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Surface impoundment design goals

This article describes a failure of a water storage reservoir. It provides a good reminder of design considerations that the author has previously recommended (Richardson 2000). With more than 4 decades of surface impoundment application experience to draw on, it would be reasonable to assume that typical designs have become routine with little opportunity for significant mistakes on the part of the designer. However, industry and personal experience show that poor designs continue to fuel construction delays, insurance claims, and litigation. The common thread through many of these problems is the failure of the design engineer to understand the function of the impoundment liner and to anticipate the impact of an inevitable defect in the liner system. The following failure example clearly illustrates the problem.

Photo 1: A significant length of geomembrane was pulled from the batten strip.

Failure chronology

During the spring of 2001, a water utility on the Colorado River constructed a small water-retention basin to allow sediment to settle out of the river water before it was processed for drinking water. The basin was constructed fully elevated above grade with perimeter berms built using coarse alluvial fills that made up the island site. The floor of the basin was a concrete slab designed to allow the utility ready access for annually cleaning out the accumulation of sediments. The interior side slopes of the basin were covered with 60-mil smooth HDPE to limit water loss through the perimeter berms. The HDPE geomembrane was attached to the concrete floor with stainless steel batten strips.

Construction of the retention basin proceeded smoothly, and by late spring of 2001 the basin was ready for required hydrostatic testing. This was to be accomplished by filling the reservoir in three stages and observing the water elevation for several days at each stage. The first two stages of testing verified the integrity of the concrete slab and the batten strip system attaching the geomembrane to the concrete. These tests proceeded smoothly and were successful. The third stage completely filled the reservoir to an overflow condition. During the initial 24 hours, the depth of water dropped one foot. During the second 24-hour period, the drop in water depth was so significant that failure of the pond was evident and it was then hastily drained.

Photo 1 shows the extensive damage that was done to the HDPE liner during the final stage of hydrostatic testing immediately adjacent to a 30-in. (76.2-cm) water-inlet pipe. Extensive tearing of the geomembrane from the batten strips was observed and a significant volume of underlying soil had simply vanished. At this time, the designer suspected the quality of liner installation, the installer questioned the heritage of the designer, and the owner had lost confidence in all involved.

Failure analysis

Called in to review the failure, it took only hours for the author to establish that two fundamental yet complementary problems had led to the failure of the reservoir:

- the designer assumed that the HDPE liner system would never leak and had not evaluated or provided an underdrain system below the liner, and
- the soil that formed the perimeter berms was so internally unstable that water flowing through the soil led to a very large loss of fines.

The designer's assumption of total liner impermeability was particularly foolish given that the reservoir design provided no protection to the geomembrane, and that staff would be repeatedly walking directly on the geomembrane during the reservoir's operation. In spite of a significant volume of published works pointing out the need for underdrains beneath liners in surface impoundments (Kays 1977, Giroud 1984, Richardson and Hase 1999, Richardson 2000), the designer was oblivious to the need. This omission would not have been noticed if the underlying soils were very pervious and stable.

Particle grain-size curves presented in the geotechnical report for this project indicated that all on-site soils were broad graded, i.e., contained a very wide range of particle sizes. Additionally, the materials were gap graded in that they lacked particles in the pea-gravel-to-coarse-sand size. This was confirmed by the geotechnical engineer in post-failure meetings. Additionally it was learned that the coarse sand fraction was missing from most soils in the river valley.

The impact of the lack of the coarse sand fraction in the materials must be understood to appreciate both the cause of failure and the goal of the repair work that will be required. As water flows through a soil, it will tend to remove the smaller-sized particles such as silts and fine sands. These smaller noncohesive particles are normally prevented from movement in a broad graded soil by the coarse sands. Additionally, the smaller particles can be restricted in movement if they constitute a majority of the material such that the coarse particles essentially float in the smaller particles, preventing the existence of large fluid pathways. However, **Photo 2** shows the observed loss of soil beneath the HDPE liner apparent when the liner is removed.

Figure 1 presents grain-size curves of the bedding soil and embankment material obtained in the immediate vicinity of the 30-in. (76.2-cm) pipe liner penetration. The embankment material is clearly gap graded (lacking coarse sand) but has approximately 50% of the smaller particle-size fraction. Since the material is non-plastic, the smaller particles consist of fine sand and silt.

Both geotechnical data and direct field observations showed that the percentage of fines could drop significantly in a fraction of the embankment soil. Additionally, cleaner coarse materials were used as backfill against the short toe walls of the concrete base slab and to backfill pipes. This use of coarse materials minimized the amount of compaction required, limiting the potential compaction-induced damage to the concrete and pipe. However, the smaller particle-size fraction of the fill and a bedding layer beneath the geomembrane can readily flush through these coarse soils.

Based on these design and material deficiencies, the following failure scenario is felt to have occurred:

- During the third stage of filling, the pond liner system developed a small leak near the 30-in. inlet pipe. This leak could have occurred due to a defect in a seam weld of the liner, a leak of the seal used to seal the 30-in. pipe to the concrete, or a leak in the batten connection of the geomembrane to the concrete. After failure, the liner was so distressed that its initial condition could not be confirmed.
- As the head of water acting on the defect increased, so did the rate of leakage through the liner. Water flowing beneath the liner mobilized the fine sand and silt particles of the bedding layer. This slurry was able to pass through those areas of the embankment that did not have a high percentage of the smaller particle size fraction. **Photo 2** shows the southwest corner of the facility immediately after removal of the geomembrane. The bedding layer's scouring through the coarse subgrade is evident.
- The continued removal of the bedding material from beneath the liner removed support from beneath the geomembrane. Near the 30-in. (76.2-cm) pipe penetration, nearly 4 ft. (1.2 m) of fine-grained bedding layer was placed. As this thick layer was removed, support of the geomembrane was lost and the geomembrane was forced to carry the weight of the water. **Photo 1** shows the significant length of geomembrane that was pulled from the batten strip as the underlying bedding layer eroded away. Once this degree of separation occurred, the water could easily move beneath the geomembrane since HDPE geomembrane actually floats in water (specific gravity at 0.95) and would not impede the water's flow. This resulted in scour of the smaller particle-size fraction adjacent to the concrete base wall. The geotextile cushion immediately beneath the geomembrane was wet and had been exposed to water.

Photo 2: Scour of bedding layer is evident after geomembrane removal.

Unfortunately, the same cohesionless fine-grained bedding layer was also used immediately beneath the concrete floor slab. Water flowing under the base slab resulted in the loss of much of these fines. This resulted in voids developing beneath the southwest corner of the floor slab and concrete near the outlet piping.

Lessons learned

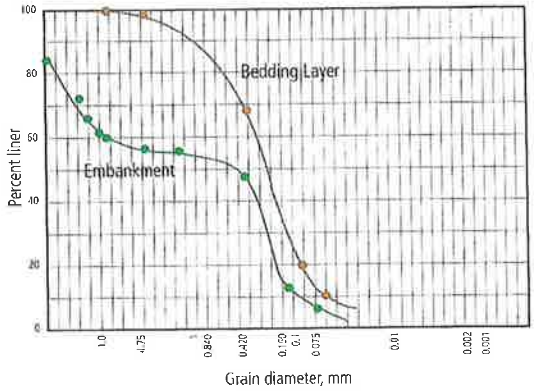
Surface impoundment failures can be avoided if their designers follow simple guidelines. If a designer is assuming the surface liner system will not ever leak, then the following provisions must be made:

- The use of such details as battens and conventional pipe penetration details that cannot be leak tested must be avoided. All components of the containment system must be pressure or vacuum tested.
- The liner must be protected from harm during its surface life. Thus, if you can see the geomembrane, you must assume that you will get a defect and resultant leakage during the liner's service life.

It is more reasonable to assume that the surface impoundment liner has a very minor rate of leakage and design to accommodate that leakage as follows:

- If the contained liquid may harm the environment, then a secondary liner/collection system should be used to monitor the performance of the primary liner.
- If the contained liquid will not harm the environment, then the ability of the leakage to drain away from the bottom of the liner must be ensured. This may require a designed underdrain where natural subgrade soils have a low permeability.

Figure 1: Grain-size curves of bedding soil and embankment material around the pipe liner penetration.



Fortunately, the majority of surface impoundments successfully provide a very inexpensive containment of liquids. Their successful design must not be taken for granted, but is certainly within the skill levels of most civil engineers. GFR

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