WATER UNDER THE SPILLWAY – CATASTROPHIC FAILURE PREVENTED

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Introduction

Mt. Carmel Dam, located in northeastern North Dakota, is a 46-foot-high earthen embankment dam with a reinforced concrete drop inlet principal spillway over the left side of the dam. An erosion and undermining failure of the principal spillway began on about March 29, 2003. During the failure, approximately 700 to 800 acre-feet of water was lost from this 4700 ac-ft reservoir. The peak flow rate exiting from under the spillway was estimated to be as much as 200 cfs during the incident.

The North Dakota State Water Commission (SWC) took emergency actions after they were notified on March 29, 2003 to prevent further damage to the embankment and spillway and to prevent possible failure of the embankment. The erosion created up to an 8-foot void in the embankment beneath the spillway. GEI Consultants, Inc. (GEI) was retained to identify the likely factors that contributed to the erosion beneath the spillway and to design a replacement spillway.

This paper will present: a) actions taken by the State Water Commission to mitigate the dam safety emergency and prevent a catastrophic failure of the dam, b) design, site geotechnical, construction and other elements that contributed to erosion, c) probable failure mechanisms, and c) modifications to the design that could have prevented the erosion and undermining of the embankment beneath the spillway.

![Figure 1. Location map for Mt. Carmel Dam Project, North Dakota](image)

Project Background

The primary purposes of the Mt. Carmel Dam and Reservoir are a) water supply for the City of Langdon and for Langdon Rural Water and b) recreational uses. Mt. Carmel Dam is located in northeastern North Dakota, as shown on Figure 1. Mt. Carmel Dam was initially constructed in 1970-71 as a homogenous earthen embankment with a crest elevation at 1,537.5 feet. The reservoir elevation was controlled with a drop inlet riser that discharged
through a 66-inch-diameter concrete pipe (original principal spillway) located at about the center of the dam.

In 1995, the dam crest was raised between 4 and 5 feet to Elevation (El.) 1541.0 and a new reinforced concrete principal spillway, which consisted of a drop inlet, chute, and stilling basin, was constructed over the left part of the existing embankment. This construction raised the normal water surface 2 feet to El. 1530.0. As part of this construction the original principal spillway was taken out of service, by constructing a concrete bulkhead at the upstream end of the 66-inch pipe and partially demolishing the drop inlet, and a new low-level outlet was constructed. The outlet discharges into the new reinforced principal spillway. A general plan of the dam and appurtenant facilities, showing the new spillway, is shown on Figure 2. A plan and profile along the new principal spillway are shown on Figures 3 and 4.

Figure 2. General plan of Mt. Carmel Dam and Reservoir Facilities as Modified in 1995
Figure 3. Profile View of 1995 Principal Spillway

Figure 4. Plan View of 1995 Principal Spillway
High spillway discharges through the new principal spillway were recorded in 1996, 1997, 2000, and 2002 as a result of large local precipitation events. Flows through the new principal spillway last occurred in June 2002.

An erosion and undermining failure of the principal spillway was reported in progress on March 29, 2003, and likely initiated on or about March 28, 2003. It is believed that the reservoir was not actively spilling over the crest of the principal spillway when the failure occurred, but was likely several inches below the crest (El. 1530) when significant leakage under the spillway started. On March 29, 2003 the reservoir level had dropped about 2-1/2 to 3 feet to about El. 1527 and the flow through the eroded hole under the spillway had reduced significantly from its apparent high point. The flow reduced because the reservoir level had dropped below the top of a soil berm around and upstream of the spillway inlet. It is estimated that between 700 and 800 acre-feet (ac-ft) of water was lost from the reservoir during the erosion failure event. The flow rate during the failure was on the order of 200 cfs. The general condition of the structure at the end of the event is shown in photographs 1 and 2.

Step 1 emergency actions were implemented by SWC between March 30 and April 2, 2003, and included lowering the reservoir to El. 1521 by re-opening the 66-inch-diameter spillway. Step 2 emergency actions were implemented by SWC between April 7 and April 17, 2003, and included installing a sheetpiling and earthfill cofferdam around the upstream end of the principal spillway inlet thereby taking the principal spillway out of service.

Contributing Factors

Possible factors that may have contributed to the erosion under the spillway were identified and divided into the following four major categories:

- Underdrain System Design
- Structure Design and Seepage Cutoff Provisions
- Climate, Freeze Thaw, and Site Conditions
- Construction Materials and Methods
A brief description of the various factors identified and potential issues associated with each factor are presented in the following sections.

**Underdrain System Design**

The underdrain system is located below the downstream part of the chute and stilling basin and consists of a dual stage granular filter blanket that envelopes a perforated drain pipe (see Figure 3). Elements of the underdrain system that may have contributed to the erosion are:

**Location of Underdrain System** – The first underdrain unit is located beneath Segment E (see inset of Figure 3) at a distance of about 61 feet downstream of the centerline sheetpiling cutoff. Therefore, a drain system was not present at the location where the highest seepage gradients, pressures, and flows would be anticipated, which is immediately downstream of the centerline sheetpiling cutoff.

**Filter Compatibility of the Drain Materials** – Contacts between the various materials where seepage is possible needs to be filter compatible. As shown in Table 1, filter compatibility was not achieved at all critical material contact boundaries.

### TABLE 1

<table>
<thead>
<tr>
<th>Case No.⁽¹⁾</th>
<th>Base Soil</th>
<th>Filter</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Embankment Fill⁽²⁾ (as sampled)</td>
<td>Fine Drainfill (as specified)</td>
<td>Yes - Filter criteria is met.</td>
</tr>
<tr>
<td>2</td>
<td>Embankment Fill⁽²⁾ (as sampled)</td>
<td>Fine Drainfill (as specified)</td>
<td>No - Filter criteria is not met.</td>
</tr>
<tr>
<td>3</td>
<td>Fine Drainfill (as specified)</td>
<td>Coarse Drainfill (as specified)</td>
<td>Qualified Yes - Coarse drainfill is slightly coarse of the D₁₀ max criteria, however it is close enough that filter criteria is considered to be met. This could cause a problem under very high gradients.</td>
</tr>
<tr>
<td>4</td>
<td>Fine Drainfill (as specified)</td>
<td>Coarse Drainfill (as sampled)⁽³⁾</td>
<td>Yes - Filter criteria is met.</td>
</tr>
<tr>
<td>5</td>
<td>Fine Drainfill (as sampled)⁽³⁾</td>
<td>Coarse Drainfill (as specified)</td>
<td>Yes - Filter criteria is met.</td>
</tr>
<tr>
<td>6</td>
<td>Fine Drainfill (as sampled)⁽³⁾</td>
<td>Coarse Drainfill (as sampled)⁽³⁾</td>
<td>Qualified Yes - Filter criteria is met but increased sand content at D₁₀ size indicates the permeability would be restricted.</td>
</tr>
<tr>
<td>7</td>
<td>Embankment Fill⁽²⁾ (as sampled)</td>
<td>Foundation Stabilization Gravel</td>
<td>No – Filter criteria is not expected to be met based on comparison with Case No. 2 above.</td>
</tr>
</tbody>
</table>

1. Assigned for identification and tracking.
2. Sample obtained from embankment exposed under spillway after failure
3. Sample obtained from under Segment B after failure

**Encapsulation and Confinement** – The design of the underdrain system did not require complete encapsulation of the coarse drain fill materials with fine drain fill material. The coarse drainfill is not enveloped by fine drainfill at the top of the pipe trench. The coarse drainfill at the top of the drain pipe trench is exposed directly to the rigid insulation. The rigid insulation is installed in two 2-inch-thick layers using 4-foot by 8-foot panels. It appears that gaps on the order of 1/8-inch thickness existed between the panels. The relative permeability of the ‘fracture’ type flow through the panel gaps would be significantly higher than the permeability of the fine drainfill, resulting in a preferred seepage and erosion pathway.

The granular drain material may not have been laterally confined during placement because it was not placed either in a trench-type condition or between concrete walls that
would have confined the material. Poor compaction at the important contact between these materials would result in loose materials that have increased porosity and potential for development of preferred erosion pathways along the contact boundary.

Capacity of Drain System – The design hydraulic capacity of the drain system may not have been sufficient to effectively collect the volume of seepage that developed prior to failure.

Effectiveness of the Pre-Fabricated Strip Drain around the Inlet Structure – Strip drains consisting of a commercially produced geosynthetic composite material drain board core covered on all sides by a non-woven geotextile fabric were installed around the inlet drop structure walls upstream of the centerline wing wall to reduce hydrostatic pressure against the concrete inlet walls. A fundamental concern with use of geotextiles for filtration and drainage is geotextiles will become clogged by suspended sediment, such as occurs when water moves through a crack in soil. Clogging occurs because the strip drain core does not provide the needed support to the geotextile, which in turn, must support the soil interface and the geotextile where seepage water is discharging. The strip drains were likely not entirely effective at reducing hydrostatic pressures at the base of the structure.

Structure Design and Seepage Cutoff Provisions

Hydrostatic Uplift of the Inlet Basin – The intent of the pre-fabricated strip drains and weep holes around the inlet basin is to reduce hydrostatic pressures on the walls and reduce uplift forces on the structure by draining seepage to the interior of the inlet basin. However, if the strip drain becomes clogged or has inadequate hydraulic capacity to pass seepage flows and if the net uplift forces were large enough to lift the basin, a preferred seepage path would form that could apply full reservoir head against the centerline sheetpiles. A layer of granular structural fill was evidently placed beneath the inlet basin based on observed granular material embedded into the concrete slab.

Based on a simplified flotation analysis, the computer factor of safety with the reservoir at normal pool is about 0.75. Potential effects of this flotation was evaluated by assuming that the spillway acts as a cantilever beam, with net uplift forces acting on Segments M and L (see Figure 3) only. Based on this analysis, it appears that the net uplift loads could lift the inlet section of the spillway vertically by as much as 0.03 inches.

Size and Type of Centerline Cutoff – The bottom of the sheetpile cutoff was designed to extend 4 feet below the bottom of the slab. In addition, the sheetpiles only extended about 6 feet left and right of the spillway structure, which also may not be sufficient for the above condition. Based on seepage analysis, it was concluded that:

a. For each condition modeled, seepage quantities would be relatively small provided that the embankment soil remains in contact with the upstream and downstream sides of the sheetpiles.

b. For each condition modeled, exit gradients into the underdrain system are about 2.0, which would be sufficient to cause internal erosion of the embankment soils and piping into materials that are not filter compatible.

The three cases modeled are:

Case 1 – Design condition. Clayey soils in contact with the bottom of the slab of the inlet basin and chute upstream of the drainage system. Drain system is as shown in the design drawings.

Case 2 – Void or coarse granular material exists below the inlet slab from the upstream end of the foundation slab to the upstream side of the centerline sheetpile cutoff. Clayey soils in contact with the bottom of the chute upstream of the drainage system.
Case 3 - Void or coarse granular material exists below the inlet slab from the upstream end of the foundation slab to the upstream side of the centerline sheetpile cutoff. Clayey soils in contact with the bottom of the chute upstream of the drainage system. Coarse gravel or void that is hydraulically connected to the reservoir is present against the inlet walls.

**Frost Protection Upstream of the Drainage System** – Insulation was only provided above the filter drain materials. No insulation was provided under the chute upstream of the underdrains or under the drop inlet structure. Therefore, the embankment materials were not protected against freezing.

**Climate, Freeze Thaw, and Site Conditions**

**Freeze-Thaw Cycles Under Structure** – Frost-susceptible soil, freezing temperatures, and a source of water contribute to the formation of ice lenses and frost-heave that can result in significant uplift forces on structures. Embankment fill used to backfill the spillway excavation generally has the following characteristics:

- Generally classifies as a moderate to high plasticity silt (ML to MH)
- Liquid limit ranges from about 49 percent to 58 percent
- Plasticity Index ranges from about 19 to 23 percent
- Gradation generally consists of about 20 to 30 percent clay, 50 to 60 percent silt and clay fines, 33 to 47 percent sand, and 5 percent gravel

The force exerted on the structure as a result of frost heave could be large enough to result in a slight, but potentially significant, uplift of the structure. Even slight uplift of the structure could contribute to further intrusion of seepage water under the slab. One result of several cycles of freezing and thawing would be the development of either a zone of low density soils or a void below the slab.

**Colder Winter than Usual with Associated Deeper Frost Penetration** – Frost depths of up to 10 feet were reported in the general area for the winter of 2002-2003, which is 3 to 4 feet more than normal.

The months of December and January were warmer than usual and the months of February and March were colder than usual. On March 8, 2003, Langdon had a record low temperature of -25°F. Seven days later, on March 15, Langdon had a high temperature of 45°F, which was 4 degrees short of the record, and on March 16, the high was 50°F.

**Solar Radiation and Differential Thawing** – The thawing of frozen soils usually proceeds from the top downward. The melt water cannot drain into the frozen subsoil, thus becomes trapped between the concrete slab and the frozen materials below. This process can be even more dramatic when the frozen surface is heated differentially. The orientation of the spillway is such that the left side of the slab and the left wall would be in the sun for most of the day. Therefore it is expected that this area of the spillway would be warmer due to solar radiation, which would result in thawing of the backfill sooner on the left side than on the right side.

**Construction Materials and Methods**

**Installed Materials versus Specified Materials** - Based on the results of gradation tests on samples of fine and coarse drainfill materials, which were obtained at the time of the site visit from the relatively intact drain system located beneath Segment C of the spillway, the as-placed fine drainfill sample is not consistent with the specifications. The fine drainfill tested
is significantly coarser than the specified material. Using the gradation of the sample tested, filter compatibility criteria between the fine drainfill and embankment fill material is not met.

**Adequate Lateral Containment of the Drain Material** – Containment of the granular drain material does not appear to have been achieved because the material was not extended laterally beyond the structure to the sides of the excavation. The footing/slab was poured on top of the drain material before any backfill was placed adjacent to the drain system. The important contact between the backfill and the drain system was not likely adequately compacted.

**Foundation Stabilization** – Measures were taken during construction to address wet subgrade conditions. In a departure from the design, foundation stabilization gravel (1-1/2-inch minus) was placed in areas of wet subgrade beneath stilling basin Segments A and B to provide a working surface. This gravel was then covered by non-woven geotextile. As a result of the higher permeability of the foundation stabilization material, seepage would tend to concentrate in this zone and a gradient would develop from the embankment soils into the foundation stabilization material and into the underdrain system.

If the overlying geotextile became clogged, seepage collected by the foundation stabilization material would be discharged either laterally into the surrounding embankment fill or a circuitous pathway around the geotextile and into the underdrain.

**Key Observations**

Key observations and information that was obtained and was influential in evaluation of the failure modes are summarized below:

- Spillway underdrains for Segment C (Drain No. 3 left and right) and E (Drain No. 1 left) were observed discharging during the August 2000 inspection. (Drains are numbered from upstream to downstream and left and right, based on looking in the downstream direction.)

- Stained concrete adjacent to underdrain discharge locations indicates upstream drains flowed more than downstream drains.

- The sound of water moving near the fifth weep hole on the left side of the principal spillway drop inlet was identified during the August 2000 inspection. This observation likely indicates development of a seepage pathway beneath the inlet slab or adjacent to the footing upstream of the cutoff about 2.5 years before the failure occurred.

**Probable Failure Mechanisms**

The likely failure mechanisms are as follows:

- Conditions leading to the large-scale erosion began to develop several years prior to the catastrophic event that occurred in March-April 2003. This opinion is based on the following:

  - SWC observations that the seepage collection system was conveying water through underdrains for Segment C (No. 3 drains on left and right) and Segment E (No. 1 drain on left) and the sound of flowing water behind the fifth weep hole on the left side of the drop inlet in August 2000, which is about 2.5 years prior to the event (refer to Figure 3 for locations of spillway segments). This evidence suggests that a seepage path existed under the spillway prior to the events of March and April 2003.

- The seepage exiting the underdrain outlets appears to have been associated with seepage flowing under the spillway slab and not general embankment or foundation seepage based on the following reasons:
- General embankment seepage that is associated with the phreatic surface in the embankment would also have been visible at similar elevations along the toe of the dam. No such seepage was identified.
- General foundation seepage associated with the documented high foundation pressures would have continued after the erosion failure. Seepage into the eroded area below the spillway or from the underdrain outlets was not observed after the event.

The specific reason for no seepage exiting from Drain No. 2 is unknown. It is possible that seepage paths developed either under or around the underdrain system at Segment D. Full reservoir head was applied to the upstream side of the sheetpiles at the centerline of the dam. Full reservoir head developed as a result of one or a combination of the following:
- The presence of coarse-grained materials (likely structural fill) that were placed beneath the inlet slab to improve foundation stability during construction.
- Cycles of freezing and thawing that resulted in uplift of the structure and associated voids at the slab/soil interface and/or the development of a low density/higher permeability zone directly beneath the slab.
- Hydrostatic uplift of the inlet structure that resulted in a void at the slab/soil interface.

Seepage paths developed under the slab or along the sides of the footings between the centerline sheetpiles and the underdrain system. These seepage paths developed as a result of one or a combination of the following:
- Cycles of freezing and thawing that resulted in uplift of the structure, voids at the slab/soil interface and/or the development of a low density/higher permeability zone below the slab.
- Inadequate compaction at the contact between drainfill materials and adjacent soil backfill because of lack of lateral confinement of the drain materials.
- Possible gaps between the rigid insulation panels.
- High seepage gradients in the foundation soils adjacent to the concrete.

Erosion of the embankment soils under the slab is a result of one or a combination of the following:
- Apparent filter incompatibility between the fine-grained silt embankment materials and the fine drainfill of the drainage system.
- Filter incompatibility between the fine-grained silt embankment fill and the coarse drainfill where the coarse drainfill is in direct contact with the rigid insulation panels (panel gaps) and is not protected by fine drainfill.

The volume of seepage significantly exceeded the capacity of the filter drain system and the seepage exited the left side of the spillway resulting in the large erosion under the spillway that occurred in March and April 2003. The sudden increase in seepage quantity was most likely the result of one or a combination of the following:
- A void developing under the left side of the slab as a result of differential thawing and subsequent volume decrease of the foundation soils. The differential thawing was the result of heating of the slab and underlying soils by sunshine on the spillway wall and floor slab.
- Progressive piping erosion of silt embankment fill through the coarse drainfill where it is exposed directly to the rigid insulation panels. This flow pathway has no filter protection against suspended sediment. Gaps observed to exist between the insulation panels provided a high permeability pathway for erosion of embankment materials. The permeability of flow through the panel gaps and coarse drainfill is
expected to be several times higher than through the fine drainfill, thereby creating a preferred pathway for erosion of soil.

Conclusions

Based on the evaluations completed, we conclude the following: The primary site elements contributing to the excessive erosion under the spillway are a) the combination of frost susceptible silt embankment fill soils with the extremely cold climate and b) the combination of highly erodible silt embankment fill soil with likely non-filter-compatible drain and foundation stabilization materials.

The primary design elements contributing to the excessive erosion under the spillway are, in order of importance:

- The lack of a filter compatible seepage collection system immediately downstream of the centerline (dam axis) cutoff.
- The lack of provisions to accommodate freezing of the soils directly under the slab upstream of the underdrain system.
- The shallow depth and limited lateral extent of the sheetpile cutoff at the dam center line.

The primary construction elements contributing to the excessive erosion under the spillway are a) the use of fine drainfill (as sampled) that does not meet filter criteria for the silt embankment fill, b) the use of foundation stabilization gravel that does not meet filter criteria, and c) the lack of lateral confinement of the granular drain materials resulting in poor compaction at the drain/backfill interface.

It is our opinion that the excessive erosion under the spillway likely would not have occurred if all or most of the following elements were incorporated into the initial design and construction:

- Provisions to either a) prevent frost heave in the soils below the spillway slab upstream of the underdrain system or b) anchor the slab to prevent upward movement of the slab from forces associated with freezing soils.
- Deeper and wider centerline (parallel to dam centerline) seepage cutoff. The cutoff should be designed to provide low exit gradients with full reservoir pressure at the upstream side of the cutoff.
- Filter/drain system immediately downstream of the centerline seepage cutoff. The filter/drain system would need to be filter compatible and have adequate hydraulic capacity to convey the expected seepage with an acceptable factor of safety.
- Place only filter compatible materials below structures and along any paths of likely seepage to prevent piping.
- Confirming that earth materials used in the construction are filter compatible with each other and the embankment materials.
- Provide filter protection to address not only likely areas of seepage but also at all possible areas of seepage.
- Provide a larger footing or other elements to increase the factor of safety against flotation.