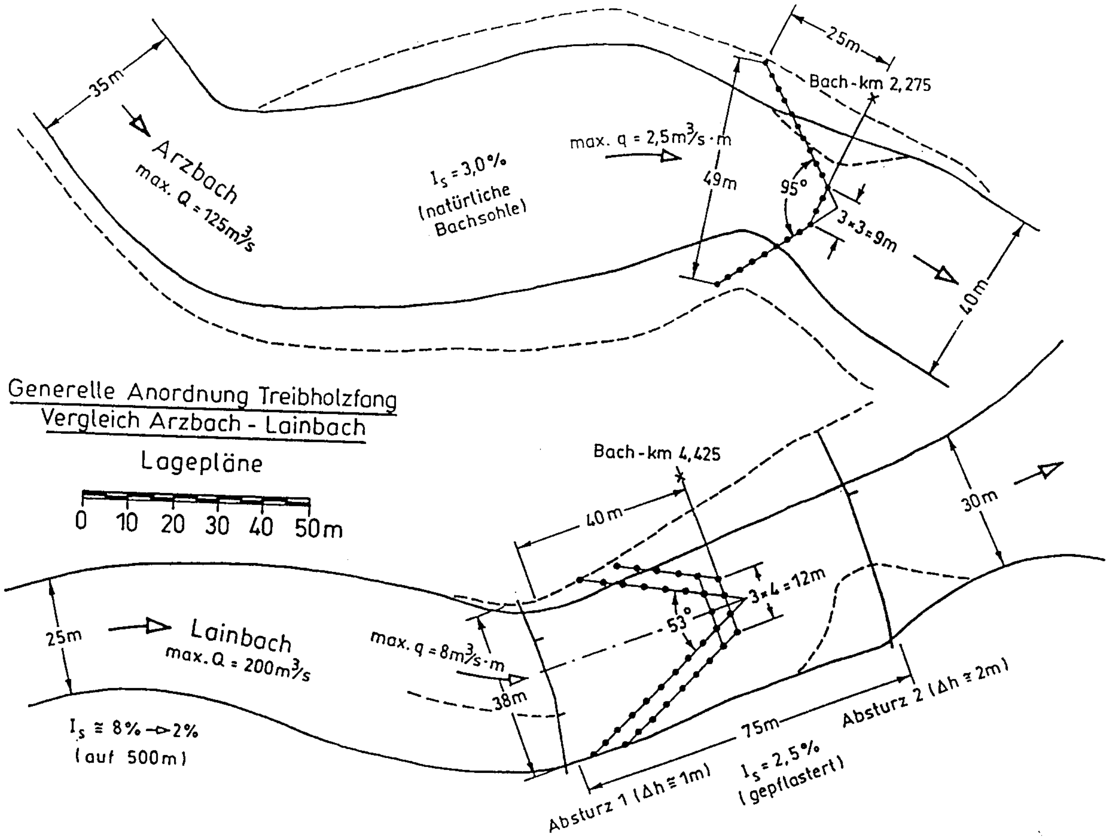


Figure 1.2 : Planform views of the model set-up for the Lainbach and Arzbach debris retention devices (after Knuass, 1985).

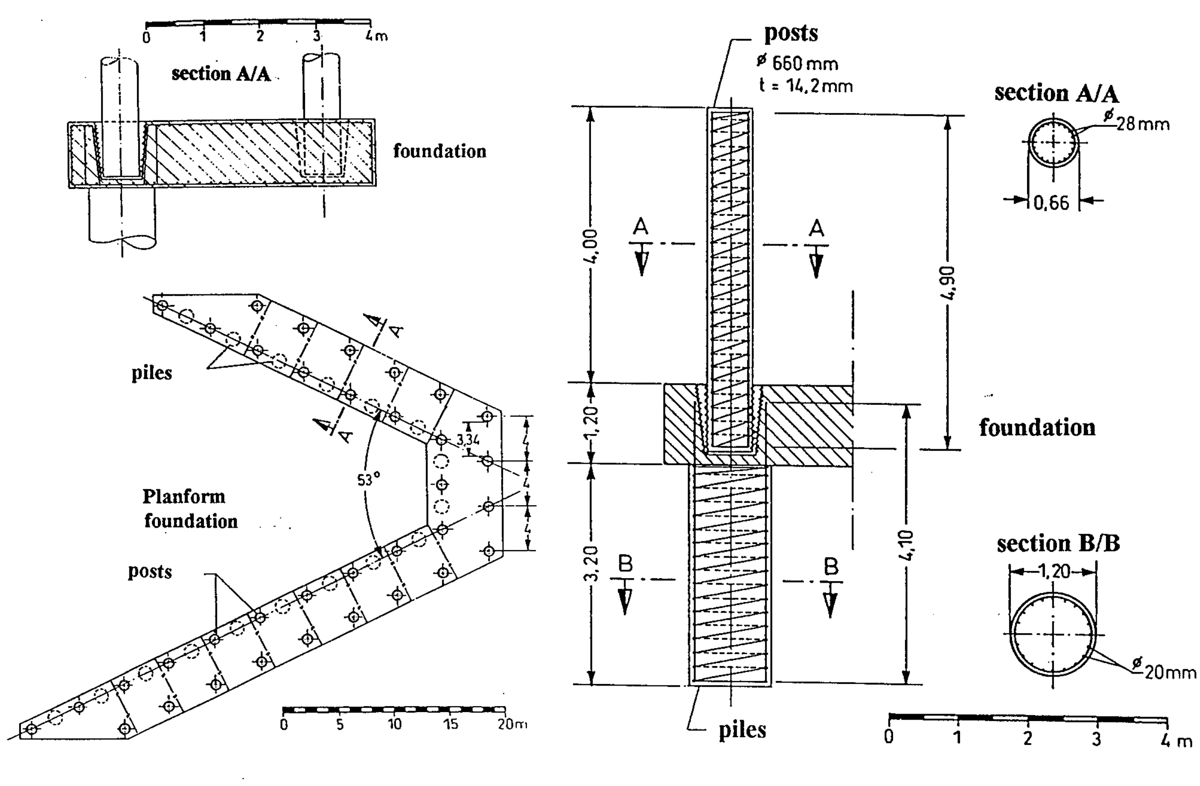


Figure 1.3 : Construction details of posts and foundations on Lainbach Treibholzfang (modified from Knauss, 1985).

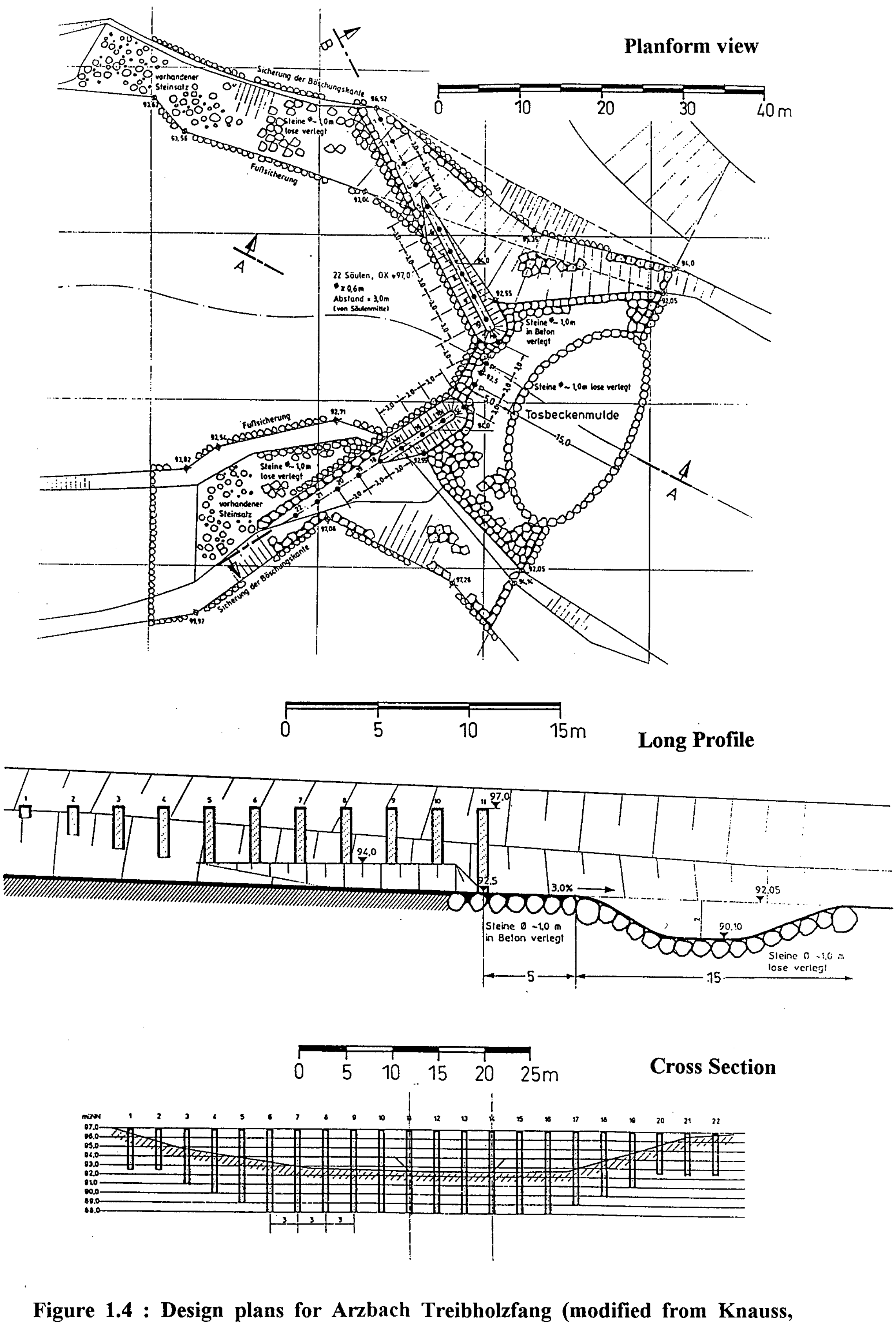


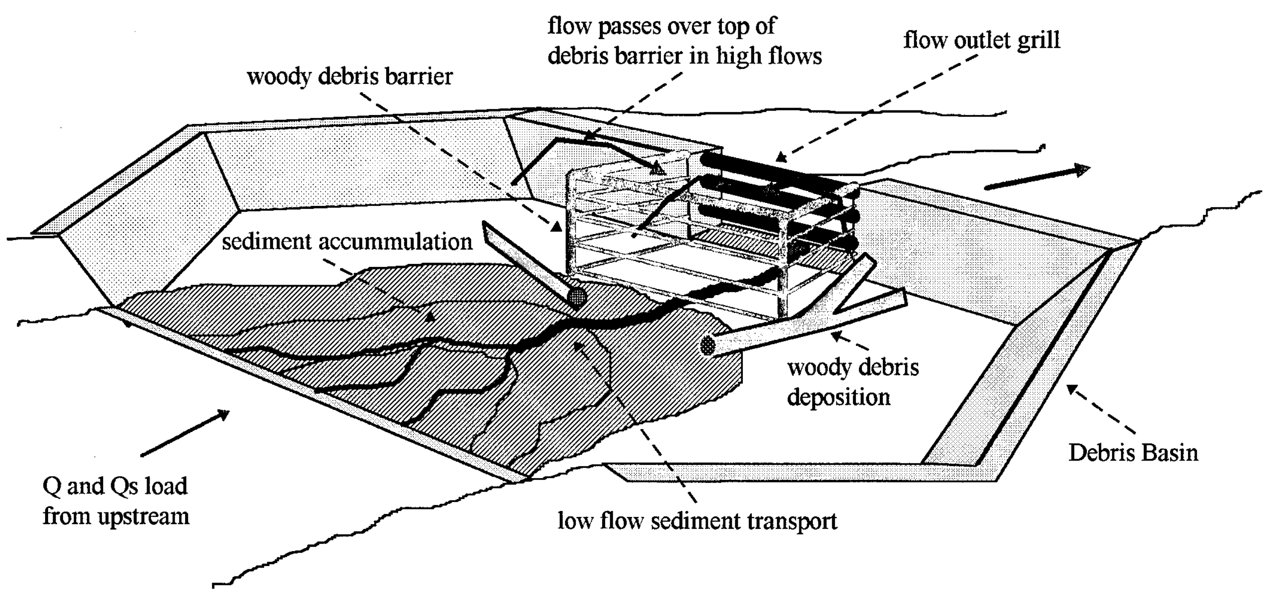
Figure 1.4 : Design plans for Arzbach Treibholzfang (modified from Knauss, 1985).

1.2 Debris Detention Basins for Torrent Control

Information in sections 1.2 and 1.3 were obtained from discussions with Dr A. Chervet at the ETH Institute of Hydraulics and Glaciology, Zurich, Switzerland.

Debris detention basins are small pools which have no continuous backwater designed to trap sediment and debris washed down by torrents from the steep flanks of Alps and are installed to protect roads and other structures in their path. The basins have small outlets at the front, so that the accumulated sediment can be flushed out by degradation at low flows. A major problem, however, is that woody debris can block the outlet grill of the basin, so that sediment flushing does not occur resulting in the structure being overtopped during flood events. The solution to this problem has been to construct slanting grilled weirs or box type trash racks around the upstream side of the outlet grill so that during storm events the flow can pass over the top of the trash rack and out through the grill plate. See Figure 1.5

Figure 1.5 : Debris retention basin with woody debris protection device.



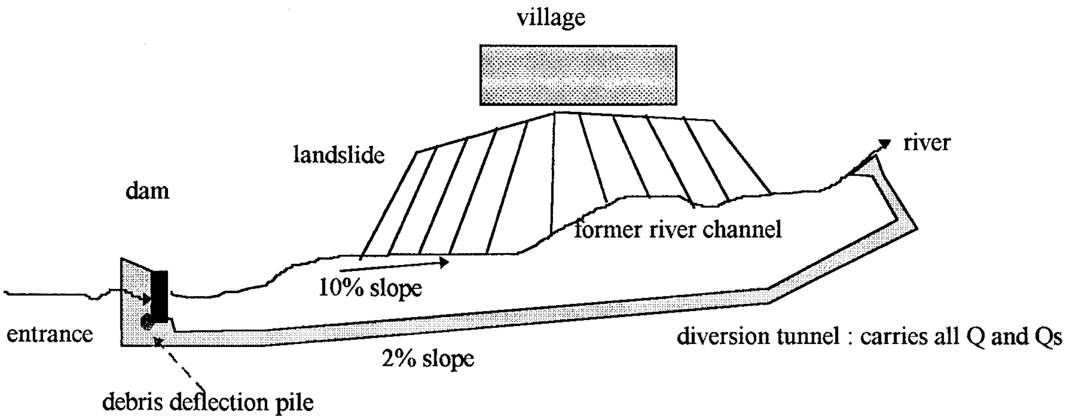
1.3 Diversion Tunnel : Campo Vallemaggia

The Campo Vallemaggia is a tributary of the river Maggia, on the border with Italy. At the site in question there is a historical problem of erosion of the left bank in a bend causing landsliding of the bank which is threatening a nearby village. The solution to this problem has been to build a diversion tunnel around the village through the opposite flank of the mountain. The upstream catchment area is forested and as a consequence floating debris could prove to be a problem at the tunnel entrance. The tunnel was designed to pass the total discharge and also sediment load to prevent downstream channel degradation. Model tests were made in 1987-88 and construction began in 1994.

The tunnel is 2km long, has a bed slope of 2% in order to prevent abrasion (while the local channel slope is 10%) and is designed to pass the 200 yr. flood (300 cumecs) (figure 1.6).

The solution tested to prevent the tunnel from clogging by woody debris was the construction of a steel and concrete pile (2.4m in diameter) upstream of the tunnel entrance to rotate debris parallel with the flow direction into the tunnel. Model test runs were carried out with/without debris and landsliding events upstream were simulated. The results showed that more debris was rotated parallel with the flow when the pile was present than when it was removed. Smaller debris was found not to accumulate in the tunnel. One problem encountered in the tests was that of scaling between the model and the prototype, as the simulated debris has far less elasticity than that found at the prototype. The pile was initially designed with a sloping, pointed upstream side, but this was found to offer a negligible improvement in efficiency as compared with a simple, and cheaper, cylindrical pile.

Figure 1.6 : Schematic diagram of the Campo Vallemaggia diversion tunnel .



2 CLOGGING OF SPILLWAYS BY DEBRIS

2.1 Recommended practice to prevent obstruction

In a discussion of spillway design and construction, Scherich (pg. 610) in Jansen (1988) lists "reservoir trash load" as one of the data requirements to support the hydraulic design criteria for effective spillway design. However spillway operation with a floating debris load is often overlooked or considered only as an afterthought in spillway design, especially in ungated structures and this has in at least one instance (see Bruschin et. al., 1982, "The overtopping of the Palagnedra dam") resulted in the failure of a spillway to convey the design flood resulting in dam overtopping.

Methods for overcoming debris problems at spillways include the use of floating or fixed booms, surface discharge chutes at deep sluices (ICOLD Bulletin 58, 1987, pg. 119) and a variety of trashracks and raking devices. Floating ice in dams is dealt with in a similar way. Ice build-up in front of gated spillways it is often broken up by an ice breaker boat and guided to special openings through which it is discharged. Vertical lift or flap gates will allow discharge of ice in a nappe up to 2m thick, but when the quantity of ice to be discharged increases too rapidly gates must be raised to their full height to completely clear the opening (ICOLD Bulletin 58, 1987).

2.2 Example of debris problems at spillways : The Palagnedra dam

The following information is taken from two articles, Bruschin et. al., 1982 ("The overtopping of the Palagnedra dam") and Vischer D. & Trucco G., 1985 ("The remodelling of the spillway of Palagnedra") and from a conversation with Dr A. Chervet at the ETH Institute of Hydraulics and Glaciology, Zurich, Switzerland.

The Palagnedra dam lies in the catchment of the Melezza river, in the southern Swiss canton of Ticino. It has a design storage capacity of 4.8×10^6 m^3 and is fed from a catchment area of $140km^2$, over 50% of which is forested and lies on steep slopes. The structure consists of an arched gravity dam, 120m long and 72m high and a 45m high diaphragm wall built within morainic material in a secondary valley. The flood spillway had an uncontrolled ogee crest on top of the dam and steep chute terminated by a ski jump. The crest was divided into 13 openings, the boundary walls of which functioned as piers for an overlying road. The nominal discharge capacity of this spillway was 450 m^3/s. (Plate 5).

On 7th August 1978 an extreme storm event occurred in the region causing a flood wave to pass down the Melezza river to the dam carrying a huge quantity of logs and wooden debris (later estimated to be about $25000m^3$ of wood). About $1.8x10^6$ m^3 of sand and gravel were also transported into the reservoir. Debris build-up at the spillway partially obstructed the openings and caused the dam to overtop over its entire length. The peak discharge at the spillway was estimated to be just under $2000m^3/s$. Plate 6 shows the dam choked with wooden debris on the 8th August 1978 after the flood event. The main dam suffered insignificant damage, but about $50000m^3$ of morainic material was eroded from the downstream side of the diaphragm wall which seriously endangered its stability. In the aftermath of the event a study was carried out to try and piece together the sequence of events that took place and to understand the meteorological and hydrological conditions necessary to cause the flood wave and associated debris build-up. The dam spillway was then remodelled and the design tested with new discharge levels and a simulated debris load at the Laboratory of Hydraulics, Hydrology and Glaciology, at the Federal Institute of Technology in Zurich. The remodelled spillway had to satisfy a new design discharge of $2,200m^3/s$, the avoidance of woody debris build-up at the weir

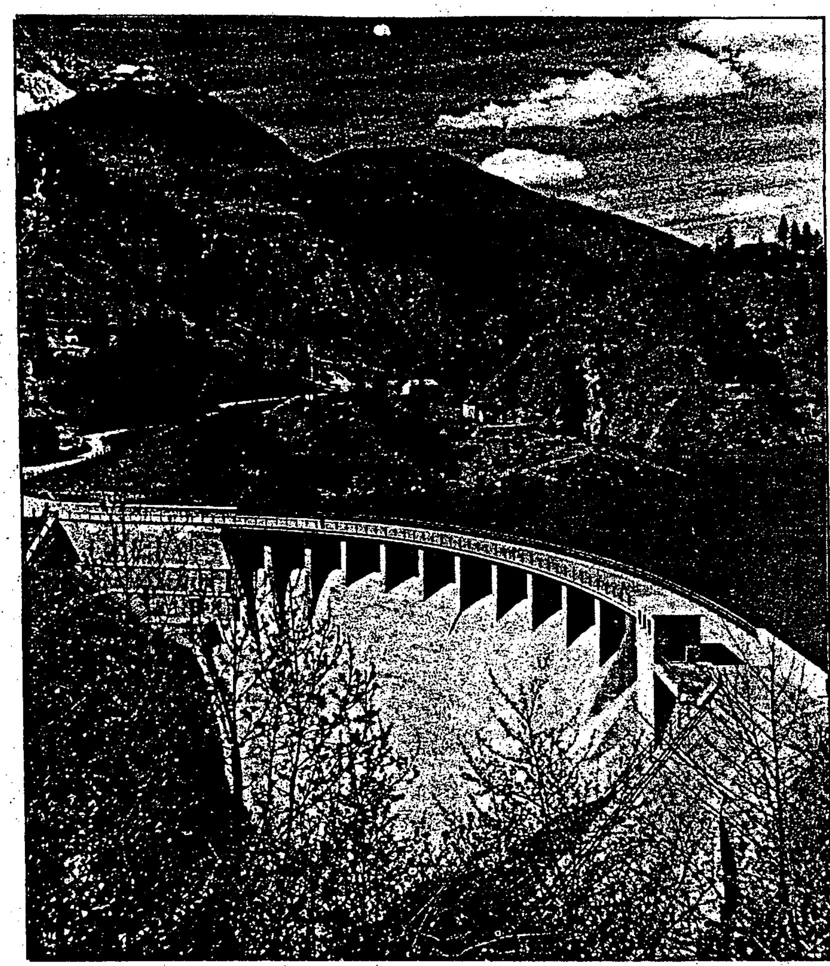


Plate 5 : Palagnedra dam prior to remodelling of spillway (after Vischer & Trucco, 1985).

Plate 6: Dam choked with debris on the morning of August 8th, 1978 (after Vischer & Trucco, 1985).

Plate 7 : Physical model (scaled 1:50) with remodelled spillway. Discharge 2.200 m^3/s (after Vischer &Trucco, 1985).

crest and satisfactory flow conditions over the weir crest and ski-jump and in the downstream canyon. Measures tested in the physical model and implemented were:

- Raising the abutments by 4m to prevent overtopping.
- Removal of the dam top bridge and supporting piers to leave a continuous weir crest.
- Raising and remodelling of the spillway guidewalls to ensure undisturbed discharge of the increased runoff. Plate 7 shows the scale model with new spillway design.

The paper by Bruschin et. al. (1982) concludes that a number of important factors must be considered in the design of spillway including: analysis of the hydrological and meteorological environment; consideration of potential extreme events; examination of high yield sediment sources and stability of slopes in upstream afforested areas. Dr Chervet also suggested that spillway pier should be set at least 12m apart to avoid potential build-up of woody debris (original pier spacing at the Palgnedra dam was 5m).

2.3 Theoretical Research

Godtland & Tesaker (1994) examine the potential for debris clogging at spillways on two dams in Norway. In both cases the spillway was of the fixed overflow type with a bridge supported by piers along the crest. As a result of the project the bridge on top of one of the dams was removed in 1991. Model tests were carried out to determine under which conditions debris tangles may cause clogging of spillways with and without a bridge superstructure and to determine the anchor forces required to hold back debris from the dams crest by trash booms and similar retaining devices. The following approximate guidelines were derived from the tests:

"-Pillar distance of bridge structure on top of the spillway should be at least 80% of the length of the arriving trees.

-The vertical free opening between the crest and superstructure should be at least 15% of the tree length.

-The downstream height of the sill should not exceed 1/3 of the tree length if a superstructure is present.) Otherwise a high downstream wall is usually better for passing the trash than a low wall.)

- If not obstructed by any superstructure, tangles and single trees may be withheld along the crest until the overflow level reaches near the root diameter of the arriving trees, about 1/6 of the tree length.

-Most (debris) tangles will pass a crest without superstructure when the overflow depth reaches 10-16% of the height of trees forming the tangle. Where a superstructure is present, with pillar distance at least 110% of the tree length most tangles will pass when overflow height reaches 16-20% of the tree length.

-The tests have given a general formula for calculation of the flow forces (F_w) on anchored trash:

$$F_w = C_d \,.\, b \,.\, (30 \,.\, t + l) \,.\, \rho \,.\, v^2/2$$

where :

$C_d = 0.006$ for $v < v_s$ | ρ = density of water

$C_d = 0.08$ for $v_s < v < 1.1 \,.\, v_s$ | v = flow velocity

$C_d = 0.10$ for $v > 1.1 \,.\, v_s$ | v_s = submerging velocity (of debris tangle)

b = width of tangle normal to flow | l = length of tangle in flow direction

t = submerged depth of tangle

- .... the flow force will increase significantly when the distance to the crest is less than five times the overflow depth, and that the flow force will be unaffected by upstream depths larger than twice the submerged depth of the tangle.

- Wind and waves normally contribute little to the total anchor force unless the flow is very slow or the wind and waves are of extraordinary strength." (Godtland & Tesaker, 1994).

Hartung and Knauss (1976) also discuss design considerations for spillways exposed to clogging by woody debris. They make the following suggestions:

1) Hydraulic Dimensions: Increase the hydraulic capacity of spillways from the standard 1000 yr. design flood to the 5000 yr. flood and have a tunnel diameter of 5m as a minimum to ensure against clogging.

2) Open or closed conduits: Open conduits are unlikely to become seriously clogged. Open type spillways are not always possible, but the authors believe that clogging can be avoided in closed conduits if three conditions are adhered to. These are: smooth walls; no contractions or obstructions, no sharp bends.

3) Shape and type of intake structure: The danger of debris build-up obviously decreases with the capacity of a spillway. The intake discharge should be concentrated in one opening and the invert of the intake made as steep as possible to produce a fast exit flow that cannot be resisted by debris jammed at the intake. If the intake has a control gate care must be taken to ensure the design hydraulic capacity through the structure even in the event of the gate becoming blocked.

4) Gates: The authors recommend that gates should be installed at spillways in order to form a concentrated jet-flow in the centre of the intake. Lift gates should be avoided unless there are a large number of openings because of the danger of trees being drawn below their lower edge during closing. Drum, sector and flap gates should used if possible to avoid this problem.

5) Interceptors and skimmers: Floating booms can be effective in keep floating debris away from spillways, but in the case of heavy debris build-up debris may be drawn under the boom. The bank based elements also have to take up the total force of impacting debris and the device must be long enough to remain on the water surface in the event of reservoir draw-down. Fixed, pier-like elements, connected by an access bridge, with a spacing corresponding to the narrowest opening in the spillway may therefore be a more effective, if rather costly, remedy.

6) Trash-racks: The authors state very strongly that trash-racks should never be used at spillway intakes because clogging could potentially compromise the spillway's design flood capacity.

7) Stilling basin: Debris passing through spillway can act as high velocity missiles, destroying protruding structural elements such as baffles. It is therefore recommend to use spatial stilling basins which slope upwards at the downstream end where a high debris load could be passed through the spillway.

8) Removal of intercepted floating material: The authors suggest dragging material ashore using motor boats. They make the point that the most effective way to prevent debris build-up at reservoirs is to intercept it upstream of the dam using a device such as that described in section 1.1, although such structures are probably cost effective only in the most serious cases.

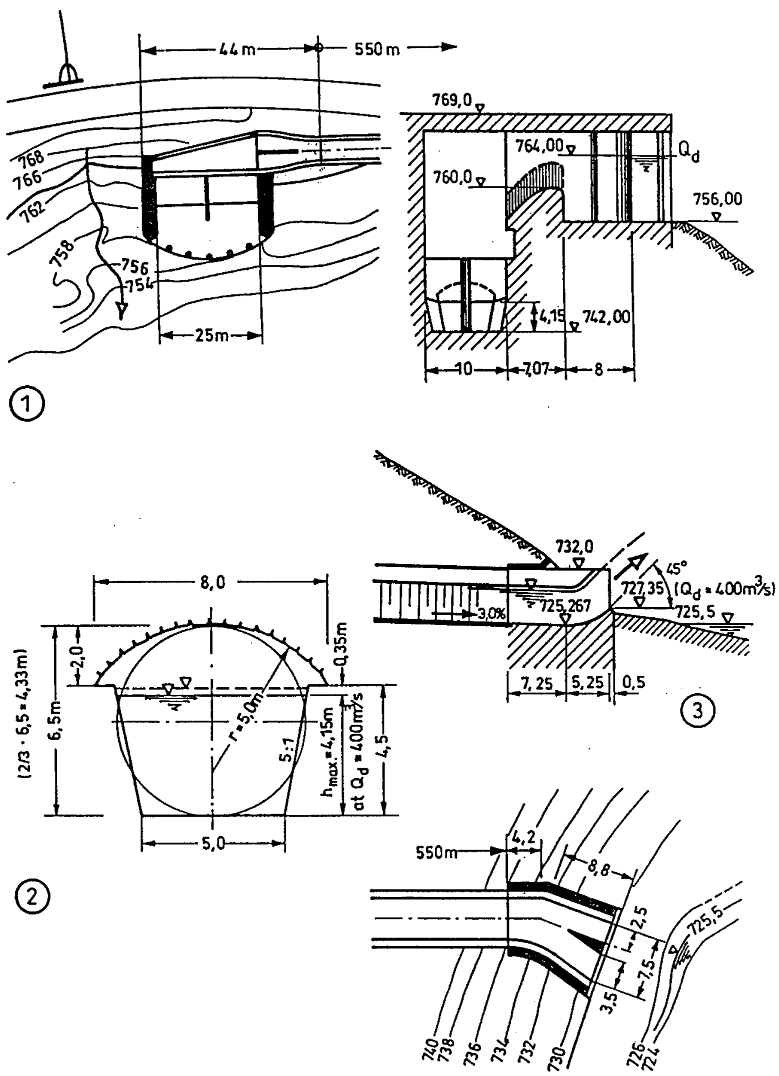
9) Model tests: Physical models are indispensable tools in the design of spillways exposed to large amounts of floating debris. Plate 8 shows a spillway model with fixed pillar debris interceptor being tested with debris load.

2.4 Practical Application of spillway design with debris retention devices

Knauss (1985) describes a model that was constructed at the Hydraulic laboratory of the Technical University of Munich in Obernach, Germany to test a new spillway on the Sylvenstein Dam. This design incorporates debris retention posts at the inlet consisting of five columns, 11m high with a free space of 4m between them (Plate 9). The tunnel itself is 6m in diameter and has free surface flow so that smaller debris that pass through the posts can be transported down the tunnel. This structure does not have a crane or mechanical trash rack to remove the debris. Figure 2.1 shows the structural details of the spillway.

Knuass (1995, conversation) has suggested that woody debris build-up in reservoirs is a problem in Bavaria where dams are often at low elevations so that debris is fed into them from upstream, whereas in Austria however debris is not such a problem in reservoirs because many dams are located above the tree line.

Figure 2.1 Structural details of the spillway for the Sylvenstein Dam (from Knauss, 1985).



1 Overspill and intake structure, lay-out and cross section

2 Cross section of the tunnel

3 Flip bucket, lay-out and cross section

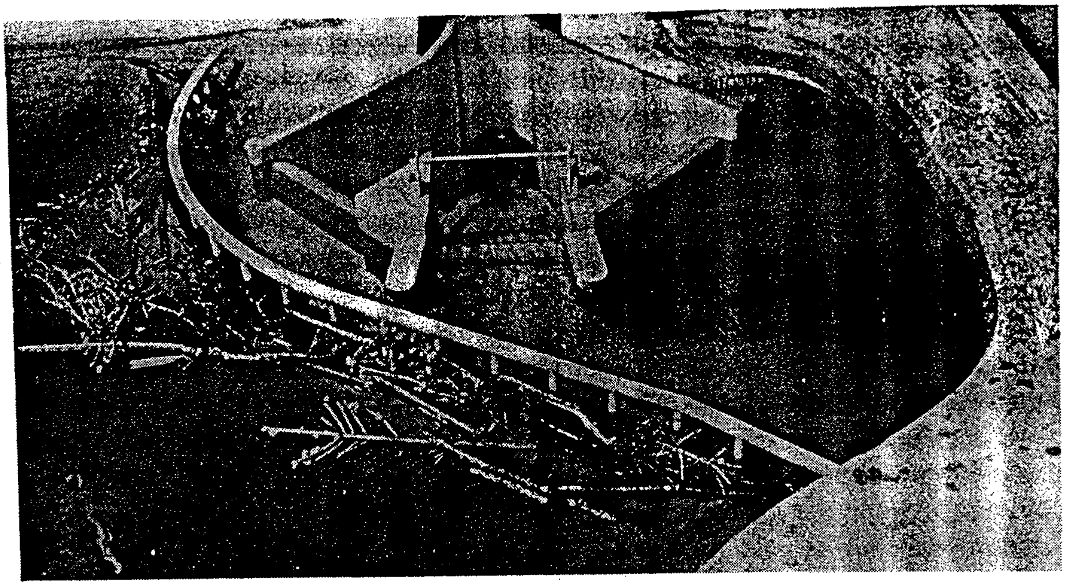


Plate 8 : Fixed pillar-interceptor with service bridge (after Hartung & Knauss, 1976).

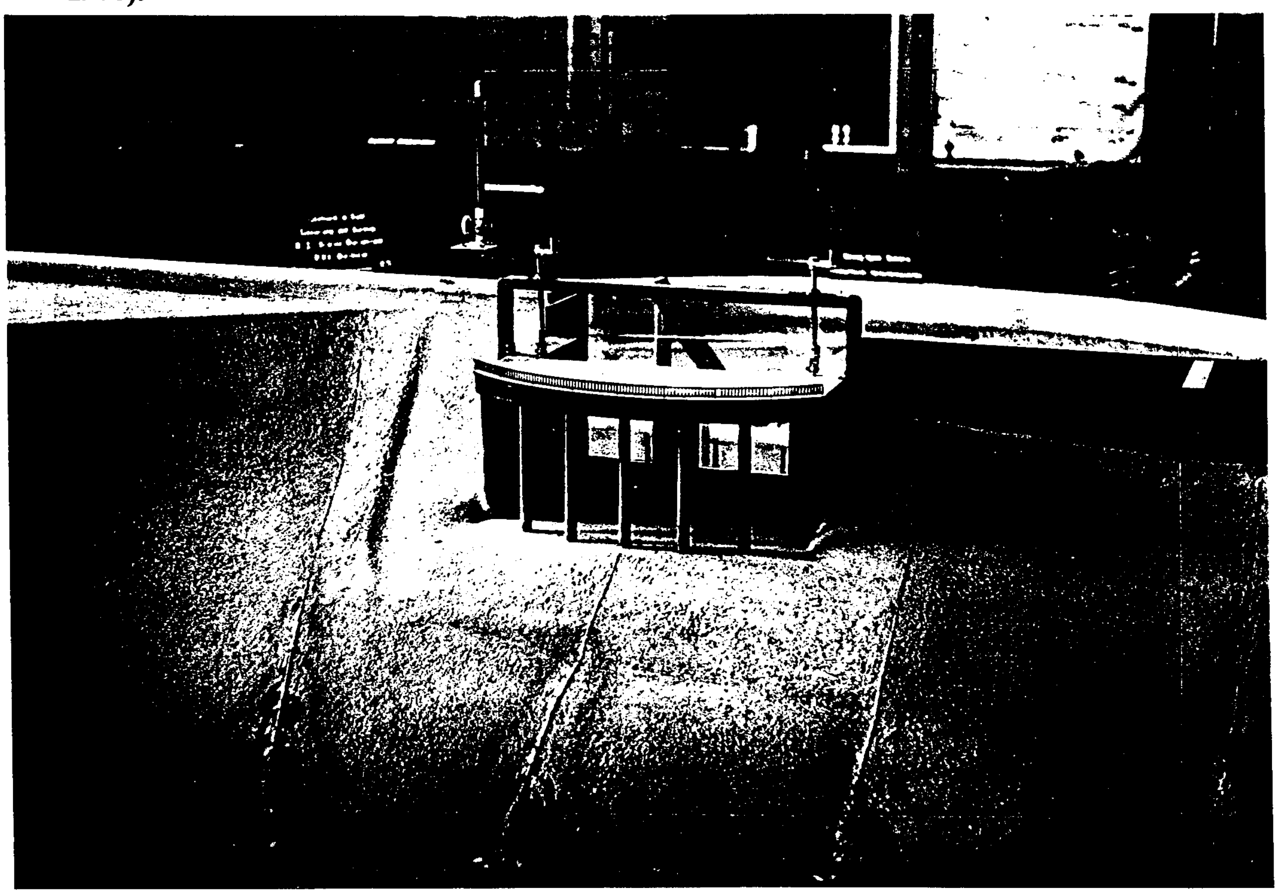


Plate 9 : Model of new Sylvenstein Dam spillway with debris retention device.

3 RUN-OF-RIVER-POWERPLANTS

3.1 Bremgarten-Zufikon Powerplant (Switzerland)

Bisaz et. al (1976) examine a phenomenon at deep-seated turbine intakes of run-of-river powerplants utilising bulb turbines where a separation layer on the upstream side of the turbine gives rise to a zone of horizontal anti clockwise rotating water. On the surface within this area a movement of water in the upstream direction occurs so that arriving floating debris is retained some metres from the trashracks or front of the upstream face, out of the range of the mechanical rake (figure 3.1). A vertical, radial current may also arise in this zone that can develop into a vortex that may suck air and debris from the surface into the intake. This can consequently impair the smooth running of the turbine. A number of tests were carried out on a scale model of a run-of-river plant on the Reuss near Bremgarten-Zufikon (Switzerland) to test a device called an injector shaft which was designed to eliminate these vortex phenomena. The injector consists of a shaft comprising the upstream face of the intake dam and a scum board (see figure 3.2). This shaft creates a suction effect because the incresing proportion of the velocity head in the total head inside the shaft induces a current near the water surface towards the front of the upstream face. Floating debris is therefore moved to the face of the trashrack and can be removed with a raking device. The model tests proved that the injector was succesful in this respect and also helped to prevent the vertical vortex from forming by disturbing the turbulent separation layer between the ponded surface water and underlying current zone.

Figure 3.1: Run-of-river turbine with separation layer and currentless zone (longitudinal section). Modified from Bisaz et. al. (1976).

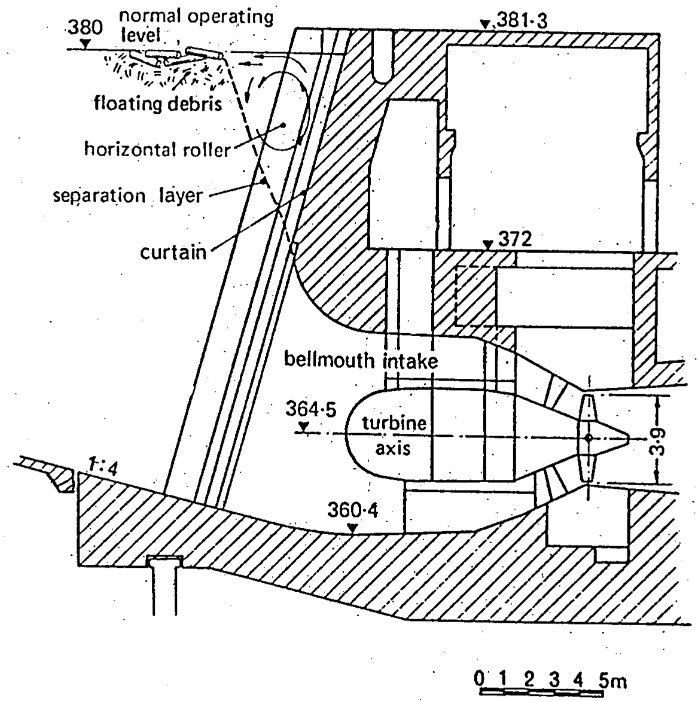
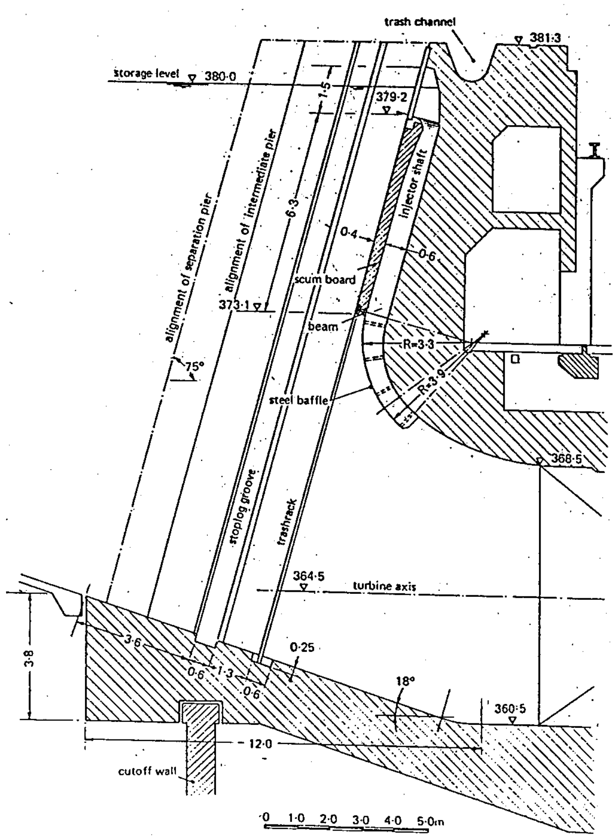


Figure 3.2: Position of Injector shaft at turbine intake. Modified from Bisaz et. al. (1976).



4 OUTLET TRASH RACKS

4.1 Introduction

Jansen et al. (1988) suggest that log booms should be the first line of defence against floating debris but trashracks are also required at most dam outlet structures, although surface intakes are more subject to debris build-up than deeply submerged ones. The size of trashrack is governed by the limiting velocities and size of downstream conduit and gates while the limiting velocities are governed by head loss and blockage considerations. Velocities are normally limited to 0.91-1.21 ft. sec. Racks are commonly designed for operation with 50% clogging and must also be designed to be vibration-free to prevent metal fatigue. Vibration problems are discussed in more depth in section 4.3. Racks must also be provided with cleaning facilities to prevent excessive clogging and overstressing (see section 4.2.2).

There are two basic trashrack types. One is a concrete or metal frame that supports a metal trashrack which is commonly constructed from flat steel bars set on edge with a spacing of 49-228 mm. This type of rake will trap small debris. The other design is concrete trash beams which have relatively large openings and are designed to trap very coarse debris which may prevent gate closure or damage turbines. The US Army Corps of Engineers commonly use trash beams with openings not more that two thirds the width and height of the gate or other constricted section to protect deeply submerged flood control outlets (Jansen et. al., 1988).

Fully submerged trashracks are favoured to minimise maintenance, but if this is not possible racks must be easy to remove to facilitate rust removal and repainting. At some plants the racks are constructed from stainless steel although this is an expensive option. If racks are exposed to freezing, ice can be eliminated from the rack by an air bubbler system which circulates warmer water from a lower level in the reservoir (Jansen et. al., 1988).

4.2 Trashracks at Hydro Plant Intakes

The information in this section is taken from an article entitled "Trashracks and Raking Equipment" by Zowski (1960).

Hydro-electric power stations depend mainly on beam-type trashracks for protection of turbines. Mesh screens are used only is special cases where removal of smaller trash is necessary, or where fish are to be protected from entering the intake. Additional protection is often provided by the use of floating log booms and skimmer walls.

4.2.1 Constructional Features of Trashracks

Trashracks at hydro-electric power stations consist of vertical or slightly inclined steel bars placed parallel to one another and spaced uniformly to permit the use of raking equipment. The vertical bars are supported by horizontal supports and the racks are usually assembled into panels to facilitate removal for maintenance. Trashracks are ordinarily constructed from mild carbon steel although more expensive wrought iron, alloy-steel and stainless steel are used at some locations.

At low pressure (low velocity) intakes racks are usually set on an inclined plane of between 15^0 and 45^0 and extend from the bottom of the inlet structure to above the water surface. This inclination reduces head loss and also facilitates hand raking because submerged debris will tend to ride up the slope of the rack with the flow. However, because mechanical rakes are normally employed now the inclination of trashracks is less important although engineers still tend to prefer racks to be slightly inclined. Zowski also notes that, "....the vertical setting is used less frequently in European designs than in America.".

At deep intakes which are submerged most of the time the amount of debris that builds up is small so that cleaning is required on a much less frequent basis. Racks are normally mounted vertically in guide slots so that they can be easily removed for maintenance although it may be necessary to employ diver to inspect racks which are set at very deep outlet structures.

Rack bar spacing is depends primarily on the size and type of turbine to be protected and also the predicted type and size of the trash load. Bars should be spaced so that the clear opening is not greater than the smallest opening in the conduit structure or the turbine. In a Francis turbine the smallest minimum distance is in the runner between the discharge edge of one bucket and the back of the next. In Kaplan blade turbines the openings are larger and Zowski offers an approximate rule which establishes the maximum clear spacing between rack bars for Kaplan turbines as 1/30, the diameter of the runner. At impulse turbines, such as the Pelton, bar spacing must be considerably tighter to prevent small twigs from clogging the nozzles. Zwoski suggests using a rule where rack bar spacing should not be greater than 1/5 of the jet diameter at maximum needle opening.

The maximum acceptable velocity through trash racks is determined by the type of intake, amount of debris build-up, method of cleaning and rack construction. Optimum velocities are mainly set by the amount of head loss that is economically permissible as compared with the area of trash rack. Velocities must also be correlated with rack design to ensure that they will be free from serious vibration problems. At low head intakes design velocities are usually around 0.9-1.2 m./sec., while at high head intakes velocities of 3-3.6 m./sec. are permissible if the racks are adequately designed to cope with the greater potential vibration.

There are a number of formula in use for determining head loss through rack bars, the one developed by Kirschmer (discussed by Zowski) is as follows:

$$h_r = K\left(\frac{t}{b}\right)^{4/3} \frac{V_o^2}{2g} \times \sin\alpha$$

where : h_r = loss of head through racks, ft.

t = thickness of bars, in.

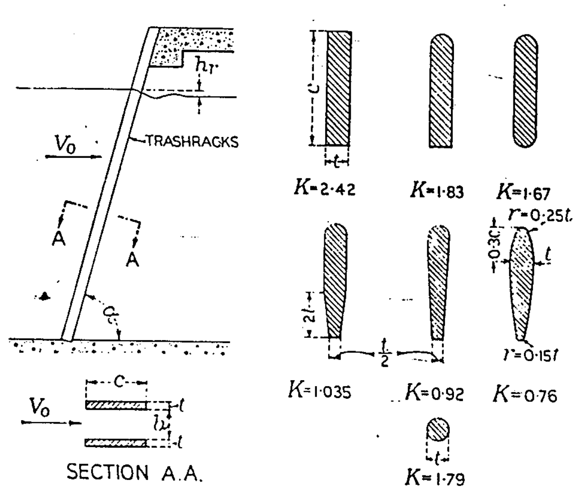
V_o = velocity of approach, ft. per sec.

g = acceleration due to gravity, ft. per sec. squared.

α = angle of bar inclination to horizontal, degrees.

K = factor depending on bar shape. See figure 4.1.

Figure 4.1 : K factor values for various bar shapes (after Zowski, 1960).



Laboratory tests in connection with a number of racks have shown this formula to consistently under predict head loss by a factor of 1.75 to 2.0. Also, the computed head losses apply to clean racks so to allow for partial clogging (assuming 10% of the rack will be obstructed) head loss should be increased by a factor of about 1.23. Where severe clogging occurres (between 25% and 50% of the rack) this factor should be increased to between 1.78 and 4.0.

A variety of bar shapes are shown in figure 4.1. Flat bar ends are usually adequate, while the use of streamline shapes is seldom justified from an economic standpoint. For hydraulic considerations however bars should be as thin as possible although it is not advisable to use bars less than 9.5 mm. thick to avoid damage from handling and debris impact. For deeply submerged intakes bars not less than 12 mm. thick should be used. The depth of bars is determined by structural requirements but to permit raking it should be made sufficient to provide 38 mm depth between the upstream face and back support struts.

Design loads on trashracks depend upon the water pressure imposed upon them when the rack becomes clogged with debris or ice. It also depends upon the relative importance of the installation, bar spacing and the provision for cleaning. If the plant is remotely controlled and unattended the racks should have higher design loads. Corps of Engineers hydro-plants, most of which are medium head with a large capacity, are usually designed for a differential head of 3 m. In US Bureau of Reclamation, and also at many privately owned plants, trashracks at low pressure intakes with adequate flow area are usually designed to withstand a differential head of 6 m without failure. At high pressure intakes the Bureau designs the trashrack structure to withstand a load equivalent to one half of the head on the racks with a maximum of 40 ft.

If trash includes large floating debris, impact forces must be considered. An approximate formula that can be employed to calculate the impact force of a log is :

$$P = \frac{W}{g} \times \frac{V}{\Delta t} = \frac{W}{32} \times \frac{3.2}{0.1} = W$$

where : P = impact force.

g = acceleration due to gravity. ft. per sec. squared.

V = inflow velocity. ft./sec. (usually 3-3.5 ft./sec at low head plants).

Δt = time interval in which velocity of log is reduced to zero due to elastic deflection of rack bars.

Thus the impact force is approximately equivalent to the weight of the log.

4.2.2 Raking Equipment

Removal of accumulated trash is usually accomplished by raking. In the past this was mostly done by hand, but at present hand raking is only performed at small capacity low head plants. In large modern hydro-plants trash is removed almost exclusively by mechanical rakes. Mechanical rakes operate on the principle of lowering a raking element in front of the trash bars to dislodge debris and then raising it up the rack face to a point where the accumulated material can be unloaded. Rakes are usually lowered and raised by motor-driven hoisting mechanisms using steel cables. There are two main types of mechanical rake; unguided, and; guided.

1) Unguided mechanical rakes: These have wide-face wheels which travel directly on the rack bars, and keep the rake teeth the correct distance from the racks. The rakes depend upon rack inclination, weight and the back pressure of water to hold them against the rack face. The width of unguided rakes is not dictated by the trashrack span but by the volume and nature of debris which accumulates. Rakes are commonly between 1.8 and 3.7 metres wide. The operating advantage of unguided rakes is their ability to pass over stubborn obstructions without becoming jammed. The rake can also serve as a grapple for large logs. The lack of guidance may become a disadvantage, however, if there are strong transverse flows at the intake which may dislodge or even overturn the rake. Unguided rakes are not suited to deep intake trashracks where the bars do not extend above the inlet structure. In such cases removable metal or wooden panels are needed which extend from the top, of the trashrack to the deck in order to prevent trash from falling from the rake as it travels upwards to the unloading point.

The cost of unguided rake installation is generally less than for guided ones because guiding mechanisms are not required and the rake width can be made smaller.

One example of an unguided rake is the Leonard type rake which is commonly used in the USA. This rake has a series of teeth on an axle which rotates through 90^0 from vertical to horizontal when the rake reaches the bottom of the rack so that debris is not pushed to the bottom as the rake moves downwards. At the top of the rack the rake is guided to the unloading position by a curved apron which prevents the loss of debris. This apron also supports the rake as it traverses from one bay to the next. Plate 10 shows a Leonard rake supported on a combined hoist, trash car and apron. Another example of an unguided rake is the Glenfield plough which ploughs through the debris on its downward travel and on the upward travel the debris thus dislodged is caught in the basket formed by the upper part of the rake. Plate 11 shows a plow rake suspended from an intake gantry crane.

2) Guided Mechanical Rakes: This type of rakes requires guides which are usually made of steel embedded in the concrete walls of the intake piers. The rake is guided by rollers or sliding blocks which travel in the channel guides. One of the advantages of the guided rake is that it may readily be used on vertical racks and is not affected by strong transverse currents. Another strong advantage of the guided rake is that it is suitable for use in intakes where the trashrack does not extend up to the operating deck. Disadvantages are that the guides may become obstructed by debris and under severe trash conditions they may need considerable maintenance work. An example of a guided rake is shown in plate 12. This is a Newport News rake and consists of a frame with rollers which travel in guides and a pivoting raking element which is operated by levers linked to the sliding upper beam. The rake is lowered with the teeth

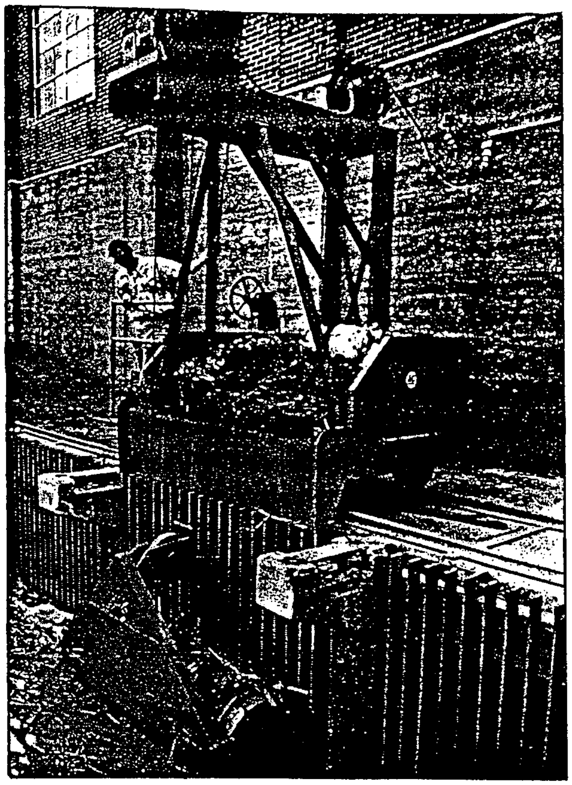


Plate 10 : Leonard type rake with combined hoist, trash car and apron (after Zowski, 1960).

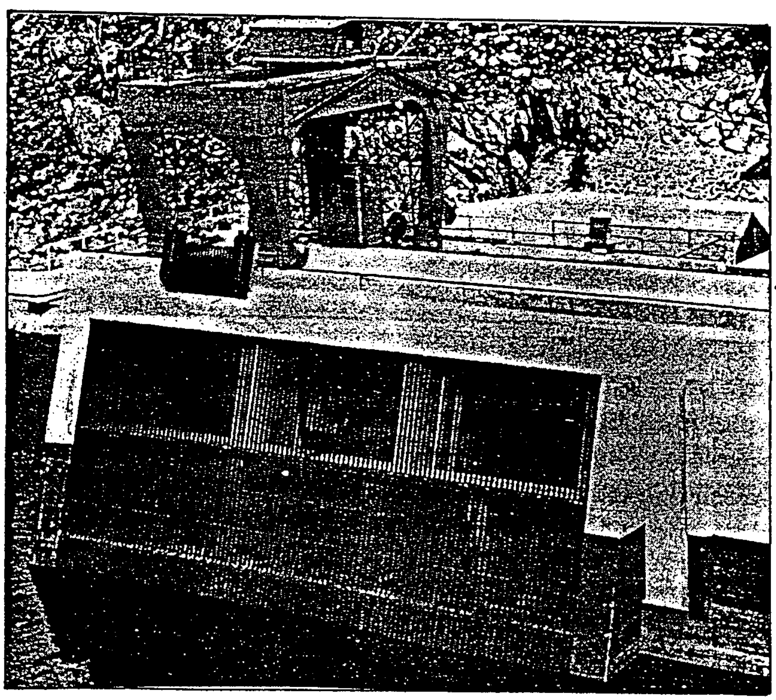


Plate 11 : Plow Rake Installation (after Zowski, 1960).

pointing downwards and as the rake reaches the bottom of the rack the mechanical action of the hoist closes it so that the teeth project into the bar-rack spaces.

There are several methods of unloading trash from rakes. At many installations unloading by manual raking is the most effective method because of the complex nature of the trash. Some raking machines have automatic sweeps however which push the trash off the rake teeth when the rake reaches its unloading position. These devices are very useful where heavy loads of light debris such as leaves, weeds and twigs occur but are less satisfactory for heavy debris such as logs. Disposal of debris from rack cleaning devices is performed by either sluicing or hauling it away in trucks.

Because of the operating limitations of mechanical raking devices and their maintenance requirements particularly under severe trash conditions, some plant operators prefer to use more simple and rugged types of rake which can be operated by an ordinary crane. Compressed air systems are also used at some deeply submerged intakes for occasional cleaning while revolving drum type self cleaning trashracks have been used in some small turbines on trash laden streams where the head water level is nearly constant. If no special cleaning devices are provided but some floating debris occasionally collects at racks it is good practice to remove it before it becomes waterlogged and sinks to the bed. Debris can be towed along the dam face to a suitable location on the shore where it can be piled up and burnt. At intakes equipped with gantry cranes for handling gates it is useful to provide a jib hoist attachment on the crane for removal of large debris and logs.

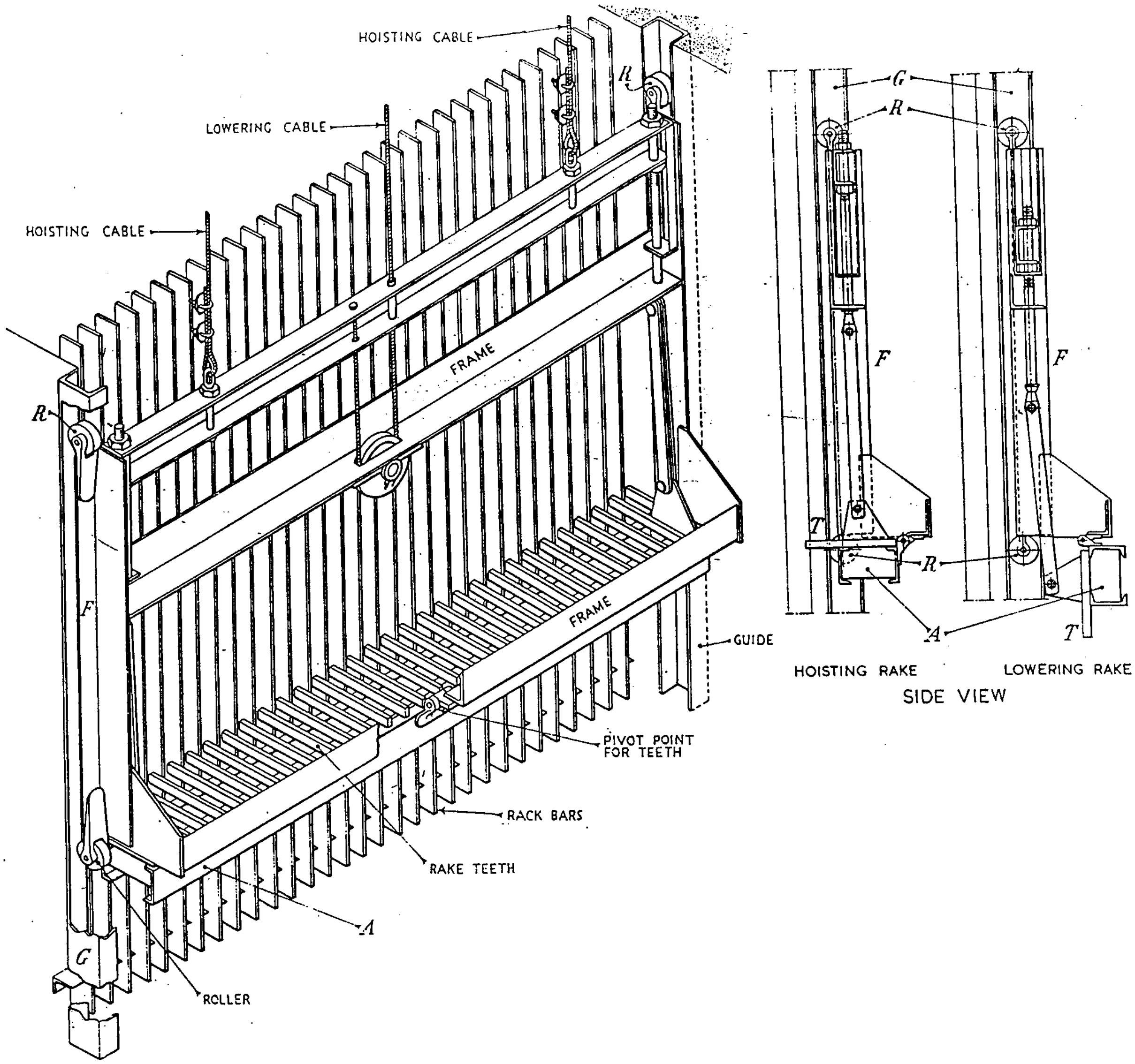


Plate 12 : Newport News mechanical guided trashrack rake (after Zowski, 1960).

4.3 Vibration Problems at Trashracks

In a review of trashrack failures Syamalarao (1989) suggests the following factors should be considered in trashrack design :

1) The differential head across the rack;

2) The bar spacing;

3) The head loss at the rack;

4) The vibration response.

The last of these aspects is complex and can be subdivided into four areas of importance:

1) The natural frequency of vertical and horizontal bars;

2) The excitation or forcing frequency;

3) The possibility of resonance;

4) The possibility of fatigue caused by strong turbulence and buffeting.

The natural frequency of bars f_n is estimated by the equation :

$$f_n = \frac{\alpha}{2\pi}\left[\frac{EIg}{wl^3}\right]^{1/2}$$

where :

w = total weight of bar including that of the vibrating fluid

l = unsupported length of the bar

E = Young's modulus

I = moment of inertia

g = acceleration due to gravity

α = coefficient dependant on the end fixings. α varies from $\pi^2 = 9.87$ for a simply supported bar to $4\pi^2/\sqrt{3} = 22.7$ for a bar fixed at both ends. The longer the bar the smaller is the value of α. Continuously supported bars can have a α value of up to 39.48.

Syamalarao (1989) goes on to give details of eleven documented trashrack failure at various plants in Europe and the US, describing the trashrack form, bar dimensions and gives comments about the type and severity of failure. Figure 4.2 shows the summary table from Syamalarao's review of trashrack failure.

Syamalarao concludes that trashrack units at the bottom of intakes, and near side walls are most susceptible to damage, with failures including breaking, twisting or complete removal of vertical bars, loss, and breakage at the point of welding, of horizontal support bars and failure of trashrack anchor bolts.

Jansen (1988) discusses trashrack vibration problems at the Edward Hyatt Powerplant, USA. Here trashracks at the dam outlet suffered from vibration problems due to the "von-Karmon" effect whereby turbulence is created in the wake of flows passing around a bar. Tiny vortices are rapidly formed and shed first on one side of the bar then the other, regularly alternating back and forth. This effect can set the bar in motion and may cause rapid failure by fatigue. To alleviate the problem lateral stabilisers made of butyl rubber were placed between the bars and diagonal bracing was added. As a consequence the magnitude of force on the bars was reduced from 2.15g to 0.1g thus ensuring that the trashrack would not fail through fatigue.

Sell (1971) also examines trashrack design considerations with special reference to vibration problems and discusses the various components of bar vibration in detail. The author concludes that, " If trashracks were to be designed purely for vibration considerations bars would be as nearly square as possible...... This type of trashrack would have a high head loss which is normally not desirable; therefore, the problem is to keep head loss at a minimum, while avoiding a resonant condition".

Figure 4.2 : Details of trashracks which failed during operation (from Syamalarao, 1989).

No.	Power Station (Ref.)	Trashrack form L. B. $\alpha°$ (mm)	Vertical bars: Shape	Vertical bars: Dimensions (mm)	Horizontal bars: Shape	Horizontal bars: Dimensions (mm)	Comments
1a	Ybbs-Persenbeug-Bugl 1	L = 16 000 B = 12 200 α = 72°	20 150	d = 20 b = 150 s = 150 L_2 = 4000		d' = 35 ϕ s' = 965	Failure of bolts after one year
1b	Aschach Bugl 2	L = 21 000 B = 14 200 α = 72°	17 200 25	d = 17-25 b = 200 s = 175 $L_1.L_2.L_3$ = 5250		d' = 30 ϕ s' = 1050	Horizontal bars cracked or broken after two years
1c	Wallsee-Mittel-kirchen Bugl 1	L = 15 800 B = 12 260 α = 72°	17 200 25	d = 17-25 b = 200 s = 175 $L_1.L_2.L_3$ = 5250		d' = 35 ϕ s' = 965	Details are not available
2	Corps of Engineers Neilson 4	L = 20 665 B = n/a α = 83°	19 76	d = 19 b = 76 s = 152	38	d' = 38 b' = 38 s' = 1320 d' ≅ 75 b' ≅ 100 s' ≅ 1320	Failure of rack through breaking of vertical bars
3	Hiwassee dam Schol 6	L = 6100 B = 5744	15.9 76.2	d = 15.9 b = 76.2 s = 152.4 $L_1.L_2.L_3$ = 762	31.8 300	d' = 31.8 b' = 300 s' = 762	Failure of anchor bolts
4	La Plate Vanbell-ingen 7	L = 4400 B = 908 α < 90°	18 180	d = 18 b = 180 s = 178	15 145	d' = 15 b' = 145 s' = 652	Rack members disconnected, bolts failed after one year
5a	Waldbeck II -original Leiss 3	L = 8950 B = 5000 α = 72°	10 70	d = 10 b = 70 s = 40 $L_1.L_3$ = 2915 L_2 = 2950		d' = 20 ϕ s' = 625	Bars broken or torn
5b	Waldbeck II -redesigned Liess 3	L = 8950 B = 5000 α = 72°	15 110	d = 15 b = 110 s = 139 $L_1.L_3$ = 2915 L_2 = 2950		d' = 20 ϕ s' = 625	No report of damage since 1983
6a	Albbruck-Dogern (1934) 5 Schlageter	L = 13 000 B = 79 000 α = 78°	16	d = 16-12 b = 120 s = 166 $L_1.L_2.L_3$ = 3250		d' = 35 ϕ s' = 1490 – 1758	Bars broken or missing
6b	Albbruck-Dogern redesigned (1954)	L = 13 000 B = 79 000 α = 78°	15 8	d = 15-8 b = 120 s = 166		d' = 35 ϕ s' = 993 – 1557	Bars broken or missing
6c	Albbruck-Dogern redesigned (1969)	L = 13 000 B = 79 000 α = 78°	18 150	d = 18 b = 150 s = 166		d' = 45 ϕ s' = 820 – 1000	Inspection in 1976 showed damage. Special clamps for horizontal bars were fixed.

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