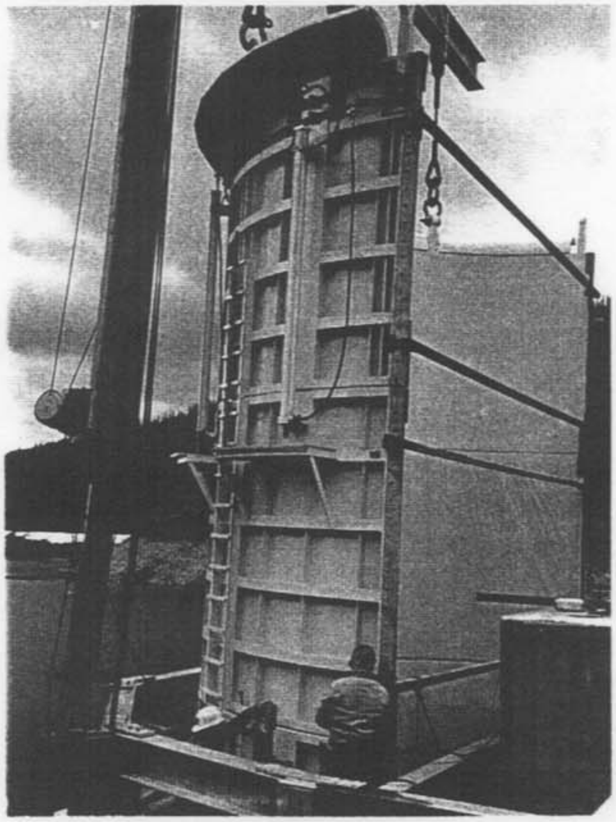
WATER OPERATION AND MAINTENANCE

BULLETIN NO. 176

June 1996



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UNITED STATES DEPARTMENT OF THE INTERIOR
Bureau of Reclamation

The Water Operation and Maintenance Bulletin is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Reclamation personnel and water user groups for operating and maintaining project facilities.

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Cover photograph: Hungry Horse Dam Selective Withdrawal System—workers installing one of the control gates. Only the top 26 feet of the 100-foot-high, 40-ton gate is actually showing.

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Bureau of Reclamation

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SELECTIVE WITHDRAWAL FOR HUNGRY HORSE DAM TO IMPROVE FISHERY HABITAT

For years it has been recognized that the discharge temperatures from the powerplant at Hungry Horse Dam have been detrimental to the downstream fish population. Last fall, a newly installed selective withdrawal system for improving downstream environmental conditions became reality.

Hungry Horse Dam, built in the early 1950's, is located about 15 miles south of the western entrance to Glacier National Park, Montana. The multifunctional dam, owned and operated by the Bureau of Reclamation (Reclamation), provides hydroelectric power, flood control, and water storage. The structure is a 564-foot-high thin arch dam, having a total storage capacity of 3,468,000 acre-feet. The powerplant has four hydroelectric units, with a total generating capacity of 428 megawatts. Releases through the plant range from 145 to 13,000 cubic feet per second.

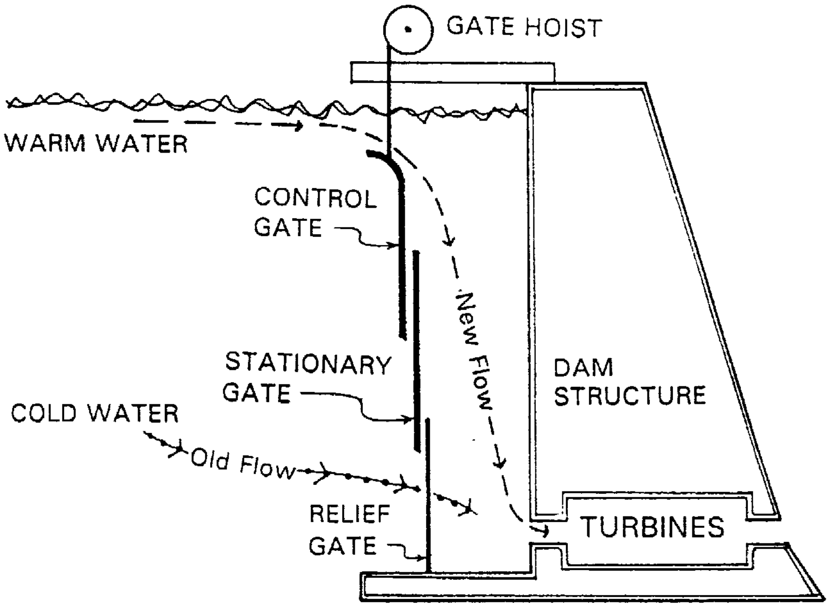
Hungry Horse Dam—564-foot-high thin arch dam located on the South Fork of the Flathead River system.

Although the Hungry Horse drainage area provides about 40 percent of the annual runoff into the Flathead basin, Hungry Horse Reservoir, which is on the South Fork of the Flathead River, provides only a minor amount of water during spring and early summer. As the summer progresses, the natural flow in the other two forks of the Flathead River decrease, and flows from the dam for power generation increase. When summer ends, water releases from the dam are significantly increased to meet water and power requirements. As a result, the dam becomes the major source of cold water for the river, heavily impacting the temperatures in the 40-mile stretch between the dam and Flathead Lake.

Prior to installation of the selective withdrawal system, water for the powerplant was drawn from about 240 feet below the surface of Hungry Horse Reservoir. Water at this level is extremely cold because the deeper water is not warmed by the summer sun. Cold water released from the powerplant causes thermal shock to fish and impacts the organisms and aquatic insect communities that the fish feed upon downstream from the dam. Two species of fish that are heavily affected by degradation of their habitat are the bull trout and westernslope cutthroat trout.

August 1995 was the first time operators of the dam were able to release water as warm as 59 °F, compared to previous normal releases of about 40 °F. Based on a study performed by the Montana Department of Fish, Wildlife, and Parks, the new selective withdrawal system is expected to help promote fish reproduction and improve the fish growth rate in the river by three times the present rate.

Located inside each of the four existing trashrack structures, the unique withdrawal system employs three semi-cylindrical gates similar to a three-section telescope cut in half lengthwise and stood on end. The three sections, when fully extended, are approximately 237 feet high. The average diameter of the semi-cylindrical gates is 20.5 feet. The upper section, referred to as the control gate, is suspended from a large hoist system on top of the dam so it can move up and down to a depth of about 120 feet. The control gate, which is 100 feet high and weighs 40 tons, forces the warmer waters from the surface of the reservoir to be withdrawn over the gate and through the dam. The depth of water being withdrawn over the gate can be controlled by adjusting the control gate height. The higher the control gate setting with respect to the water surface, the warmer the releases. Five side-by-side slide gates, which are individually controlled by underwater hydraulic cylinders, are located within the control gate, about 50 feet from the top. These gates provide additional fine tuning of the system to balance warm water discharges with other biological concerns within the reservoir.



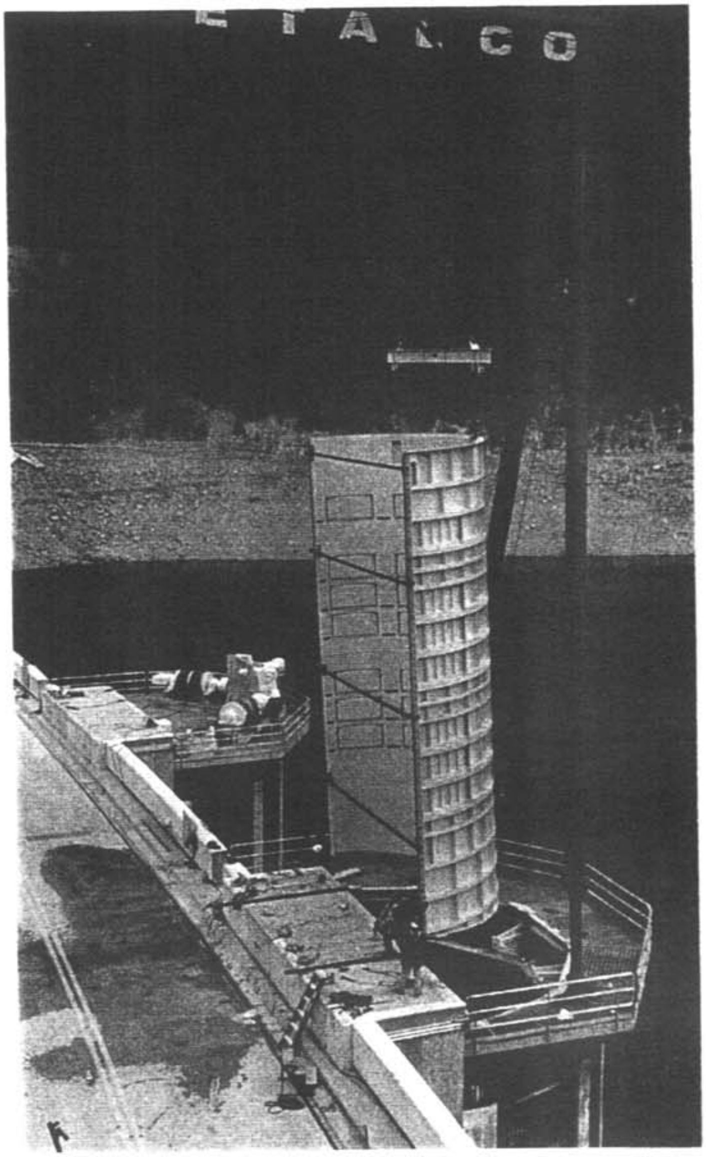
The three gate sections located inside each trashrack structure are the major components of the selective withdrawal system. The 100-foot-high control gate moves up or down past the stationary gate. Its position, controlled by the hoist, is determined by flows, water surface elevation, and water temperatures. When not in use, the relief gate is lifted to the surface and stored on hangers under the gate hoist platform.

The other two gates of the withdrawal system are the intermediate section, referred to as the stationary gate, and the bottom section, referred to as the relief gate. The stationary gate, which is actually three independent stacked gates comprising a total height of 100 feet, acts like the barrel of the telescope, which the control gate slides by. The function of the relief gate, which rests on the concrete approach apron at the bottom of the trashrack structure, is to protect the system from overloads. If the system is ever improperly operated, relief panels within the relief gate will open and reduce the pressure against the system. Each relief gate has 35 relief panels approximately 2 feet high by 4 feet wide. During the winter months, or whenever the selective withdrawal is not needed, the relief gates, which are approximately 37 feet high, are raised and stored just below the hoist platform to minimize head loss, consequently increasing the turbine efficiency.

The gates were fabricated with structural steel rolled plates reinforced with channels or wide flanged beams. All the gates work within a provided guide system that runs the full height of the trashrack structure. The guide system was installed in the existing penstock stoplog guides. By using the existing stoplog guides, a significant cost savings was made.

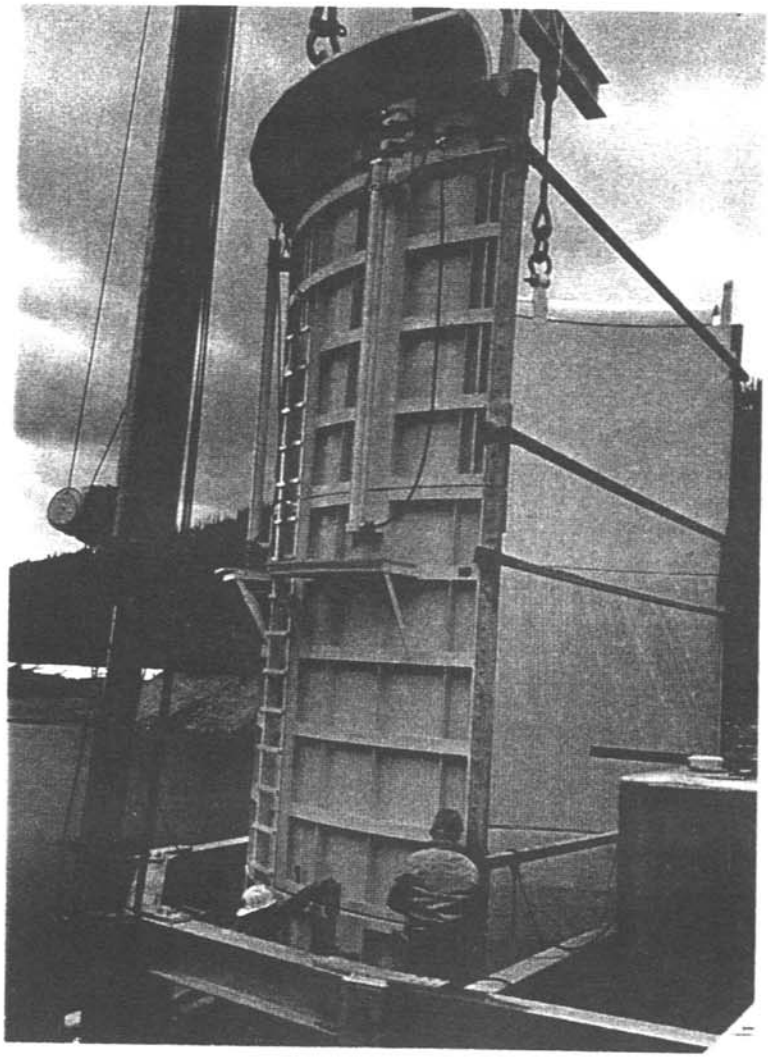
Temperature sensors were installed every 5 feet within the top 180 feet of the reservoir and also at each turbine. The reservoir temperature profile, water release temperatures, and the gate positions are all monitored by a programmable logic controller (PLC) located within the powerhouse. The PLCs continuous monitoring provides needed information to the operators for adjusting the gate settings to produce the required water temperature.

Before the actual design could be completed, several studies were required to predict the performance of the system. Water hammer pressure spikes during emergency turbine shut downs, head losses across the system during start up and normal operation, and increased susceptibility to vortex action due to the restricted entrance were major concerns that had to be addressed.



Using the contractor's crane, the 37-foot-high relief gate is being inserted into the guides of the number 2 trashrack structure. Also visible is some of the 35 relief panels located within the relief gage.

A physical model performance study was conducted at Reclamation's Water Resources Research Laboratory in Denver. A 1:18 scale hydraulic model of a single power penstock intake and trashrack structure was constructed for this purpose. The two primary objectives of the physical model test were to determine the maximum additional head loss that will be developed by the introduction of the selective withdrawal system and to establish the minimum submergence necessary to prevent



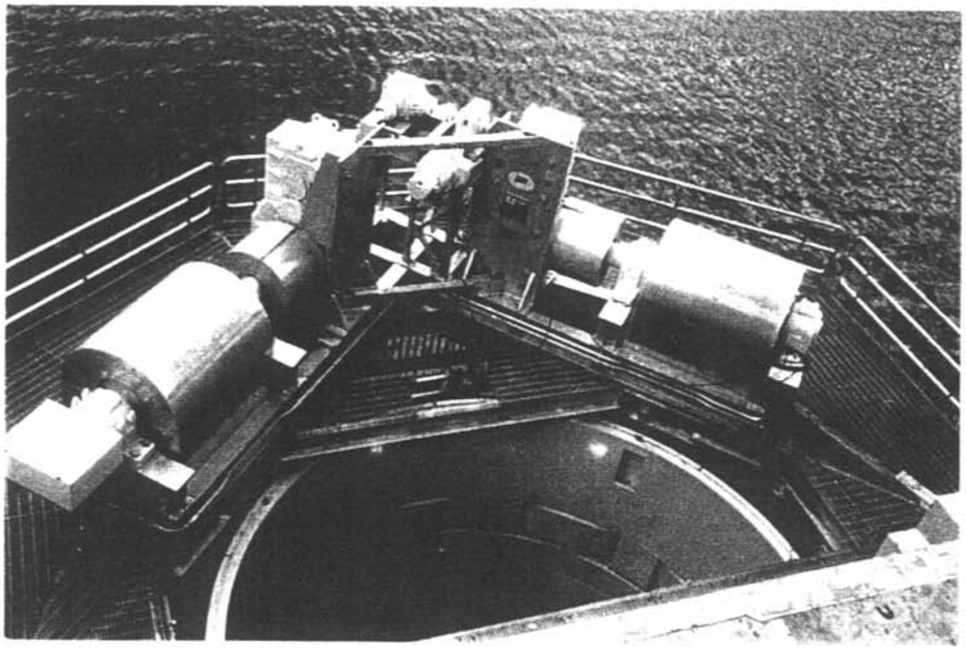
Workers installing one of the control gates. Only the top 26 feet of the 100-foot-high, 40-ton gate is actually showing.

unfavorable air entraining vortex conditions over the range of discharges. The minimum submergence was identified to be approximately 20 feet. The maximum expected head loss was found to be 5.0 feet at the maximum passable discharge at the minimum submergence of 20 feet. The head loss information provided by the model study was very important for the structural design of the system and for determining the friction loads generated by the control gate, since the gate will be operated with the hydro units in operation.

A computer model was set up to predict the negative pressures spikes associated with water hammer that would occur when the wicket gates at the power turbines undergo an emergency closure. The program also helped determine the positive differential head developed during start up of the units. The results of the study indicated that the governor speed for the wicket gates would have to be reduced to keep the pressures within safe limits.

To the delight of the designers and powerplant operators, the actual prototype correlated closely with the model studies. The maximum head loss, for the system operating at minimum submergence of 20 feet and a maximum flow through the turbines, is between 4 and 5 feet.

The new system was developed, designed, modeled, and tested by the Bureau of Reclamation's Technical Service Center in Denver, Colorado, in cooperation with Reclamation's Pacific Northwest Regional Office at Boise, Idaho. Actual cost for the selective withdrawal system was about $6.8 million. The 1-year construction project has gone well and is nearly completed. After completion, the system will be able to control the temperature of the water from the powerplant throughout its full operating range up to its maximum discharge of 13,000 cubic feet per second, returning the river to its almost natural state.



The 60-ton dual drum control gate hoist system. The hoist deck grating is removed, showing the relief gate in its upper stored position.

Individuals contributing to this article were Dennis Christenson, Project Manager; Robert Sund, Principal Designer; Rick Christensen, Mechanical Equipment Group Team Member; Joseph Kubitschek, Water Resources Research Laboratory; Christopher Morell, Engineering Services; and Brian Marotz, Montana Department of Fish, Wildlife, and Parks.

For further information concerning this article, please contact Mr. Bob Sund, Mechanical Equipment Group, D-8410, PO Box 25007, Denver, Colorado 80225; telephone: (303) 236-8410 ext. 260.

ACCESS TO FORMERLY INACCESSIBLE FEATURES

by Al Graves[1]

The examination of inaccessible features on dams and other hydraulic structures has been a problem for operations and maintenance examiners as well as dam safety examiners. The need to examine the inaccessible feature has been agonized over and in many cases postponed. Bridges usually require the rental of a crane with a man-basket and, in some cases, the closure of a highway. Large spillway gates involve the rigging of temporary scaffolding or other costly means of accessing the critical sections of the gates. These problems have led project managers to essentially neglect the close-up inspection of the inaccessible features and assume that examination with field glasses is sufficient.

The failure of a 50-foot-high spillway gate at Folsom Dam, outside Sacramento, California, in July 1995 has led to new ideas about the examination of normally inaccessible features. Following the failure, Corps of Engineers, Bureau of Reclamation, and California Department of Transportation (Caltrans) engineers mounted an effort to access and inspect the other seven spillway gates at Folsom. Based on the Caltrans model of using alpine mountaineering techniques to safely access the gate structures, which hang over the top of the 300 foot high spillway, engineers from the three agencies donned climbing harnesses and rigged belay lines to inspect every joint on the remaining seven gate structures.

The techniques used in the Folsom inspection were new to dam inspections but tried and proven in mountaineering for years. The application of roped access to damsite cliffs and even dam faces had been a part of the Bureau of Reclamation's (Reclamation) investigations for decades, but the old "high scaling" techniques differ in many ways from the new techniques.

The first difference between the two approaches is the rope itself. Old standards were based on manila lines with steel cores. The use of the lines, the equipment used with the lines, and the upkeep and storage of the lines were all based on the properties of manila rope. Tests conducted by Reclamation have concluded that the standard rope used for years in high scaling activities is no longer considered safe and that the techniques based on that rope no longer apply.

Mountaineering techniques are based on the use of dynamic and static nylon kernmantle ropes. The kernmantle rope has two components: the kern and the mantle. The mantle is the tough nylon sheath which protects the kern, or the interior of the rope. Dynamic kernmantle ropes are designed to stretch. During a fall, significant loads are placed on the rope (and the falling climber) and the elongation of the rope consumes much of the energy of the fall, preventing a fatal shock load on the falling climber.

Static kernmantle ropes do not have the ability to stretch and are used for purposes different from the dynamic line. Static nylon ropes are essentially replacements for the old manila line.

The second difference between high scaling and mountaineering techniques is in the method of access. In high scaling, the roped personnel usually start at a high point and descend to a low point

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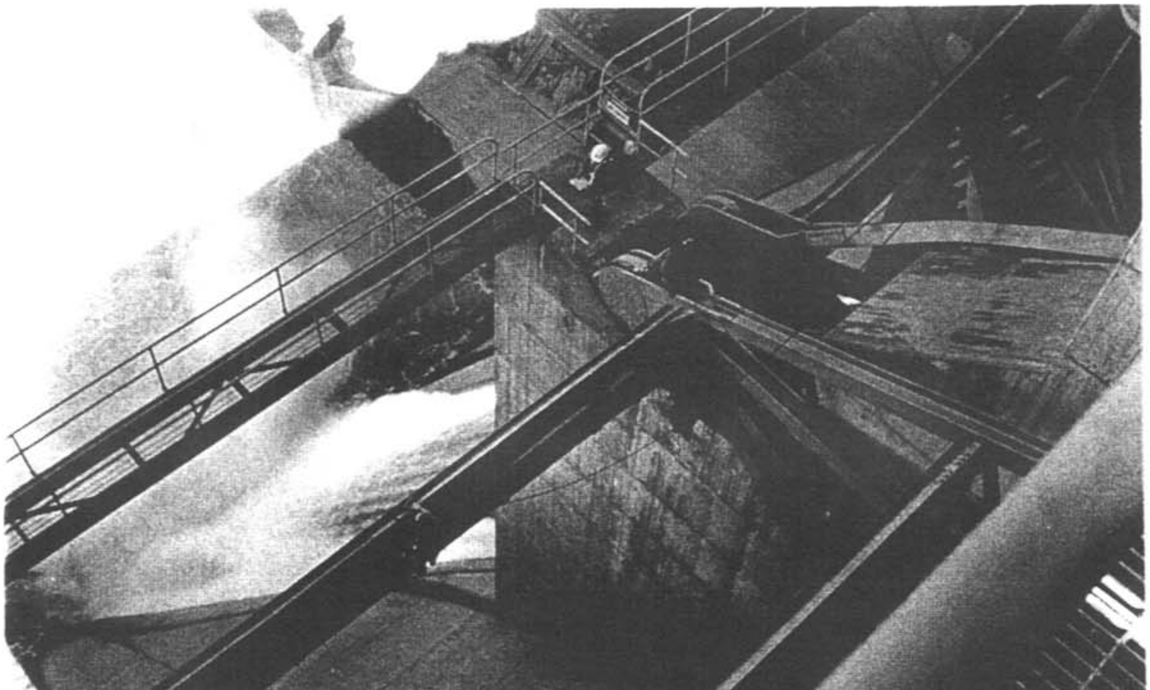
Examination of radial gate at Folsom Dam.



(commonly known as rappelling), or the roped personnel are at a fixed location and tied to a fixed rope. The fixed line used in the high scaling techiques is anchored at a high point above the roped personnel.

In the new approach, the roped personnel are connected to an anchor point through another person who is referred to as the "belayer." Using a dynamic line, the climber ascends, descends, or traverses a structure with his life line rigged through a friction device which is usually connected to a belayer, and the belayer, in turn, is connected to a solid anchor. The belayer feeds out rope to the climber through the friction device, and if the climber should fall, the belayer locks the friction device with his brake hand, arresting the fall.

The new techniques and materials allow safe access to previously inaccessible features and relatively inexpensive examination of features previously inspected from the end of a crane. But, like the old high scaling techniques, the new approach still requires extensive training of personnel to assure safe operations.

Reclamation is currently in the process of writing new fall protection standards based on the new materials and techniques, and it is hoped that these standards can be incorporated in Reclamation's Occupational Health and Safety Manual. The standards will include minimum requirements for training as well as the proper application of techniques to various situations.

Personnel in Reclamation's Technical Service Center (TSC) have formed a team called the TSC Climbing Services (Climbing Services). Members of the Climbing Services participated in the Folsom inspections and have subsequently received 40 hours of training using the new techniques. In addition, during their short existence, they have performed examinations of spillway gates, spillway tunnels, concrete dam faces, and bridge trusses.

Personnel in Reclamation's regional and area offices also have capabilities to access formerly inaccessible features using the new techniques, and efforts to coordinate training and techniques are underway. Four of Reclamation's five regions and the TSC are working together to write new fall protection standards and to produce guidelines on the application of the new materials and techniques.

Information regarding the new techiques and materials and the Climbing Services can be obtained by contacting the author at (303) 236-9000, ext. 682.

Photos were provided by Mr. Frank Jackmauh, Bureau of Reclamation, Structural Analysis Group, D-8110, PO Box 25007, Denver, Colorado 80225.

Understanding Piping and Seepage Failures - The No. 1 Dam Safety Problem in the West[2]

by J. Lawrence Von Thun

BACKGROUND

No, it is not earthquakes! No, it is not overtopping as a result of floods! It turns out that for dams greater than 50 feet high, piping is the predominant failure mode in the Western United States.

An awareness of the relative criticality of the various threats to the safety of a dam is important in the conduct of dam safety programs. Thus, in the early 1980's, as part of the Bureau of Reclamation's (Reclamation) dam safety program development, the author attempted to gain a general understanding of the relative risk of failure of dams in the United States. This was done by examining failure rates according to height, date of construction, type, region of the country (Eastern or Western United States) and mode of failure [1, 2]. Some of the results of that study that are relevant to earthfill dams of the Western United States are summarized in tables 1, 2, and 3. Table 1 illustrates the distribution of dams by type, height, age, and location; table 2 illustrates failure rates for earth dams by these categories; and table 3 provides a breakdown of the percent of failures by type.

The key statistic, relative to the subject of this paper, is that the study showed that 60 percent of the dam failures in the Western United States for earth dams greater than 50 feet high were classified as piping failures.

THE PROBLEM

The presence of seepage or potentially adverse symptoms of seepage raises many questions for consideration by engineers responsible for making dam safety evaluations:

- Is this seepage serious? Is failure likely? Is it imminent?
- Should the seepage be monitored? If so, how and how often?
- Is the seepage carrying any materials?
- Does the seepage flow have the potential to pipe material from the dam and from the foundation?
- What are the potential consequences of an upward gradient producing seepage flow at and beyond the downstream toe at the site?
- Under what circumstances of seepage and potential piping and uplift should instrumentation be installed, inspection and monitoring be conducted, or remedial measures be taken?

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[2] This article is adapted from a paper presented at the 1996 Western Regional Conference of the Association of State Dam Safety Officials.

Table 1.—United States dams inventory
Number of dams and length of service
Categorized by age, height, type, and location[1]

	Constructed					
	Before 1930		1930-60		After 1960	
Height (feet)	No. of dams	No. of safe years operation	No. of dams	No. of safe years operation	No. of dams	No. of safe years operation
Type: arch—location: east (of 105° meridian)						
0 - 50	51	3,837	20	837	4	53
50 - 100	8	459	9	351	2	12
100 - 300	8	469	4	174	1	17
>300	—	—	—	—	—	—
Type: arch—location: west						
0 - 50	31	1,996	11	440	3	43
50 - 100	38	2,250	8	356	5	70
100 - 300	31	1,824	36	1,345	12	179
>300	2	102	4	129	7	93
Type: buttress and gravity—location: east						
0 - 50	1,632	125,361	1,040	40,248	283	3,761
50 - 100	134	8,531	70	2,373	38	500
100 - 300	29	1,804	49	1,723	11	145
>300	—	—	1	36	—	—
Type: buttress and gravity—location: west						
0 - 50	83	5,467	72	2,675	18	247
50 - 100	24	1,639	15	662	4	61
100 - 300	25	1,605	18	518	13	166
>300	1	51	4	126	4	40
Type: earth—location: east						
0 - 50	3,418	264,562	15,697	458,624	19,622	241,506
50 - 100	139	9,452	517	15,064	1,211	13,877
100 - 300	24	1,506	100	3,213	149	1,612
>300	—	—	1	25	—	—
Type: earth—location: west						
0 - 50	1,616	113,556	3,324	103,256	1,867	24,207
50 - 100	114	7,836	260	8,200	270	3,295
100 - 300	23	1,480	108	3,278	139	1,666
>300	—	—	3	72	14	193
Type: rockfill—location: east						
0 - 50	249	20,953	90	3,116	42	567
50 - 100	10	812	12	376	24	301
100 - 300	3	172	12	394	13	117
>300	—	—	—	—	3	28
Type: rockfill—location: west						
0 - 50	48	3,347	37	1,401	22	257
50 - 100	12	887	4	145	8	105
100 - 300	9	557	13	376	14	199
>300	1	54	5	150	5	42

Note: Table is continued on following page.

Table 1.—United States dams inventory
Number of dams and length of service
Categorized by age, height, type, and location[1] (continued)

	Constructed					
	Before 1930		1930-60		After 1960	
Height (feet)	No. of dams	No. of safe years operation	No. of dams	No. of safe years operation	No. of dams	No. of safe years operation
Type: other—location: east						
0 - 50	291	24,257	210	7,476	142	1,881
50 - 100	2	187	7	198	5	37
100 - 300	1	63	7	175	37	190
>300	—	—	2	49	8	55
Type: other—location: west						
0 - 50	43	2,898	32	1,172	17	226
50 - 100						
100 - 300						
>300						

[1] From U.S. Army Corps of Engineers Inventory of Dams through 1979.

Table 2.—Western United States - earth dams
Failure rate data for parameter groups by age and height

Dams considered	No. of dams	Years operation	No. of failures	Annual rate x 10^{-4}	Rate dam	Accident	Annual rate x 10^{-4}	Rate dam
By age								
<1930	1,850	122,872	50	4.0	.027			
<1930 > 50 ft	171	9,316	17	18.2	.099	44	47.2	.257
1930-60	3,727	114,806	11	1.0	.003			
1930-60 >50 ft	377	11,550	3	2.6	.008	17	14.7	.045
>1960	2,314	29,361	13	4.4	.0056			
<1960 >50 ft	433	5,154	5	9.7	.0115	17	33.0	.039
By height								
<50	6,910	241,019	49	2.0	.007			
<50 >1930	5,231	127,463	16	1.3	.003			
50-100	689	19,311	20	10.4	.029	44	22.8	.064
50-100 >1930	545	11,495	5	4.3	.009	16	13.9	.029
100-300	278	6,424	4	6.2	.014	32	49.8	.115
100-300 >1930	251	4,944	2	4.0	.008	16	32.4	.064
>300	18	265	1	37.7	.055	2	75.4	.111
>300 >1930	18	265	1	37.7	.055	2	75.4	.111

Essentially every embankment dam examined and evaluated for dam safety has seepage—some of it observable, some not, and some of it controlled, some not. The evaluation and response to evidence of seepage, high uplift pressures, sand boils, and sinkholes varies widely, but not necessarily for the right reasons.

Table 3.—Percent failures by type of failure
United States earth dams

	Category	Overtop	Foundation	Piping	Sliding	Structural	Spillway	Earthquake
All dams	Eastern	42	12	23	4	8	11	0
	Western	45	5	34	3	9	1	3
Dams >50 ft	Eastern	20	16	20	12	16	16	0
	Western	20	8	60	8	4	0	0
Dams <50 ft	Eastern	46	11.5	23.5	2.5	6.5	10	0
	Western	57	4	21	0	12	2	4

From a dam safety perspective, the problem is determining what the degree of risk of a piping or seepage failure is at a particular dam and what the appropriate response should be from the standpoint of public safety and cost effectiveness (responsible use of public/user funds).

APPROACH

Categories of the various seepage-related failure modes are proposed, and the nature of these failure modes (piping, uplift, and seepage erosion) are presented. The physical conditions required for a piping failure to occur are described, and various piping mechanisms are illustrated.

Next, we take a look at understanding empirical evidence. The relationship of seepage quantity observations to potential failure is discussed, and the nature of the formation of sinkholes and sand boils is described. (There are at least three different types of each, and their causes and effects vary significantly).

The next step is evaluation of the site. Steps to be taken to evaluate the potential for a seepage- or piping-related failure are given. (Note, however, that detailed discussions on accomplishing these steps are not presented. Suffice to say that this effort needs to be accomplished by personnel experienced in the evaluation of geologic conditions, dam design and construction, and flow regimes through and under the dam.)

Finally, a matrix of possible responses ranging from no action through monitoring to emergency repair are presented.

MODES OF FAILURE

Seepage through and under embankment dams is a natural, expected, physical process. The amount of seepage is directly related to the permeability (k) of the various flow paths that the reservoir water encounters, the total water pressure head between the entrance and exit associated with each flow path which establishes the gradient (I), and the cross sectional area of the flow path (in essence, the total seepage Q = the sum of $q = kiA$ for all flow paths). However, the amount of seepage observed is not the key indicator of whether or not the seepage at a dam presents the potential for dam failure. Rather, the key to failure potential determination is the assessment of the conditions that the subsurface seepage encounters on its path from reservoir to daylight.

Three types of failure that can result from seepage passing under or through a dam are:

- Piping
- Blowout (heave, uplift)
- Seepage Erosion

Mode 1 (Piping)—Subsurface erosion conveyed through an open "pipe" in soil or rock or under a roof of natural or manmade materials.

Almost all seepage-related failure concerns have been referred to as "piping." However, to better understand and categorize the physical processes involved, the term "piping," as used in this paper, is limited to the unique process of subsurface, backward erosion that is sustained by the formation or presence of an open "pipe" in the soil or rock or a "roof" over the erodible soil. The process often accelerates as a result of volumetric expansion of the source zone of seepage with resultant increase in capacity for material supply and transport.

For piping to occur, four conditions must exist:

1. There must be a flow path from a source of water.
2. There must be an unprotected exit (open or unfiltered) from which material can escape.
3. There must be erodible material within the flow path that can be carried to the exit.
4. The material being piped or the material directly above it must be able to form and support a "roof" or "pipe."

Mode 2 (Uplift, Blowout, or Heave)—Failure as a result of excessive uplift pressures is actually a slope stability failure. This type of failure, if it were to occur, would be expected the first time the reservoir reaches a critical elevation. The failure would be very rapid. The alternative to a complete, rapid failure is a local blowout at the toe area which relieves the pressure that could have caused instability.

Mode 3 (Seepage Erosion)—Failure as the result of loss of material from an erosional surface (crack through a dam, dam/foundation contact, downstream toe). This loss could be rapid or prolonged and gradual. The erosion ultimately results in loss of reservoir through the eroded area or in loss of resisting forces which leads to instability.

All three of these failure modes relate to the flow of water under or through a dam, and they all have been referred to as piping. However, the actual process, mechanism, and development of failure is distinctly different for each mode. These failure modes are summarized and illustrated on figures 3 through 7 (at the end of this article).

THE ROLE OF SEEPAGE MEASUREMENT AND OBSERVATION

It seems natural that a lot of attention would be paid to the amount of seepage when considering seepage- and piping-related failures. However, seepage quantity, especially controlled seepage, is rarely a direct indicator of the potential for a piping- or seepage-related failure mode. Monitoring and observing seepage does have an important role in detecting the potential for the development of seepage-related problems.

Key aspects of seepage that need to be observed are:

1. Are there new seepage sources developing?
2. Are the seeps passing clean or dirty water; are they carrying material?
3. Is the observable seepage just the upper "collectable" portion of the total seepage?
4. Is the seepage quantity consistent with season and reservoir level? Is it increasing or decreasing?
5. Is the quantity large enough to mask transport of material?

SAND BOILS AND SINKHOLES

Just as seepage can represent a wide spectrum of potential conditions, sand boils and sinkholes can represent quite different conditions and risks of potential failure or adverse response.

Sand Boils—Three basic types of sand boils are shown on figure 1. The fundamental appearance and causative mechanism of all three types is the same—that is, a subsurface to surface gradient producing a flow that leaves a deposit of material at the ground surface. The difference in the types is the source of the material deposited.

In the first case, the seepage water is not transporting material as it passes through the surface deposits. The force of the upward flow of water (acting much like a relief well) simply piles up the finer-grained surfical deposits.

In the second case, no material is being carried by the seepage water when it reaches the surface deposits, but the upward flow is competent enough to remove the finer materials from surface materials.

In the third case, seepage is carrying material from either the dam or the foundation and, due to the coarseness of the surface deposit, this material being carried is able to escape. Since material from the flow path source is being carried away, the threat of tapping into the reservoir source is great.

Sinkholes—Three types of sinkhole development are illustrated in figure 2. As with sand boils, one of the three types of sinkholes is critical. The other two are potential problems but much less urgent. The first type, located at or near the reservoir floor, I believe typically develops during drawdown; the sinkhole basically results from caving of flow path channels that, prior to drawdown, were filled with water under pressure. During the late stages of drawdown, not only does water pressure decrease (or go to zero), but also, there can be a vortex, or suction (as observed when a bathtub is drained). The inflow cannot keep up with the discharge capacity. I believe that this is the reason sinkholes are observed to form when the pool is drawn down to only a few feet or less over a reservoir area. This condition is not as critical as the second type.

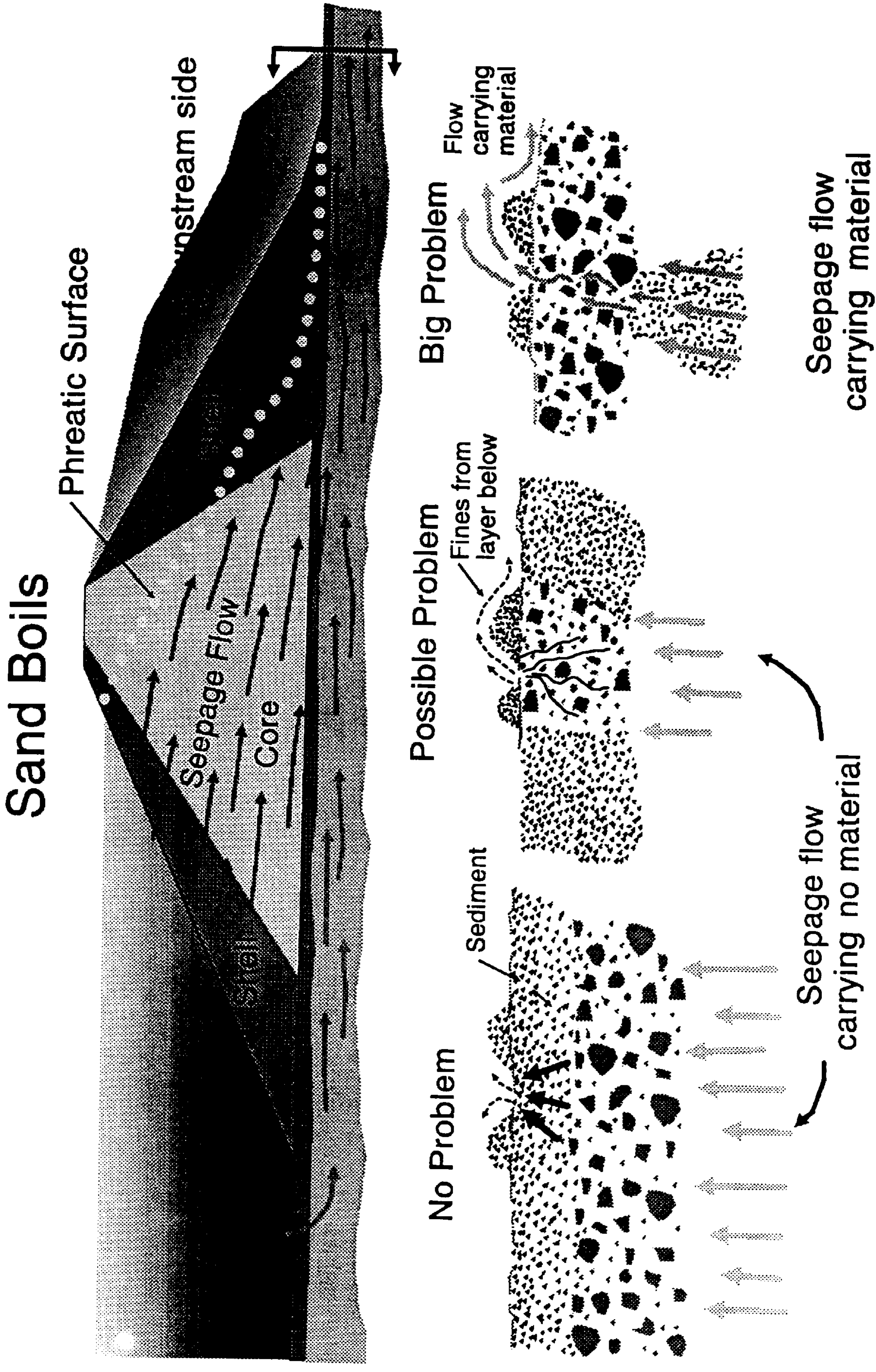
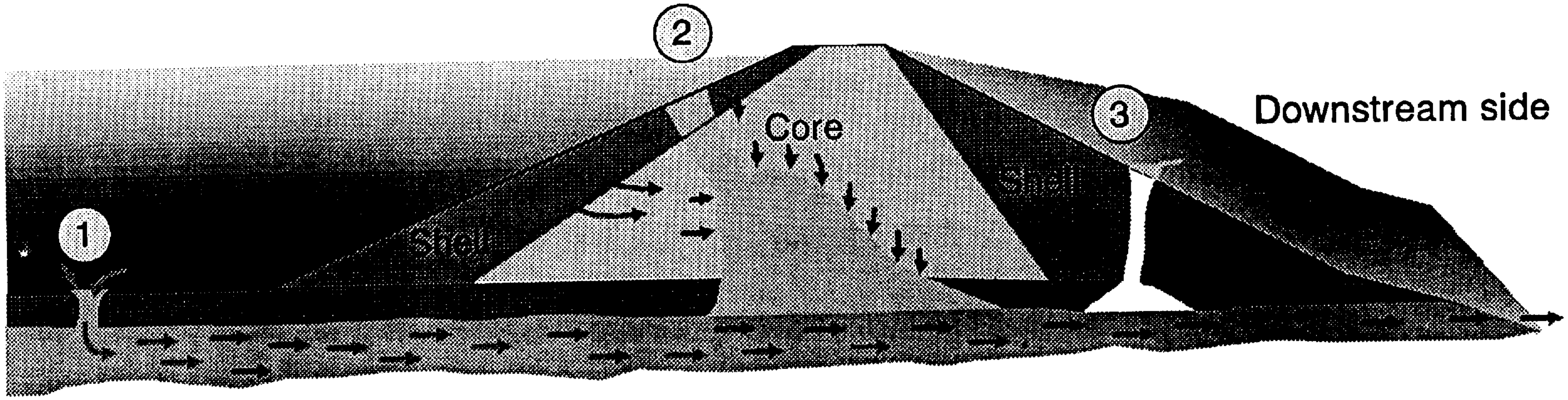

Sand Boils
Phreatic Surface
nstream side
Shell
Seepage Flow
Core
Shell
No Problem
Sediment
Possible Problem
Fines from layer below
Big Problem
Flow carrying material
Seepage flow carrying no material
Seepage flow carrying material

Figure 1

Sinkholes



TYPE ①

Flow induced
Limited erosion
of materials
Reservoir floor
During drawdown
bathtub analogy
capacity out > supply in

TYPE ②

Flow + Collapse
True piping
symptom

TYPE ③

Collapse
Erosion is
from surface
of materials

Figure 2

The second type is related to the true piping phenomenon where direct access to the reservoir is reached via the embankment. The climactic step in the sinkhole formation is the collapse of the shell or other materials composing the upstream face into the piping cavity.

The third type is formed from vertical caving into a subsurface erosional channel or flow path. This type is most evident on the downstream face and would tend to occur when the shell materials have a very fine-grained, low plasticity matrix. Again, this type is not as critical as the second type.

EVALUATION OF FAILURE POTENTIAL

The difficulty of problem evaluation and the need for judgment was emphasized by Terzaghi and Peck [4] in their statement:

> *"The factor of safety with respect to piping by subsurface erosion cannot be evaluated by any practicable means."*

There are five fundamental factors to consider in evaluation of failure potential from seepage- and piping-related failure modes. They are:

1. The physical conditions of the dam and foundation (geology and dam design and construction features).
2. The nature of the gradients through the dam and foundation (direction of flow based on piezometric data).
3. The historical/operational performance of the dam in terms of observation of direct evidence of potential seepage-related problems (sinkholes, sand boils, material transport).
4. The nature of seepage at the site (always clear, does or does not change as a function of reservoir, is constant for a given reservoir elevation, is observable, etc.).
5. The presence and effectiveness of defensive design measures.

RESPONSE TO OBSERVATION OF POTENTIAL SEEPAGE AND PIPING CONCERNS

The physical conditions at the site that could either allow or inhibit a seepage- or piping-related failure must first be thoroughly evaluated. Then, the failure likelihood, based on the performance of the dam and foundation, is evaluated. This information provides the basis for deciding what the appropriate response should be at the site.

Table 4 presents a first cut at outlining the various categories of conditions that may be identified on the basis of the answers to the evaluation factors given above. (See "condition description" column.) For each of those categories, a possible course of action is identified under the column titled "course of action."

Table 4.—Categories of response to observance of potential seepage and piping concerns

Category	Course of action	Condition description
1	None required.	Seepage would not be expected to lead to a dam safety problem.
2	Monitor with weirs to determine any change in seepage quantity and include features to determine whether material is being carried in flow.	No specific data to indicate a problem, but possibility of adverse conditions that could lead to piping exist.
3	Monitor/remediate with filtered toe drain and weir measuring system as described above.	Strong likelihood that adverse conditions[1] that could lead to piping exist, but to investigate and prove that these conditions exist would be very costly.
4	Specific monitoring to water future response - Monitored decision.	Conditions[1] that could cause piping exist, but long history with no problem or recognition that present condition is better than past—key indicators of a future developing problem can be and are targeted for monitoring.
5	Investigate with a field program to try to show piping will or will not occur.	Conditions[1] that could cause piping may all exist but are not all verified.
6	Study to determine appropriate least-cost corrective action.	Conditions[1] conducive to piping are known to exist (but not currently active) and are serious enough or threatening enough that monitoring alone is not an acceptable long-term solution .
7	Restrict reservoir and fix immediately.	Emergency condition-piping is actively occurring; therefore, failure could develop suddenly.

[1] Conditions necessary to produce piping (subsurface erosion) are:
Unprotected exit
Erodible material
Flow path from reservoir or abutment seepage through or along erodible material
Material being piped or material directly above erodible material can "roof" or form a pipe.

It should be recognized that considerable judgment and recognition of site-specific hazard and risk go into determining what physical processes are occurring or could occur and into the decision on what action to take at a particular site. This has always been the case, as indicated by Terzaghi [3] in the following statement:

> *"To avoid the shortcomings with present practice requires first of all expert translation of the findings of the geologist into physical and mechanical terms. Next it requires the evaluation of the most unfavorable mechanical possibilities which could be expected under the existing geologic conditions; and finally to assume for design of the structure the most unfavorable possibilities. These mental operations represent by far the most important, most difficult, and most neglected tasks in the field of dam foundations."*

CREDITS

The author's interest in and fundamental knowledge concerning piping- and seepage-related failure came as a result of a special correspondence course given to a group of Reclamation engineers on

this subject by Dr. Ralph Peck. The author appreciates peer review of the paper by Gregg Scott, preparation of the figures on sand boils and sinkholes by illustrator Tony Rozales, and the manuscript preparation by Joanne Posluszny.

REFERENCES

1. Von Thun, J. Lawrence, Selection of Criteria for Rehabilitation of Existing Dams, In: *Proceedings of Alberta Dam Safety Seminar*, September 1986, Alberta Environment, Edmonton, Alberta, Canada.

2. Von Thun, J. Lawrence, *Application of Statistical Data From Dam Failures and Accidents to Risk Based Decision Analysis on Existing Dams*, Bureau of Reclamation, internal (unpublished) report, October 1985, Denver, Colorado.

3. Terzaghi, Charles, Effects of Minor Geologic Details on the Safety of Dams, *American Institute Mining & Metallurgical Engineers*, technical publication 215, pp. 31-44, reprinted in Terzaghi Volume, From Theory to Practice in Soil Mechanics, Wiley, 1960, pp 119-132

4. Terzaghi, Karl, and Ralph B. Peck, *Soil Mechanics in Engineering Practice*, second edition, John Wiley and Sons, Inc., New York, London , Sydney.

Figure 3.—Seepage-Related Failure Modes

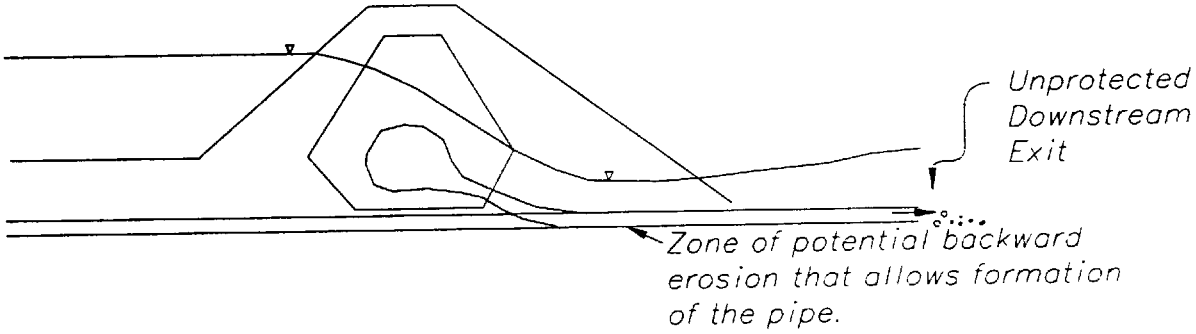
Potential dam failure related to seepage can come about as a result of one of three modes:

1. True piping (subsurface erosion)
2. Blowout (excessive uplift at toe of dam)
3. Seepage erosion
    - > Along dam/foundation contact surface
    - > Along transverse crack
    - > Development of a "blowout" or unstable slope condition

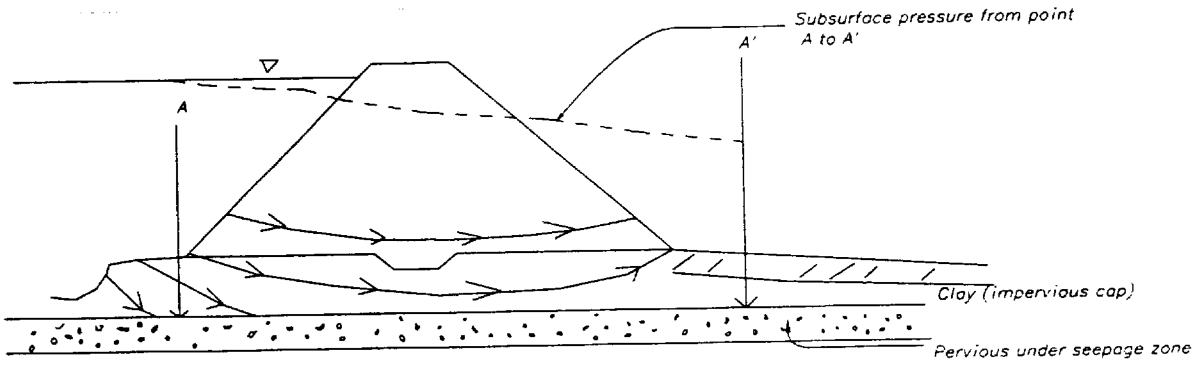
---

I. True Piping

- Unprotected exit
- Pipes or roof must be able to form
- Gradient to initiate need only be great enough to move one particle from flow path
- Once initiated, piping can go undetected—then at some point rapidly accelerate



II. Blowout



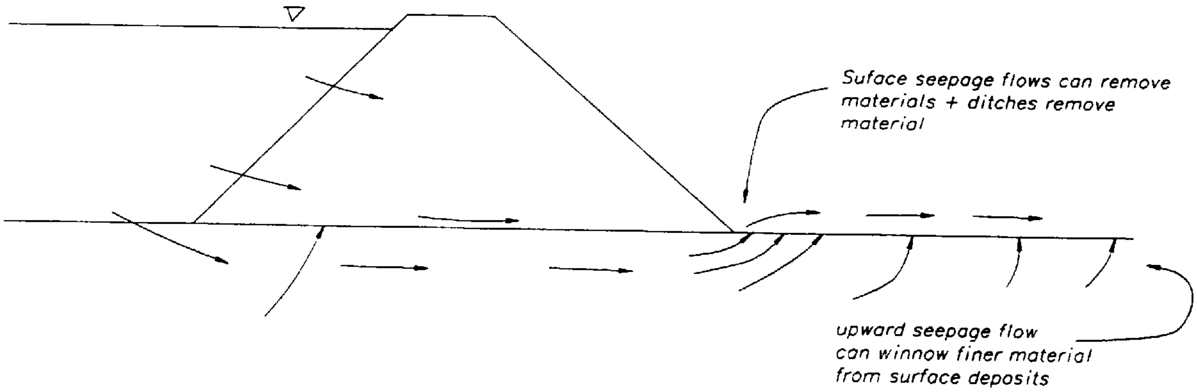
Net forces ↓ and ← due to weight and friction less than forces ↑ + → due to water pressures (Imagine a beach ball held below water).

Figure 3.—Seepage-Related Failure Modes (continued)

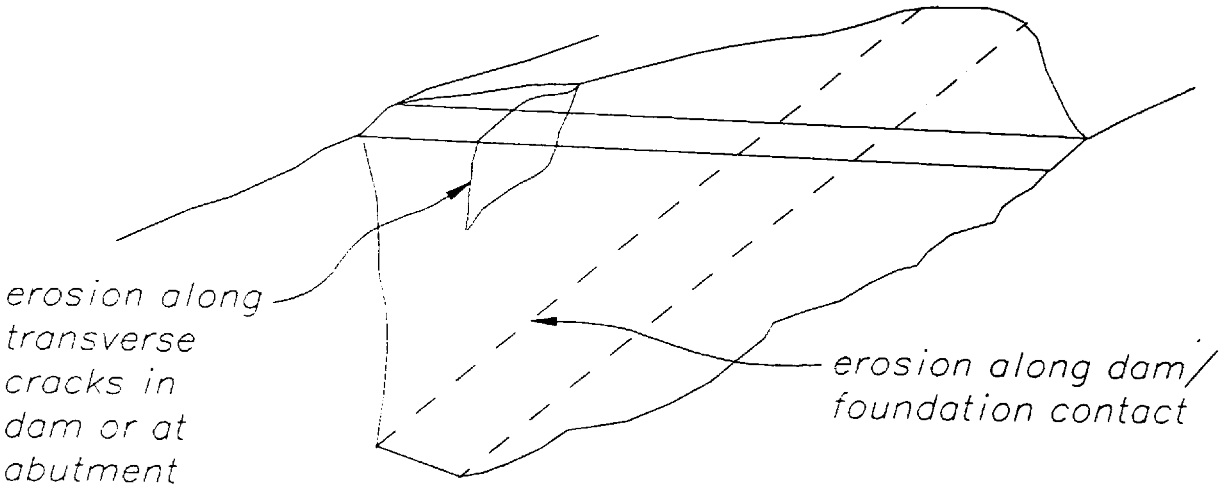
III. Seepage Erosion Leading to:

Blowout—Blowout or slope instability occurs because seepage erosion removes material providing a stabilizing force.

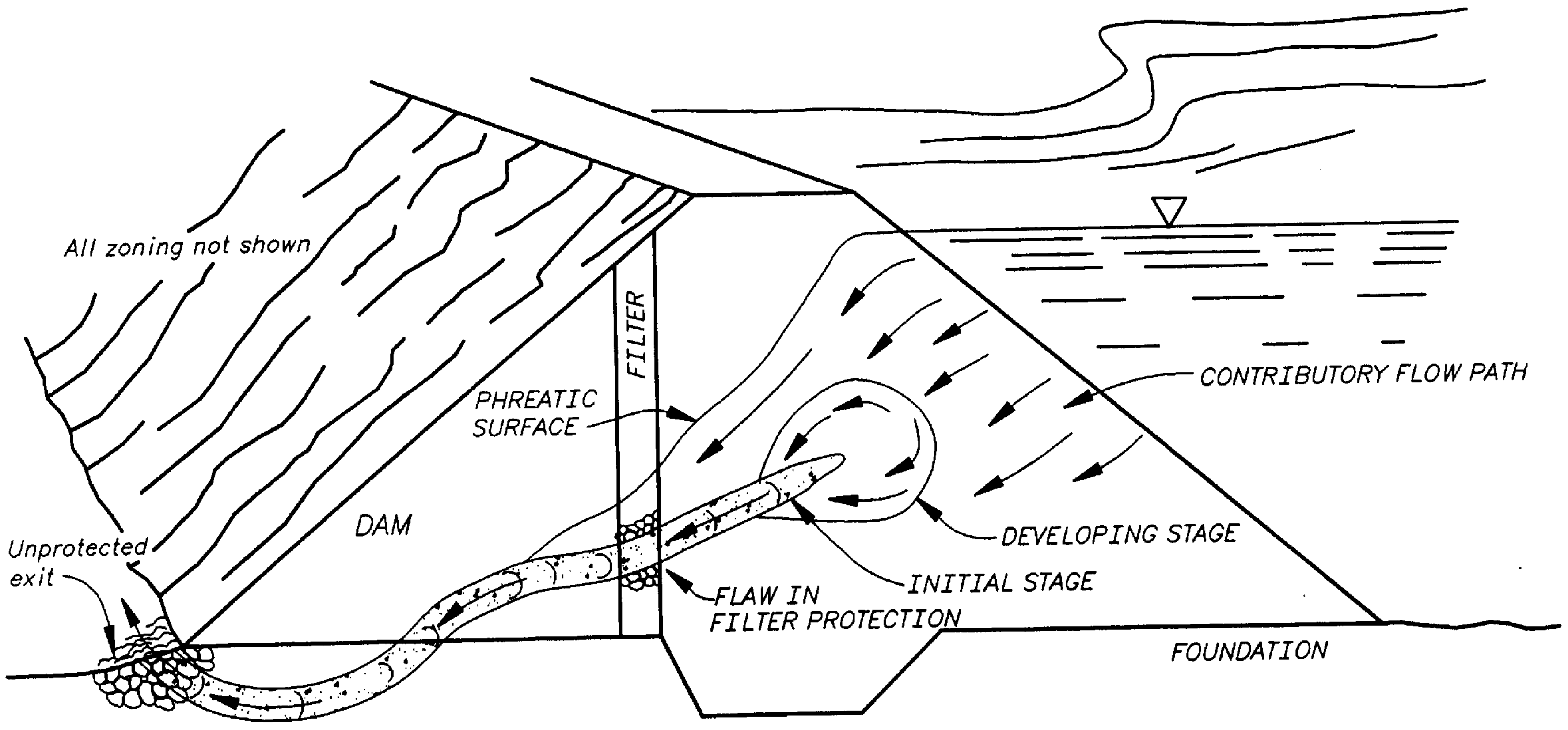
(A) Seepage erosion from surface deposits



(B) Seepage erosion along contact surfaces



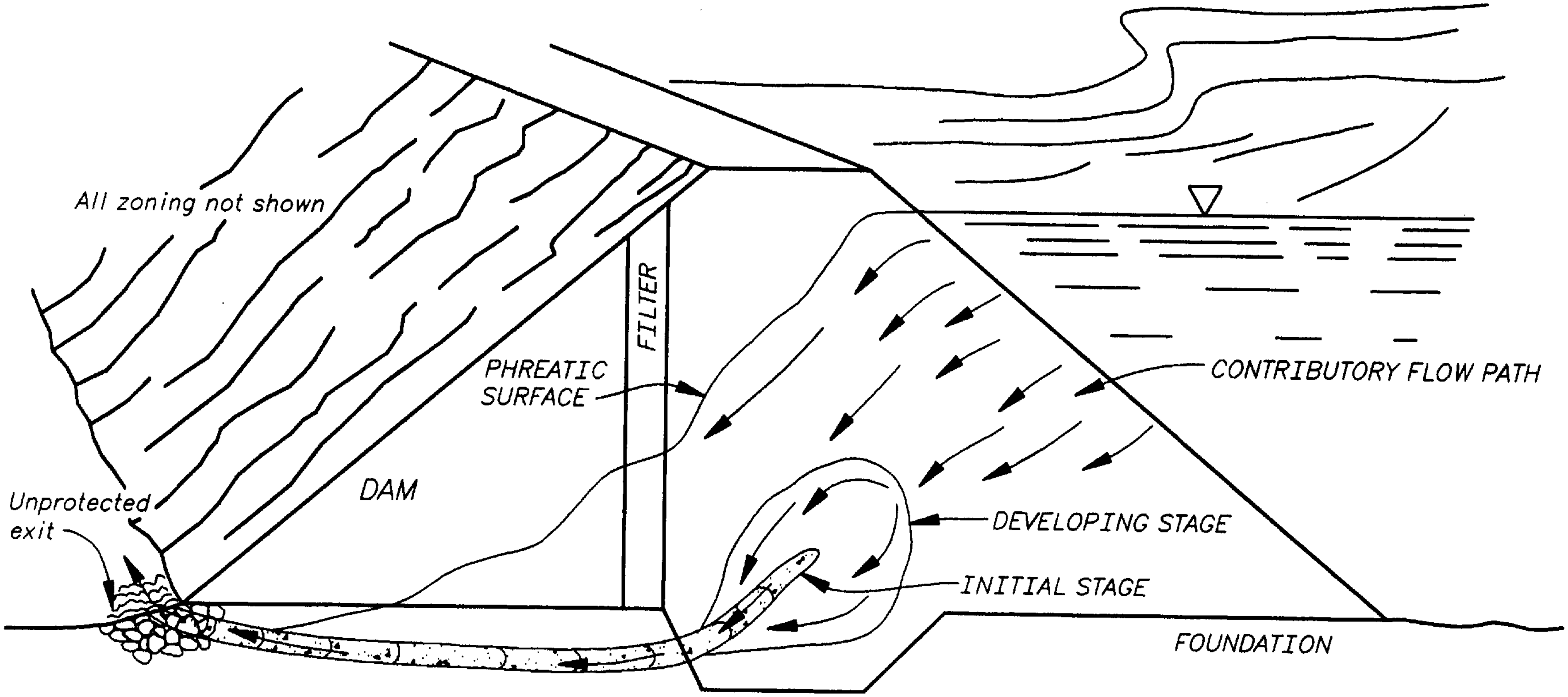
Blowout or slope instability results from combined effects of surface erosion and subsurface winnowing.



NOTE: As piping progresses upstream, the hydraulic gradient increases. As the hydraulic gradient increases, flow volumes and velocities increase upstream piping potential.

GENERAL PIPING MECHANISMS
MECHANISM – 1
THROUGH EMBANKMENT

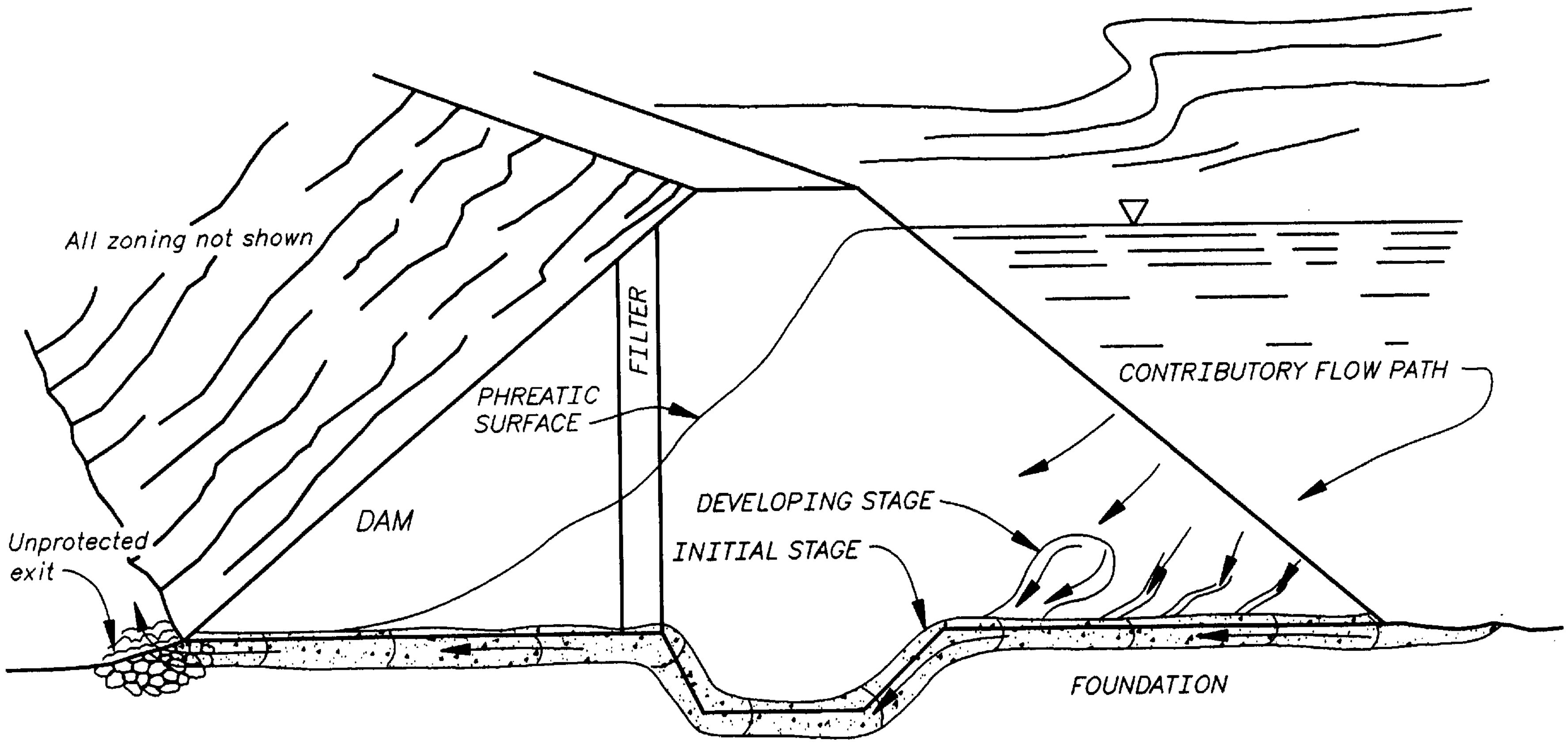
FIGURE – 4



NOTE: As piping progresses upstream, the hydraulic gradient increases. As the hydraulic gradient increases, flow volumes and velocities increase upstream piping potential.

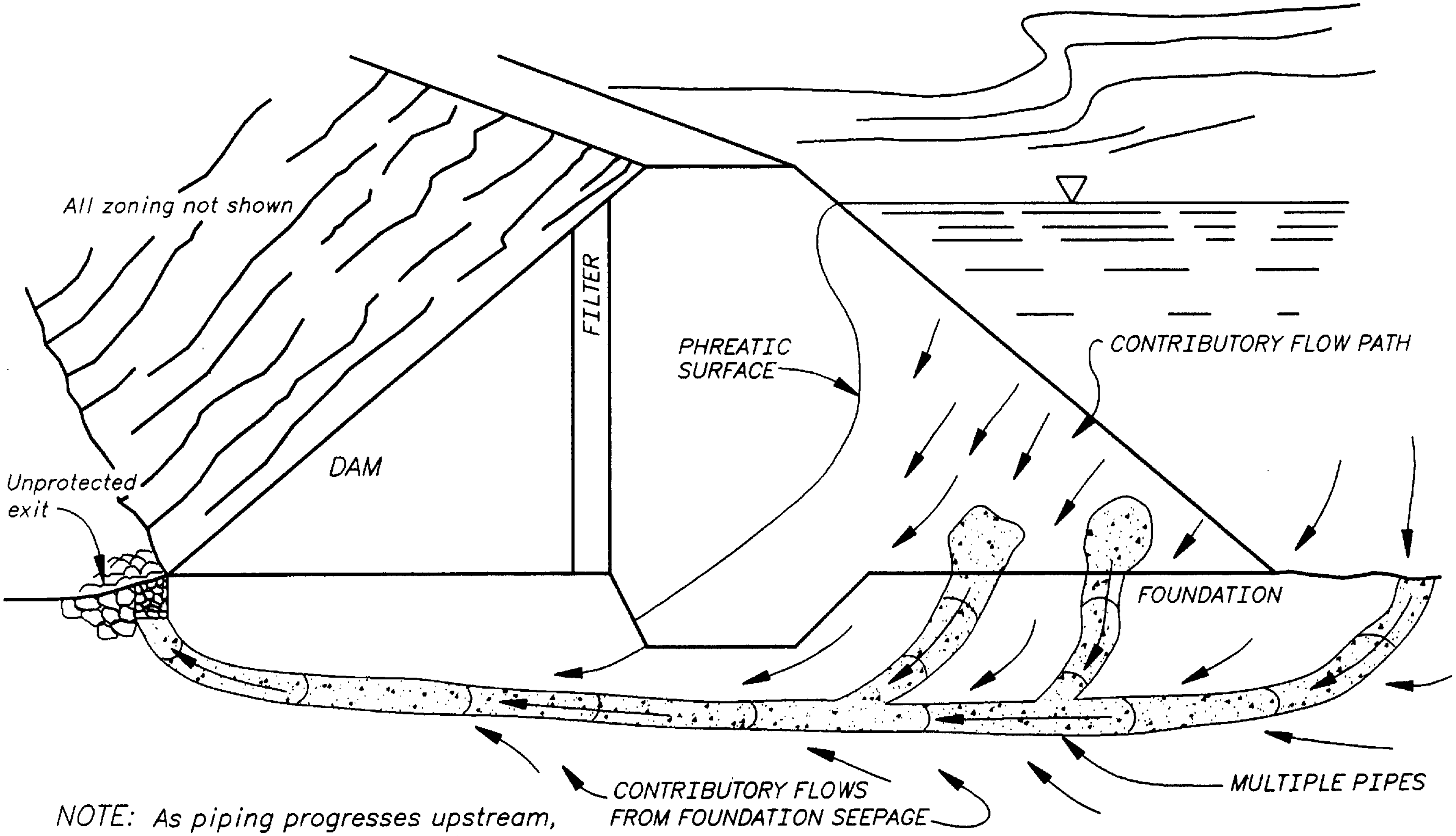
GENERAL PIPING MECHANISMS
MECHANISM – 2
THROUGH CUTOFF TRENCH AND FOUNDATION

FIGURE – 5



NOTE: As piping progresses upstream, the hydraulic gradient increases. As the hydraulic gradient increases, flow volumes and velocities increase upstream piping potential.

GENERAL PIPING MECHANISMS
MECHANISM – 3
ALONG CONTACT AND UPSTREAM
PORTION OF EMBANKMENT
FIGURE – 6



NOTE: As piping progresses upstream, the hydraulic gradient increases. As the hydraulic gradient increases, flow volumes and velocities increase upstream piping potential.

GENERAL PIPING MECHANISMS
MECHANISM – 4
THROUGH FOUNDATION AND UPSTREAM PORTION OF EMBANKMENT
FIGURE – 7

NEW STANDARD SPECIFICATIONS AVAILABLE FOR REPAIR OF CONCRETE

A new revision to the Bureau of Reclamation's (Reclamation) *Standard Specifications for Repair of Concrete*, M-47 (M0470000.296) (Standard), was completed in February 1996. Changes in the new document include the addition of a section on how to use the specification; addition of specifications for epoxy bonded dry pack, silica fume concrete, and epoxy-bonded silica fume concrete; new surface preparation specifications requiring removal of microfractured surfaces before application of repair materials; and new specifications for resin injection repairs.

Copies of the new Standard can be downloaded from the internet by going to the Materials Engineering and Research Laboratories address, http://donews.do.usbr.gov/merl/reprhome.html, and clicking on "Publications." Alternately, hard copies of the document or a computer floppy disk containing the document can be obtained by contacting:

W. Glenn Smoak or Kurt VonFay
Bureau of Reclamation
Code: D-8180
PO Box 25007
Denver, Colorado 80225
Phone: (303) 236-3730

The March 1990 revision of the Standard is no longer valid and should be discarded.

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