REMR TECHNICAL NOTE HY-N-1.3

GUIDANCE FOR REPAIRING SCOURED AREAS BELOW NAVIGATION DAM STILLING BASINS AND SPILLWAY APRONS

PURPOSE: To describe causes of scour below navigation dam stilling basins and spillway aprons and to identify methods and techniques being used to repair scoured areas.

PROBLEM: Inspections of Corps of Engineers' navigation dams often show that large scour holes exist downstream from the stilling basin or from the spillway apron if the project has no stilling basin. At some projects, the scouring has undercut the basin or apron foundation to a point at which the integrity of the structure may be threatened.

CAUSES OF SCOUR: A number of hydraulic model studies of various types of structures have been used to determine the flow conditions that cause scour. These studies have been of Corps navigation dams which consist primarily of two types of structures: uncontrolled fixed-crest dams with short spillway aprons but usually with no stilling basins, and gated spillways that usually have a stilling basin.

a. Uncontrolled fixed-crest dams. Scour downstream from this type of structure is often caused by a plunging flow jet that exits the spillway apron at a high velocity as shown in Figure 1. This high-velocity jet causes severe turbulence capable of displacing large stone and uplift pressures that cause piping of the subgrade material. This flow condition when viewed from above appears as a gentle hydraulic roller, and the turbulence occurring on the bottom is not evident. The characteristics of the plunging jet are affected by discharge, tailwater, and the design or shape of the crest, spillway, and apron. Various combinations of these dictate when plunging flow will occur.

   Review of data collected from previous model studies has generally indicated that, if the depth of tailwater above the crest, h, divided by the gross head on the crest, H, is below 0.8, plunging flow will occur. The shape of the crest will have an effect on the plunging flow. A curved spillway crest will induce the flow to cling to the face of the spillway, and the flow streamlines will exit parallel to the floor of the apron. A flat crest that has sharp edges causes the nappe of the jet with higher unit discharges to spring from the downstream corner away from the spillway and plunge through the tailwater downstream from the spillway apron severely attacking the area immediately below the dam.

b. Gated Structures. Gated structures usually have a stilling basin that dissipates energy adequately when the project operation schedule is followed. Scour downstream from these structures is usually caused when the structure is not operated properly due to one or more of the following: operator error, equipment malfunction, vandalism, or operating the structure beyond its normal operation range to pass ice or debris. An example would be raising a single gate higher than the operation schedule allows in order to pass ice through the structure. The increased discharge due to the gate being raised higher than normal with the low tailwater causes significant turbulence in the downstream channel, often times resulting in severe scour and failure of the stone protection. This flow condition is depicted in Figure 2.

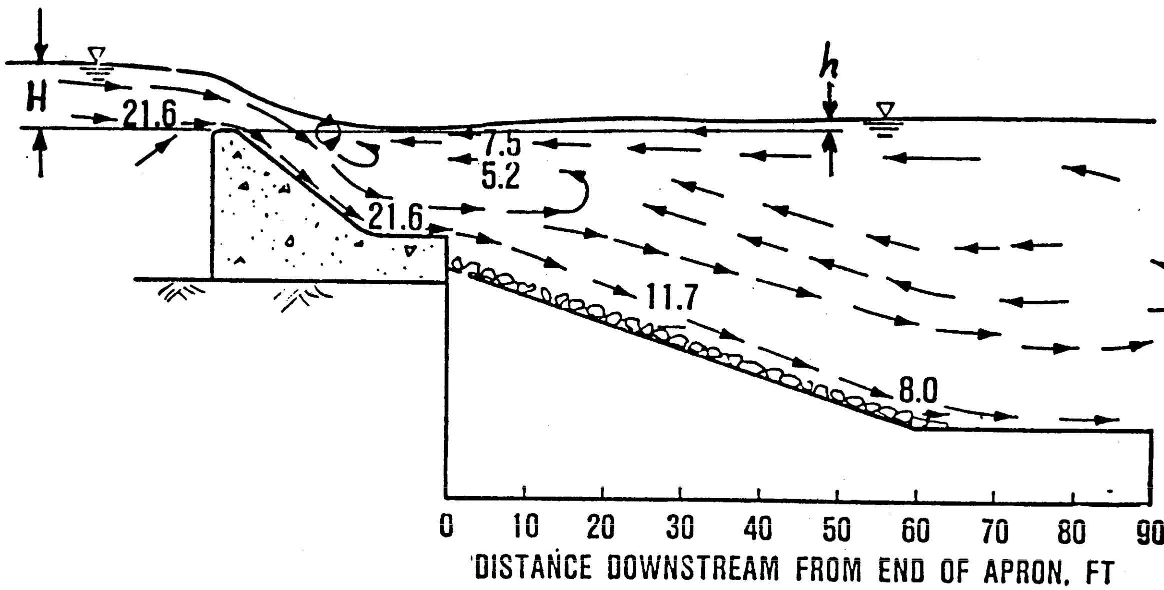

Figure 1. Uncontrolled fixed-crest dam with plunging jet flow

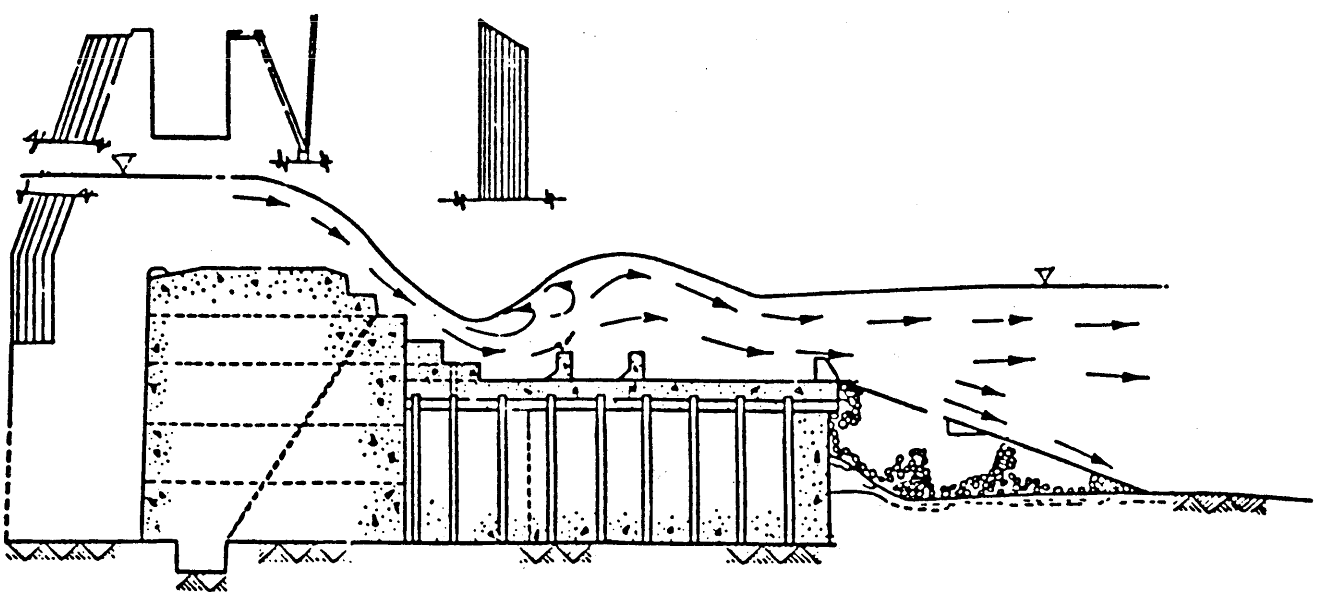

Figure 2. Gated structure with normal upper pool, one gate full open, and minimum tailwater

Inadequate energy dissipation in the stilling basin can be attributed to improper basin design or to project conditions differing from those anticipated when the basin was designed. An example would be tailwater elevations lower than expected due to a scoured streambed below the structure.

Another flow condition that has been observed to cause scour downstream from a gated structure is an undulating jet. This occurs when high tailwater forces the flow entering the basin to undulate and ride the surface of the tailwater through the basin and then plunge through the tailwater after leaving the basin. This flow condition is shown in Figure 3. The plunging jet often is strong enough to reach the streambed or the stone protection and cause scour.

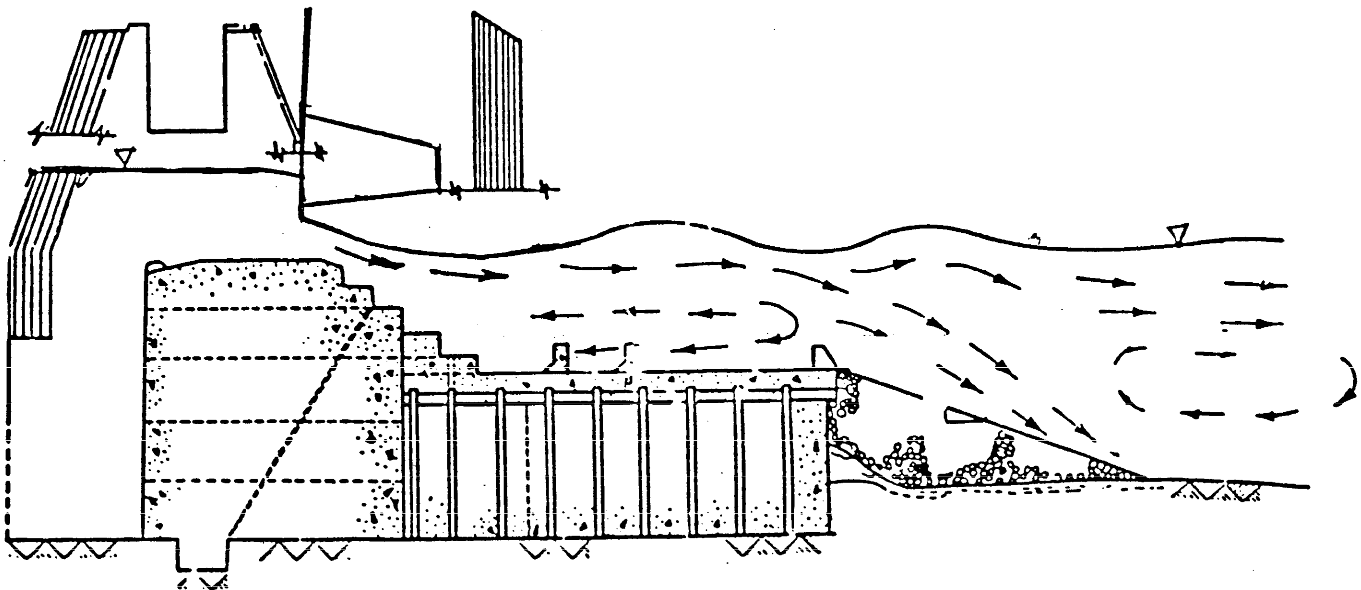

Figure 3. Gated structure with undulating jet flow

SCOUR PROTECTION TECHNIQUES: Physical, hydraulic model studies have been conducted since the early 1980's to develop site-specific scour protection for various navigation dams on the Allegheny, Arkansas, Monongahela, Upper Ohio, and Upper Mississippi Rivers. Most of the studies have been conducted for Pittsburgh District which is actively engaged in repairing damaged areas below its navigation dams. Table 1 briefly describes the results of these studies to date.

The scour protection required for a specific project depends on numerous parameters. Guidance is provided in Engineer Manual (EM) 1110-2-1605, "Hydraulic Design of Navigation Dams," for establishing design life and rationale for the scour protection. Scour protection for uncontrolled fixed-crest dams should be designed to remain stable for the plunging flow conditions described above. Often the design flow conditions for a gated structure are based upon updated criteria provided in Engineer Technical Letter (ETL) 1110-2-290, "Low Head Navigation Dam Stilling Basin Design," dated

31 October 1983. These criteria generally pertain to new project design, but certain features should be addressed in repairing existing structures. Experience has indicated that many structures are required to operate outside the normal range for one reason or another; therefore, single-gate operation with the minimum tailwater criteria stated in ETL 1110-2-290 should be considered when developing scour protection for these structures.

a. Model Study Findings. Many of the projects listed in Table 1 required protection more substantial than riprap and also structural modifications to the existing spillway. The stone protection designed from a model study for Emsworth Dam on the Ohio River consisted of 4- to 5-ft-diam stone placed on a 1V-on-3H downward slope. This protection was designed for normal operating conditions: normal upper pool and gate opening adjusted according to discharge and tailwater elevation. Once the plan had been installed, the stone protection behind one of the gate bays failed during operations with tailwater elevations 1.0 to 1.5 ft lower than shown on the operation schedule. The tailwater at Emsworth Dam is not sufficient to produce a hydraulic jump in the stilling basin; consequently, supercritical flow exits the basin, and energy dissipation occurs over the scour protection material. Conventional methods for designing riprap protection are not valid in such a high-energy environment. The high velocities present in supercritical flow cause uplift of very large stone and piping of subgrade material, and when the high-velocity jet impinges directly on the stone protection, displacement of extraordinarily large stone will occur. Large stone is considered to be that weighing more than 5500 lb per stone.

Existing fixed-crest structures such as Dam Nos. 4 and 7 on the Allegheny River required modifications to the existing spillway apron to develop satisfactory scour protection plans. The plunging flow conditions observed in the model studies of these projects were so severe that large stone placed below the dam would not provide adequate protection without modifying the spillway apron. An end sill placed at the end of the existing spillway apron was required to deflect the plunging flow towards the surface away from the stone protection for Dam No. 7. Once the end sill was installed, 4- to 5-ft-diam stone placed on a 1V-on-3H downward slope below the spillway apron provided adequate protection.

A 56-ft extension to the existing spillway apron employing sunken barges filled with grouted riprap followed by 4- to 5-ft-diam stone was developed for scour protection at Dam No. 4, Allegheny River. The spillway extension intercepted the plunging flow and provided the additional apron length needed for proper energy dissipation.

Many existing gated structures that are being repaired to meet single-gate and minimum tailwater criteria will require a secondary stilling basin constructed below the dam. The secondary stilling basin is necessary to dissipate the energy in supercritical flow that exits the existing basin. The basin may be constructed of sunken barges filled with grouted riprap, an approach currently

Table 1. Model Studies of Scour Protection Below Navigation Dams

Project (District)	Structure Type	Unit Discharge Tested cfs	Recommended Scour Protection
Emsworth (ORP)	Gated	13-343	o 4- to 5-ft-diam stone placed on 1V-on-3H downward slope for normal operation o 4-ft concrete cubes cabled together for ice passage o Large grout-filled fabric bags (20 by 6.67 by 2.75 ft) placed on 1V-on-3H downward slope for ice passage
Montgomery (ORP)	Gated	41-175	o 3-ft-diam stone (avg wt, 2330 lb) placed on 1V-on-3H downward slope for operations with normal upper pool (el 682), one gate open full, and minimum tailwater (el 664.5)
Pike Island (ORP)	Gated	60-200	o 4- to 6-ft-diam stone placed on 1V-on-3H downward slope for operations with normal upper pool (el 644), one gate half open, and minimum tailwater (el 623)
Dashields (ORP)	Uncon-trolled fixed-crest	31-303	o 3-ft-high sloping end sill installed at end of existing spillway apron with 54-in. blanket of riprap (D_{50} = 27 in.) placed on 1V-on-3H downward slope immediately downstream from dam o 5.5- to 6.5-ft-diam stone offset 2 ft below existing spillway apron and placed on 1V-on-3H downward slope o Large grout-filled fabric bags (20 by 6.67 by 2.75 ft) offset 2 ft below existing spillway apron and placed on downward slopes 1V on 2.4H and milder
Upper Missis-sippi River (NCS)	Gated		o Large graded riprap of varying thicknesses placed on slopes slightly steeper and milder than 1V on 3H, and this blanket placed on top of quarry-run stone of varying thicknesses
Dam No. 2, Allegheny River (ORP)	Uncon-trolled fixed-crest	36-215	o 4- to 5-ft-diam stone offset 3.5 ft below existing spillway apron and placed horizontally for 50 ft downstream from structure o 4- to 5-ft-diam stone offset 2 ft below existing spillway apron and placed on 1V-on-3H downward slope o 3-ft-high sloping end sill installed at end of existing spillway apron with either of plans above

(Continued)

Table 1 (Concluded)

Project (District)	Structure Type	Unit Discharge Tested cfs	Recommended Scour Protection
Dam No. 7, Allegheny River (ORP)	Gated	6-218	o 3- to 4-ft-diam stone placed on 1V-on-3H downward slope below 28-ft extension to existing spillway apron with 3-ft-high sill installed at end of extension o 4- to 5-ft-diam stone placed on 1V-on-3H downward slope below existing spillway apron with 3-ft-high sloping end sill installed at end of existing spillway apron
Dam No. 2, Monongahela River (ORP)	Uncon-trolled fixed-crest	67-274	o 4- to 5-ft-diam stone offset 2 ft below existing spillway and placed on 1V-on-3H downward slope o 54-in. blanket of riprap (D_{50} = 27 in.) offset at least 7 ft below existing spillway apron and placed on 1V-on-3H downward slope
Dam No. 4, Allegheny River (ORP)	Uncon-trolled fixed-crest	57-343	o 4- to 5-ft-diam stone offset 2 ft below 56-ft extension to existing spillway apron and placed on 1V-on-3H downward slope o 3-ft-high sill placed at end of spill-way extension in plan above to improve flow conditions with low discharges
Dam No. 3, Monongahela River (ORP)	Uncon-trolled fixed-crest	22-276	o 3- to 4-ft-diam stone offset 2 ft below existing spillway apron and placed on 1V-on-3H downward slope o Large grout-filled fabric bags offset 2 ft below existing spillway apron and placed horizontally downstream from structure
Dam No. 7 Monongahela River (ORP)	Uncon-trolled fixed-crest	33-262	o Large grout-filled fabric bags placed horizontally downstream from existing structure with 3-ft-high sloping end sill installed at end of apron
Dam No. 2 Arkansas River (SWL)	Gated	130-667	o Revetment constructed of barges filled with large riprap and grouted and sunk below existing stilling basin with large graded riprap placed downstream from sunken barges (currently being model tested)
Morgantown Dam, Monongahela River (ORP)	Gated	90-180	o (Currently being model tested)

being tested for Dam No. 2, Arkansas River, or if design rationale indicates the necessity, the project could be dewatered in stages and a new basin constructed.

b. Design Guidance. From review of previous model studies, the following design guidance is offered for repairing existing scoured areas below navigation structures. It should be noted here that recommendations (d), (e), and (f) apply to structures that have existing scour holes below them and for which modifications to the existing stilling basin or spillway apron to improve energy dissipation are not feasible. New projects should be designed with a stilling basin that has two rows of baffle blocks and a sloping end sill to provide adequate energy dissipation. The area downstream from the stilling basin should be protected with sufficient size riprap placed as a level or mildly sloping blanket in decreasing size and blanket thickness for an appropriate length downstream from the stilling basin until a non-scouring velocity is achieved. A level or mildly sloped blanket allows the flow to distribute more uniformly in the exit channel, and the flow circulations (eddies) on the channel side slopes are not as severe which reduces the attack on the channel side slopes. To repair a scour hole below an existing structure, a horizontal blanket of riprap may not be feasible and recommendations (d), (e), and (f) may be useful.

1. Initial Steps:

(a) Identify flow condition that caused the scour.

(b) If operations permit, avoid these flow conditions.

(c) If conditions cannot be avoided, design scour protection that will remain stable for these conditions.

2. Recommendations for Design of Scour Protection:

(a) Use graded stone protection if the repair will be done underwater and it is determined that riprap will provide the necessary protection.

(b) If velocities exiting the stilling basin or spillway apron are greater than 15 ft/sec, stone 48 in. in diameter (5500 lb) or larger will probably be required.

(c) Use of large tightly graded stone does not provide the best interlocking capability so a double layer of stone to increase interlocking is preferred.

(d) Stone protection should be placed in a manner that armors the upstream slope of the existing scour hole if the slope is not too steep.

(e) Placing the stone on a downward slope away from the structure often allows the use of smaller rock.

(f) Placing stone on a 1V-on-3H downward slope has been observed to perform satisfactorily. The turbulent environment and uncertainty involved with placing stone underwater are not conducive for steeper slopes.

(g) It is preferable to offset the top of the stone at the upstream portion of the blanket at least 2 ft below the spillway apron (away from the high-velocity jet), or if the stilling basin has an end sill 2 ft or higher, place the stone at the basin apron elevation.

(h) If stone protection is inadequate, alternative methods and materials must be used.

(i) Large grout-filled fabric bags (20 by 6.67 by 2.75 ft) have been model tested and remained stable when large stone failed.

(j) If bags are chosen, attempts should be made to tie the bags together with reinforcing bars or cables to help prevent failure from instantaneous uplift forces. There is some concern over the durability of grout-filled bags if the unit cracks, but experience at two projects has shown good performance to date.

(k) If the area below the dam will be subjected to supercritical flow, a secondary stilling basin placed below the existing structure followed by stone protection is preferred.

(l) Design guidance is presented in EM 1110-2-1605 and can aid in the development of a secondary stilling basin.

(m) If dewatering the structure is not possible, a basin constructed from sunken barges filled with grouted riprap or some type of underwater forms to accommodate tremie concrete might be used.

(n) A model study of scour protection required for existing structures that have supercritical flow or high-velocity flow exiting the basin would be desirable to finalize the design.

(o) A properly designed filter(s), preferably a graded granular filter, is required beneath scour protection materials consisting of stone or grout-filled bags. The filter immediately below the scour protection should consist of a riprap blanket large enough to prevent piping through the voids of tightly graded large stone.

(p) Toe protection (see following).

3. Toe Protection. Flow over riprap causes locally high boundary turbulence that often leads to scour at the downstream end or toe of the riprap blanket. This requires special treatment to prevent undermining. EM 1110-2-1605 suggests three methods for toe treatment in design of new projects. The need to key in the riprap becomes more important where the riprap protection does not extend as far downstream from the end sill as the manual suggests. The first method shown requires extending the riprap at the toe to a depth equal to or greater than the anticipated scour (which is difficult to determine). This may be difficult to accomplish in a repair job because the riprap

used as scour protection will probably be placed on a downward slope, and extending the slope farther than the anticipated scour or to a competent foundation material may require excessive excavation. Excavating below a stilling basin should be avoided if possible. The second method incorporates a toe trench that provides sacrificial riprap to armor the scour at the end of the blanket as it occurs. This method is more practical when repairing an existing scour area. The third method provides the most substantial protection, but also would be most difficult to construct. It consists of providing a coffer dam at the toe of the scour protection material driven to an adequate depth or to competent material, filled with stone and capped with concrete. This serves as a retaining structure for the scour protection material placed below the end sill. This would be an excellent method for a project that could be dewatered.

PRECAUTIONS: Successful repair of a scoured area below a stilling basin requires careful planning and close coordination among responsible officials from the affected District and Division and from Corps Headquarters. Accurate hydrographic surveys of the damaged area before construction begins and after the repair work is finished are essential in formulating plans and evaluating construction. Careful inspections of the repair work must be made to ensure that the desired accuracy is maintained. District personnel knowledgeable of the project design and operation should be on site during construction of the repair work to make sure that changes in operation will not cause significant problems. For instance, an operator working for a contractor was observed using a dragline and bucket to prepare or grade off the filter (being dumped off a barge) below the stilling basin. He would swing the bucket upstream trying to get as close to the stilling basin (which was submerged) as possible, release it, and drag the bucket back towards the barge in an attempt to achieve the proper slope and thickness of filter material. Often when the bucket was released at the peak of its upstream swing, it landed violently on the end sill of the basin. This could damage the basin and adversely affect the performance of the stilling basin or scour protection material. Marking the end of the stilling basin with buoys or poles may help operators doing this type work. Instances such as this point out the need for knowledgeable personnel on site. Repairing scoured areas below stilling basins that are not dewatered demands sound engineering judgment with a touch of intuition. Any problems that can be addressed before the construction begins will contribute to a successful repair job.

ENVIRONMENTAL CONSIDERATIONS: Monolithic forms of protection tend to be ecologically inferior to stone riprap because the numerous cracks, crevices, and interstitial voids in riprap provide habitat for a wide variety of aquatic organisms. However, the localized use of grout-filled bags in extremely high energy zones instead of stone would eliminate only a small amount of relatively low-quality habitat.

An environmental concern associated with use of grout-filled bags is potential dewatering of river reaches below stilling basin during repair work. Efforts should be made to provide flows that do not interfere with repair work but that do prevent downstream dewatering. If dewatering is unavoidable, then consideration should be given to: (a) performing repair work during the fall to avoid impacting spring-time spawning or causing summertime water quality problems (increased temperature, stagnation, etc.) and (b) performing repair work as quickly as is reasonably possible.