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PAP 199

International Association for Hydraulic Research

APPLIED RESEARCH IN CAVITATION IN HYDRAULIC STRUCTURES

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SYNOPSIS

Applied research has been an invaluable tool in minimizing or eliminating destructive cavitation erosion in Bureau of Reclamation structures. Analytical studies, laboratory work, and field investigations have helped to identify the problems, reveal practicable solutions, and demonstrate results obtained. Examples are cited where design changes have greatly reduced or eliminated cavitation in regulating slide gates, at changes of alinement of flow surfaces, at surface irregularities and roughnesses, and in control stations in pipelines having large differential heads and small back pressures. Areas where additional research is needed are also given.

RESUMÉ

La recherche appliquée a constitué un instrument inestimable dans la méthode de réduire ou d'éliminer l'érosion de cavitation très nuisible aux structures du Bureau of Reclamation. Les études analytiques, les travaux de laboratoires et les enquêtes effectuées sur le sol ont aidé à identifier les problèmes, à révéler les solutions possibles, et à démontrer les résultats obtenus Des exemples ayant trait à chaque cas sont cités: à savoir les changements de projets ont beaucoup réduit ou même éliminer la cavitation grâce à l'ajustement des fermetures à grilles, aux changements d'alignement des surfaces d'écoulement, aux irrégularités et à la rugosité du terrain, et enfin au contrôle des stations dans les canalisations ayant de fortes têtes de différentiel et peu de pression de retour. Les régions nécessitant un travail de recherche supplémentaire, sont également mentionnées.

INTRODUCTION

The Bureau of Reclamation, in common with other large water resource development organizations, has encountered damaging cavitation in some of its structures. Typical examples include control valves and gates in facilities which operate under high heads; flow surfaces in sluices, spillways, and outlet works stilling basins that are subjected to high-velocity flows; and in pipeline energy dissipating systems.

In instances where cavitation erosion has occurred, research has been undertaken to determine the cause of the cavitation and means of eliminating or minimizing it. Hydraulic model testing has proven to be a valuable tool in disclosing the general flow mechanisms involved, and in devising modified design concepts that have greatly reduced or prevented further damage. Field testing, theoretical analyses, and library research are used hand in hand with laboratory studies to complete the formidable array of available research tools.

The performance under field conditions is, of course, the ultimate test of the hydraulic design of a structure or component. Wherever possible, full advantage is taken by field and design office personnel to observe prototype structures in operation. Evidences of undesirable performance, operational difficulties, flow-induced vibrations, or damage due to cavitation or other factors are noted. The information is forwarded to the office of the Bureau of Reclamation's Chief Engineer in Denver, Colorado. Analysis of this information, followed when necessary by air or water model studies of the structure, and by library studies using the Bureau's information retrieval system, will usually reveal a practicable method of overcoming the difficulties.

However, most of the Bureau's hydraulic research is done prior to building the structures. On the basis of previous research and experience, a general knowledge has accumulated of the types of problems likely to be encountered in new work. Analytical investigations based on this knowledge, and supplemented when necessary by laboratory studies, are employed to find the best practicable arrangement before the final design is completed. This procedure results in eliminating the cause of difficulties so that the least expensive, most trouble-free hydraulic structures are obtained. It is the procedure extensively used by the Bureau of Reclamation.

HIGH-HEAD SLIDE GATES

The relatively low cost, efficiency, and ruggedness of slide gates make them desirable as controls for high-head outlets. However, in designs made prior to about 1952, serious cavitational erosion occurred on the bottom of the leaves and on the gate bodies. Much of this damage occurred during operation under moderately severe service conditions. To overcome the hydraulic deficiencies, research studies have been made over a period of years to determine general flow conditions in the vicinity of the leaves and in and near the gate slots.

To provide better flow conditions, the gate leaves and housings were revised (Figure 1). The upstream face of the gate leaf was made flat to direct the flow straight downstream and eliminate flow components toward the passage centerline. Secondly, the upstream lower portion of the leaf was sloped 45° This slope joined the upstream face with a long radius convex surface, and joined the seating surface at the extreme bottom with a very short-radius concave curve. The latter provided a sharp, definite spring point for the flow and avoided any tendency for flow to cling and for low pressures to develop. Thirdly, the bottom seating surface was made as narrow as structural considerations permit to place the control point as far downstream as possible. This arrangement allowed use of relatively small gate openings without producing short-tube action and possible cavitation. To obtain a minimum horizontal dimension for the bottom surface, the seal clamp bar was chamfered on the downstream corner (Figure 1). Finally, only the structural thickness needed to support the hydraulic loads of the gate was carried into the gate slots. This permitted great reductions in the dimensions of the gate slots and consequent reductions in slot-induced disturbances. The gate slots, in addition to being greatly reduced in size, were specially shaped.1/ The downstream edges of the slots were offset away from the upstream edges and the offset side faces of the waterway converged at a rate not greater than 1:24 to return the passage to the normal width (Figure 1). The intersection of the converging surfaces with the parallel walls must be very gradual to avoid severe pressure reductions. Ideally, the flat surface is omitted and the downstream slot edges are joined to the parallel walls by curved surfaces having very long radii.

The downstream edge of the opening in the roof of the gate body was offset the same distance as the slot edges on the sides. The floor of the body was horizontal and continued in a straight line. Steel lining was used downstream from the slots to help insure smooth, well alined, obstruction-free surfaces where high-velocity flows occur and no appreciable boundary layer is present.

The excellent performance of this type of slide gate has been proved by years of nearly trouble-free operation on Bureau of Reclamation projects. Examples are found in the 7.5- by 9.0-foot (2.29- by 2.75-m) gates operating under a 235-foot (71.7-m) head at Palisades Dam in Idaho; the 2.25- by 3.0-foot (0.69- by 0.91-m) gate under a 155-foot (47.2-m) head at Carter Lake Dam outlet works in Colorado; the 4.0- by 4.0-foot (1.22- by 1.22-m) gate under a 165-foot (50.3-m) head* in Navajo Dam, New Mexico; and in the three 9.0- by 10.5-foot (2.74- by 3.20-m) gates under a 240-foot (73.2-m) head* in the tunnel plug outlet works in Glen Canyon Dam, Arizona.

Currently, in designing the 3.5- by 4.0-foot (1.07- by 1.22-m) outlet control gates for the 355- and 290-foot (108.2- and 88.4-m) heads of the Morrow Point and Ruedi Dams in Colorado, the waterway through the gate was sloped downward 30°. The gate leaves and bonnets were placed vertically for ease of handling during erection and maintenance. This resulted in an angle of 60° between the flow passage and the gate leaf instead of the usual 90°. Furthermore, the walls of the downstream gate body of the Ruedi gates were diverged to obtain maximum spreading of the flow before the water enters the hydraulic jump-type stilling basin.

These departures from the usual concepts of our high-head slide gates left serious questions about the adequacy of the new designs. Model studies on a 1:9 scale ratio quickly showed that the previously mentioned gate slot design would not perform satisfactorily with the sloping waterway. Diverging the downstream walls intensified the problem and severe cavitation inevitably would have occurred. A new slot design using an abrupt 2-inch (5.08-cm) outward offset of the walls a short distance downstream from the slot (Figure 1) was developed for the new gate. Studies indicate that this slot design, in conjunction with a gate leaf having a 60° sloping bottom, can be used with converging, parallel, or diverging downstream gate bodies without inducing cavitation. The same slot design probably can be used on horizontal gates, and diverging downstream bodies will probably be practical for almost any operating heads.

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1. "Hydraulic Characteristics of Gate Slots," by J. W. Ball, Paper No. 2224, Journal, Hydraulics Division, ASCE, October 1959

*Actual heads experienced during operation to date. Design heads are appreciably higher.

102-INCH RIVER OUTLETS--GRAND COULEE DAM

An example of a "built-in" cavitation generator was found near the exits of the 102-inch- (2.59-m) diameter outlet tubes in Grand Coulee Dam in the State of Washington. Sixty of these outlets pass through the dam--20 in the lower tier, 20 in the intermediate tier, and 20 in the upper tier. In the intermediate and upper tiers the downstream ends of the passages turn downward to direct the flows onto the spillway face (Figure 2). The ring-follower gates controlling the flow through these outlets are operated either fully opened or fully closed. When the gates are opened, the conduits flow completely full and the downward bends near the conduit exits tend to create a siphoning effect which could lower the pressure gradient in the horizontal portions of the tubes to the point where cavitation could occur. To prevent this, constricting cones were placed at the end of the closed-conduit portions of the outlets to keep the pressure gradient at or above atmospheric pressure.

This part of the design proved very satisfactory during operation of the structure. However, an unnoticed, abrupt, away-from-the-flow change of alinement of the boundary surfaces occurs at each cone outlet where it discharges into a concrete trough leading to the spillway face. This abrupt change of alinement is the "built-in" cavitation generator, which is located in a region where flow velocities reach 116 feet per second (30.4 meters per second). The destructiveness of this cavitation was demonstrated by extensive erosion in all 40 of the intermediate and upper outlets a short distance downstream from the cones (Figure 2). The most seriously damaged outlet is shown in Figure 3.

To solve the problem in this existing structure, aeration grooves similar in cross section to conventional gate slots were cut into the concrete just downstream from the ends of the steel cones. The grooves were 6 inches wide, 5 inches deep (15.3 and 12.7 cm), and the downstream edge of each groove was offset 3/4 inch (19 mm) from the normal surface of the concrete trough (Figure 2). The edge was rounded to avoid chipping and spalling, and was followed by a slope of about 1:36 that intersected the normal surface of the trough some distance downstream. No further damage has occurred on the concrete surfaces since these revisions were made, although some of the tubes have been in service for periods ranging from 3,000 to 5,000 hours.

SURFACE IRREGULARITIES

Experience has shown that surface irregularities such as voids, roughness, changes of alinement, protrusions, undulations, and abrupt offsets can cause cavitation damage in regions of high velocity flows.2/3/ The Bureau of Reclamation has carried out considerable research on this problem to develop design standards for the degrees of surface smoothness required for different types of hydraulic service. At present, these studies are far from complete, but a number of guides have been formulated for interim use.4/5/ These guides

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2. "Cavitation in Hydraulic Structures," a symposium by J. K. Vennard, J. C. Harrold, J. E. Warnock, and G. H. Hickox, Transactions ASCE, Volume 112, 1947, Paper No. 2295
3. "Cavitation in Hydraulic Structures: Problems Created by Cavitation Phenomena," by F. R. Brown, Paper No. 3393, Journal, Hydraulics Division, ASCE, January 1963
4. "Cavitation Damage of Roughened Concrete Surfaces," by Donald Colgate, Paper No. 2241, Journal, Hydraulics Division, ASCE, October 1959
5. "Construction Finishes and High Velocity Flow," by J. W. Ball, Paper No. 3646, Journal, Construction Division, ASCE, September 1963

are based upon the type of surface irregularity, the average velocity, evaluation of the probable boundary layer thickness and distribution, quantity of air present in the water, and depth of flow. Very smooth, well alined finishes are needed for surfaces subjected to high velocity streams, particularly in areas immediately downstream from gates and valves where the turbulent boundary layer has been destroyed.

Cavitation damage has been known to occur at relatively small surface imperfections. On the cast iron bodies of the 54-inch (1.37-m) hollow-jet valves at Monticello Dam in California, (head = 242 feet), sags in the coal-tar paint triggered cavitation erosion. At points of casting imperfections, cavitated areas 7 inches wide, 13 inches long, and 1-1/4 inches deep developed (18, 33, and 3.2 cm). In the 96-inch- (2.44-m) diameter hollow-jet valves at Trinity Dam outlet works in California (head = 375 feet or 114 m) imperfections at inadequately dressed welded joints in the flow path caused damage. Cavitation also resulted near the downstream end of these valves where the rolled plate forming the outer shell was pulled outward by a continuous weld to an exterior stiffening ring. These difficulties in the hollow-jet valve are of considerable significance because experience has shown the basic design to be entirely free of cavitation. Unfortunately, this inherently good performance can be negated by improper construction.

Obtaining the smooth, well alined flow surfaces during initial construction is only part of the problem. Retaining the smooth surfaces over a period of years is also necessary. Structures that have withstood high velocity flows for long periods without distress have been known to eventually show cavitation damage due to uncorrected weathering, accumulated wear, or abuse from impacts of heavy objects. Specific examples are found in structures like the approach chute to the stilling basin at Palisades Dam and in the outlet works of Wanship Dam.

One method of avoiding cavitation erosion in hydraulic structures is to place the flow surface away from the high velocity flows. This method is now used to a limited degree, and may find greater use in the future. For instance, research may show that the conventional chutes leading from control gates or valves to stilling basins can be omitted. Another method of avoiding cavitation might be to develop designs which would insure that air is present in intimate mixture with the water flowing along the boundary surfaces. This method is limited to systems where entrained air can escape before trouble is experienced with downstream air accumulations. Still another method would be to cover the concrete or steel surfaces with resilient materials, such as neoprene, to absorb the cavitation implosions and prevent cavitation erosion.

A better but more expensive first-cost method is to provide corrosion-resistant, paint-free, accurately alined metal surfaces. This practice is being followed in recent Bureau of Reclamation slide gate structures by using stainless steel-clad plates firmly anchored to concrete walls and floors. Studies are underway to determine how far downstream these plates must be placed to allow sufficient turbulent boundary layer development so that no damage will occur when the flow moves onto the concrete surfaces.

SUDDEN ENLARGEMENTS

Sudden enlargement-type conduit sections downstream from fixed orifices or regulating valves provide simple and economical energy dissipation systems (Figure 4).6/ However, when the head differentials across the orifices or

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6. "Hydraulic Model Studies of a Sudden Enlargement Energy Dissipator Used Downstream from a Gate Valve," by W. P. Simmons, Report No. Hyd-535, Bureau of Reclamation, Denver, Colorado, August 1964

valves become great, cavitation can be severe and damage to the control valves and the interior surfaces of the enlargement may result. Cavitation will be particularly severe when the flow discharges into regions of relatively low back pressures. Extensive research has been done to prevent the cavitation and to take advantage of the simple and economical energy dissipators afforded by the sudden enlargements.

Studies made with fixed, circular, concentric orifices at head differentials up to 300 feet (91.5 m) of water and total upstream heads up to 500 feet (152.5 m) established nondimensional index values for incipient cavitation.7/8/ Similar but more limited tests established values for standard water works gate valves and for special valves followed by sudden enlargements.7/8/9/ Tests now in progress are establishing values for butterfly valves followed immediately by enlargements, or connected to enlargements by very short pipelines.

Practical use is being made of sudden enlargements downstream from control valves. On the Delano-Earlimart irrigation distribution system in California, 8-inch-(20.3-cm) diameter gate valves with special downstream bodies that diverge rapidly to join 14-inch-diameter downstream conduits have operated since 1957 without cavitation erosion. Maximum head on the system is 150 feet (45.7 m) and the back pressure is 8 feet (2.44 m). Most operation has been at somewhat smaller upstream heads due to heavy water demands on the system. At some valve installations in this system, and in other systems where sudden enlargements are undesirable, neoprene-lined pipes having the same diameter as the valve have been successfully used to avoid cavitation damage under moderate operating conditions.

Sudden enlargements also have been used successfully in the Davis Aqueduct in Utah. In this system, 18 small turnouts deliver up to 15 cfs (0.42 cms) each, at upstream heads up to 415 feet (126.5 m). Discharge is into pipe laterals operating under only a few feet of head. This system, in which each turnout is operated by the owner of the farm being served, has been performing without difficulty since 1959.

CONCLUSIONS

Applied research into general flow mechanisms has developed considerable information on how to avoid cavitation and cavitation erosion in high-head and high-velocity flow systems. This research also has indicated that structures may be designed for long, trouble-free life when cavitation is unavoidable within the system.

Regardless of the great advances made to the present, much work remains. On the subject of gate slots we must learn if our new design for gates with sloping passages would also be better for gates with horizontal passages, and

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7. "Sudden Enlargements in Pipelines," by J. W. Ball, Paper No. 3340, Journal, Power Division, ASCE, December 1962.
8. "Progress Report on Hydraulic Characteristics of Pipeline Orifices and Sudden Enlargements Used for Energy Dissipators," by J. W. Ball and W. P. Simmons, Report No. Hyd-519, Bureau of Reclamation, Denver, Colorado, December 1963
9. "Cavitation Characteristics of Gate Valves and Globe Valves Used as Flow Regulators Under Heads up to About 125 Feet," by J. W. Ball, Paper No. 56-F-10, Transactions, ASME, August 1957

whether or not some other design might be even better. We must determine the degree of boundary layer growth needed before high velocity streams can pass safely from specially protected surfaces onto concrete surfaces. We must more specifically determine the maximum sizes of voids, air-bubble cavities, and degrees of surface irregularities that are permissible in surfaces subjected to high-velocity flows. Additional testing is needed to develop and evaluate cavitation-resistant protective coatings, including rigid, hard-curing epoxies and softer coatings like rubber, neoprene, and resilient epoxies. Methods of application and bonding characteristics of the coatings also must be considered to obtain systems that will endure severe prototype conditions. Further development work in the field of sudden enlargements in pipeline flow control stations is needed to obtain optimum economy and best service life. To encompass these and other factors, we need a better knowledge of construction tolerances required to avoid initial damage as well as later trouble due to surface deterioration with time and use.

On the basis of this information, new design concepts and new design parameters must be evolved to make better, more efficient use of our materials, time, and money. The Bureau of Reclamation will continue to do its part in developing this knowledge.

FIGURE CAPTIONS

Figure 1. Slide gate details

Figure 1. Détails sur la fermeture à grilles

Figure 2. Cavitation in outlet tubes at Grand Coulee Dam

Figure 2. Cavitation dans les conduits dégorgeoirs du barrage de Grand Coulée

Figure 3. Severest damage in Grand Coulee outlets prior to repair. New reinforcing steel and longitudinal screeds are in place

Figure 3. Très graves dégâts survenus dans les conduits du barrage de Grand Coulée. Avant les travaux de réparation. Nouvelles tiges de renforcement en acier et placées longitudinalement

Figure 4. Typical sudden enlargement downstream from a gate valve

Figure 4. Aggrandissement soudain et caractéristique de l'ecoulement en aval d'un robinet-vanne

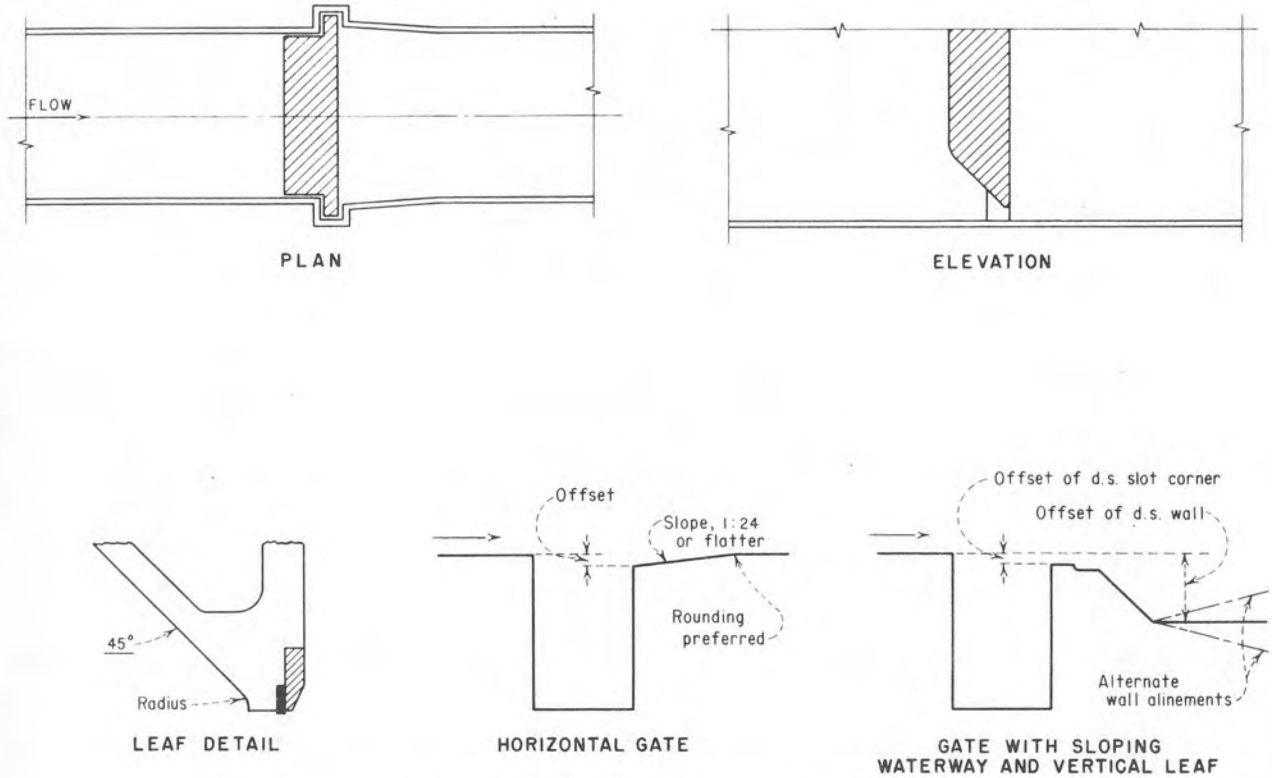

Fig. 1. Slide gate details.

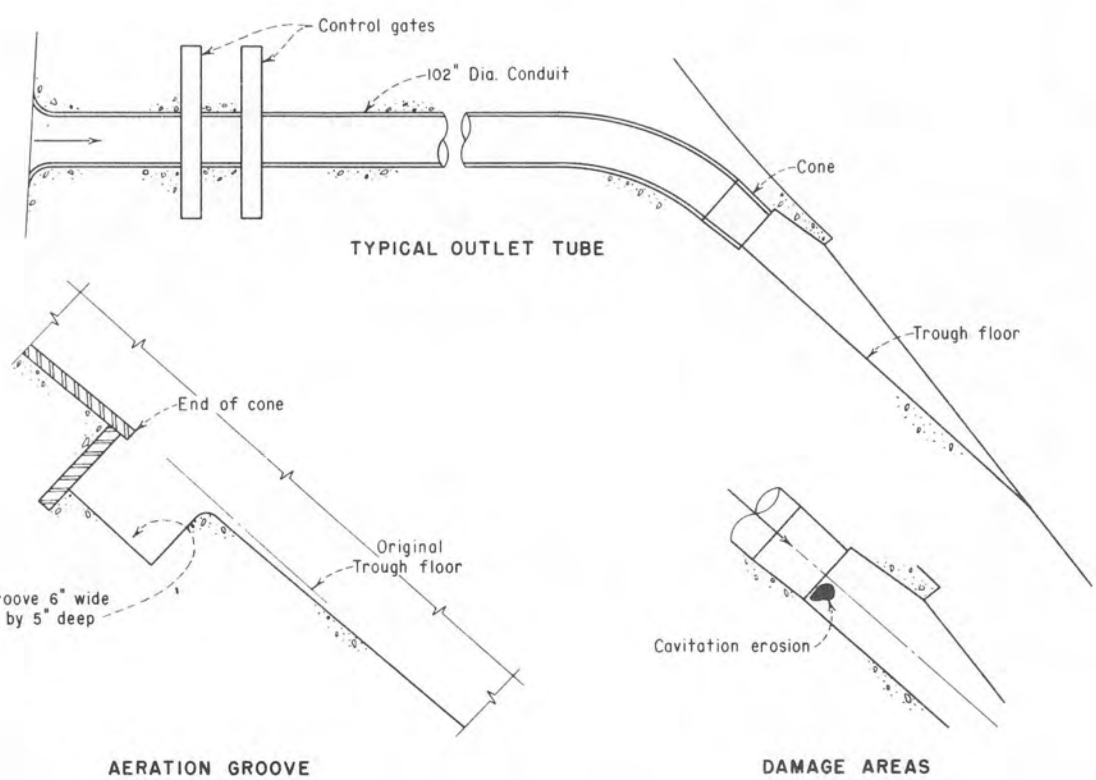

Fig. 2. Cavitation in outlet tubes at Grand Coulee Dam.

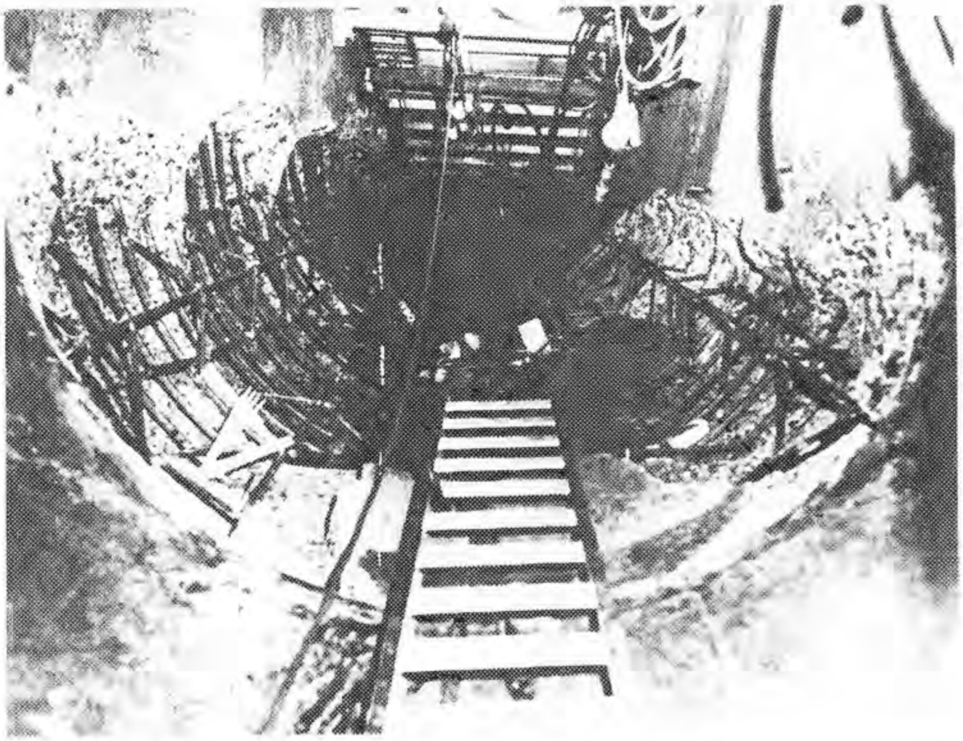

Fig. 3. Severest damage in Grand Coulee outlets prior to repair. New reinforcing steel and longitudinal screeds are in place.

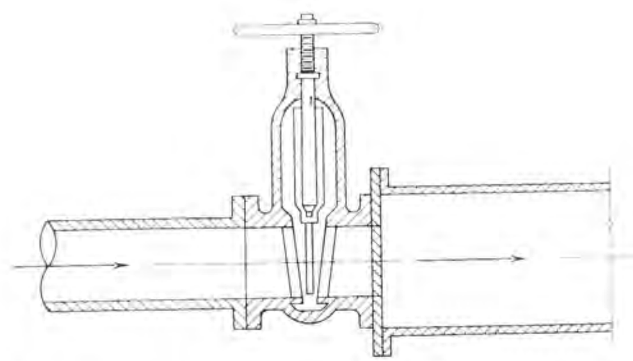

Fig. 4. Typical sudden enlargement downstream from a gate valve.