CASE STUDY:
SURFACE IMPOUNDMENT FAILURE AND RECONSTRUCTION

The April 2002 *Geotechnical Fabrics Report (GFR)* contained a case study on the failure of a liner system for a surface impoundment. A follow-up article was published in the April 2003 *GFR* to describe the redesign and reconstruction of the surface impoundment. Taken together, these articles identify many common liquid containment design flaws which can have disastrous consequences for engineers and owners of such structures. These articles offer valuable lessons and strategies for minimizing the potential for failure.

Why do such failures occur? The author of the article believes, “The common thread through many of these problems is the failure of the design engineers to understand the function of the impoundment liner and to anticipate the impact of an *inevitable defect* in the liner system.” IN this project, one such “inevitable defect” around a pipe penetration caused a leak which washed out the underlying subsoils and resulted in a completed containment failure when the geomembrane no longer had any foundation to support the weight of the overlying water.

Designing with a geomembrane alone therefore requires careful analysis of the subsoils and their relative stability. Questions must also be asked about the difficulty in attaching geomembranes to various structures and penetrations. Furthermore, the difficulty in obtaining a perfect seal in complex geometries is daunting. The author recommends covering the liner system to prevent long-term damage. Finally, the author recommends using multiple liners in order to add redundancy to the project.

All of these recommendations can be met by using a CL-series GCL from CETCO. With a thin geomembrane placed over a full-function GCL, out CL series offers redundancy, ease of application around penetrations, leak sealing via the bentonite component of the product, and long-term stability by the required placement of cover soil. For these reasons, a GCL was one of the materials selected for use in the reconstruction of the impoundment.

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By Gregory N. Richardson, Ph.D., P.E.
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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.

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:

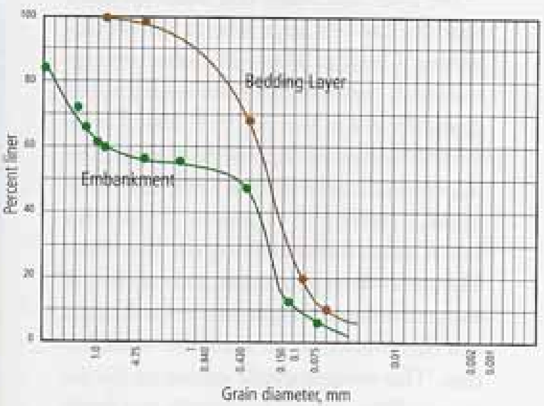
- The use of such details as battens and conventional pipe penetration details that cannot be leak tested must be avoided. All components of the containment system must be pressure or vacuum tested.
- The liner must be protected from harm during its surface life. Thus, if you can see the geomembrane, 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:

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

- 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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By Jean E. Bierwirth, P.E. and
Gregory N. Richardson, Ph.D. P.E.

Surface impoundment rehabilitation

In a previous Designer's column (April 2002), the second author presented an evaluation of the failure of a surface water reservoir. This reservoir had failed during post-construction hydrostatic testing and had not provided a single day's service for the water district. As detailed in that article, the failure was the result of a combination of unstable subgrade soils and design assumptions that did not manage seepage through the geomembrane and steel battening system. At the time Red Mesa Consulting Inc. was retained to provide remedial design services, the water district was approximately two years behind schedule in its plans for expansion. To further aggravate circumstances, water supply reservoirs upgradient were experiencing severe decreases in storage because of persistent drought conditions. This article presents the rehabilitation of the reservoir that is now in service and functioning in accordance with the design.

Key redesign decisions

Recall that the original pond liner system consisted of a single layer of HDPE geomembrane with slopes that transitioned to concrete walls and fastened using steel battening. The original geometry of the impoundment was irregular with abrupt changes and a slope of 1:1 in the vicinity of the inlet pipe. The concrete walls and floor were extensively cracked after the failure and were unable to contain water. Further, the HDPE liner had deteriorated from exposure to high winds. It was decided to remove the HDPE liner and steel battening early on to identify the degree of damage from the catastrophic failure and subsequent weathering.

The first step in the rehabilitation was the evaluation of different design options with consideration to cost and schedule. The extreme option was complete removal of the current liner system and impoundment berms. This would eliminate the unstable subgrade soils, but would be the most expensive and time consuming option. Instead, it was decided to use the existing berms and design a liner system that would ensure the subgrade remain unsaturated.

The rehabilitation had to maintain the embankment and foundation soils in an unsaturated condition by keeping the material isolated from water infiltration. The design incorporated two relatively impervious liners and a seepage collection system for redundancy to ensure an unsaturated environment. The double liner system with seepage collection provided the necessary safeguards for the intended use of the pond. Further, the existing geometry of the pond was simplified, and abrupt changes in lines and grades were eliminated. This allowed for a simpler liner system that made construction easier. It should be noted that the authors do not recommend the use of a steel battening system where it will be subject to even a minor fluid head. Eliminating the steel battening and concrete containment basin meant that the geosynthetic liner would be continuous throughout the impoundment's interior.

Photo 1. The completed access ramp and base clear the way for the geosynthetic redesign of the structure.

Revised liner system

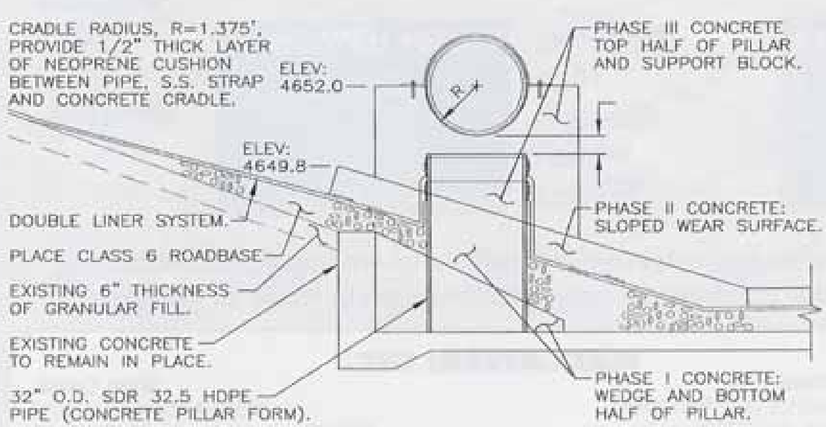
Given that a repeated failure of the pond would be catastrophic particularly with respect to the client's schedule, the revised liner system was designed to provide both performance monitoring and redundancy. The revised liner system incorporated the following components (bottom up):

- geosynthetic clay liner,
- 40-mil PVC secondary liner,
- geosynthetic drainage composite, and
- 60-mil HDPE primary liner.

Dissimilar liners were selected to improve the redundancy of the system. The HDPE liner offers superior UV protection and resistance to typical exposure damage. The PVC liner offers superior biaxial elongation in case localized erosion and deformation occurs. The geosynthetic clay liner was selected in lieu of reconstructing the embankment with materials that meet filter criteria.

At the onset of the project, it was decided to stabilize the foundation under the cracked concrete floor using low-pressure

Figure 1. Inlet pipe support detail.



grout placement. The majority of the grout was placed near the area of failure and along trenches originally intended for dewatering the sediments. Additionally, road base was placed to the height of the concrete stemwall to eliminate the abrupt change in geometry; however, filling the bottom reduced capacity. To offset the loss of storage volume, the embankment was raised an average of 2 ft. (60 cm). **Figure 2** shows the revised liner system placed over the failed reservoir floor. Sub-drain lines were retained and currently drain the granular soil placed above the original concrete floor. In addition, the geosynthetic seepage collection system reports to these same lines and a weir was added to the combined outlet of the sub-drain lines to allow the accurate quantification of the liner performance. The failed concrete bottom now provides another level of liquids collection to protect the unstable subgrade.

Pipe penetrations

The failed design incorporated over a thousand feet of steel battening to connect the original geomembrane liner to the concrete walls. This connection could not be tested for continuity and was subjected to approximately 20 ft. (6 m) of head. The use of a continuous liner limited the potential leakage points to 10 locations where either pipes or pipe supports penetrated the composite liner. Given that 30-in. (76-cm) pipes feed and drain the reservoir, the handling of the pipe penetrations was considered critical to the success of the reservoir.

With the exception of the inlet pipe, all of the liner penetrations were made using a neoprene cushion and stainless steel straps encapsulated in concrete. **Figure 2** shows how the new liner was integrated into the inlet pipe support columns. The penetration of the liner was protected from exposure and direct contact with the water in the reservoir by more than 6 in. (15 cm) of concrete.

Photo 2. The rehabilitated reservoir is finally able to begin serving the water district.

However, the large 30-in. inlet pipe penetration was not protected by concrete. As shown on **Figure 3**, the performance of the pipe boots around the pipe was verified by using two neoprene cushion and stainless steel strap seals on each liner boot such that they could be pressure tested. The pipe was also placed in a concrete block to limit its movement and any potential erosion near the pipe.

Access to pond interior

To allow the water district access to the interior of the reservoir for clean out, a concrete ramp and base slab were placed on the liner system. A 12 osy nonwoven was used as a cushion between the concrete and the underlying liner. This also provided for drainage from beneath the concrete access system. The access ramp into the reservoir bottom is supported by both adequate interface frictions in the underlying liner system and from buttressing by the concrete base slab. **Photo 1** shows the completed concrete access ramp and base. Note that "Jersey" style barriers were incorporated at the perimeter of the concrete base liner to protect the exposed HDPE side slope liner from damage during future sediment clean out operations.

In addition to the need for access to the pond for equipment, the water district required a drain located at the low point of the concrete base slab. A 16-in. (40-cm) PVC pipe with a sliding gate valve was pro-

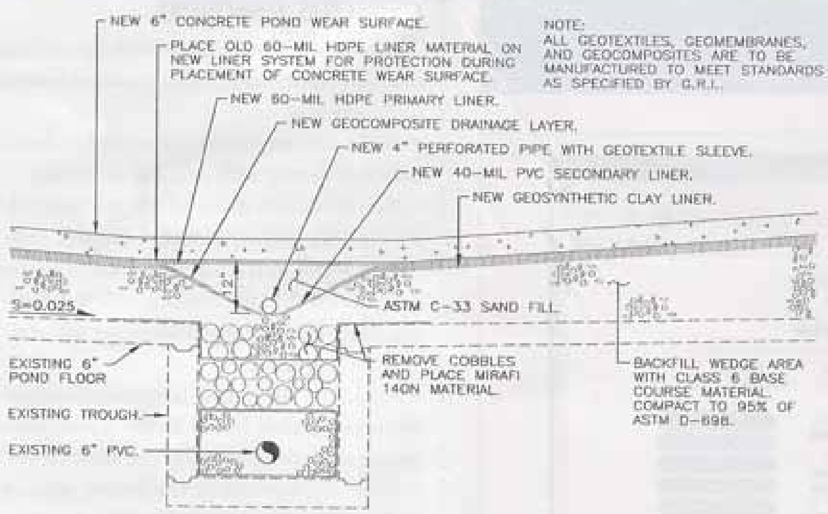


Figure 2. Liner system detail.

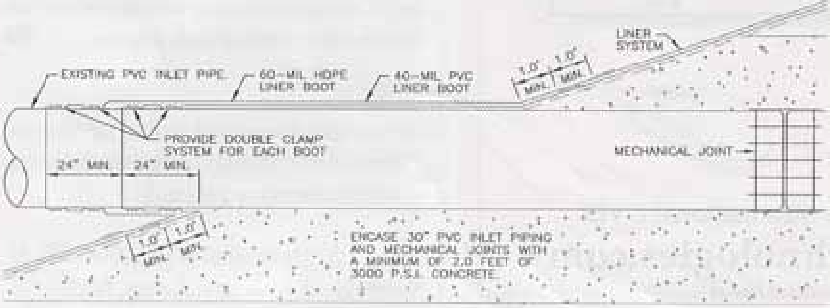


Figure 3. Inlet pipe boot detail.

vided at the base of the reservoir. The penetration seals for this pipe were also cast into the new concrete base slab. This pipe provided a drain in the event the water district needs to use high pressure hoses to clean out river sediment.

Construction

Reconstruction of the reservoir began in late July 2002 by Nielsons SKANSKA. The liner system was installed by Simbeck & Associates. Redesign, construction oversight and CQA for the rebuild was provided by Red Mesa Consulting Inc. Construction was completed in early November 2002. The rebuild of the impoundment cost the water district approximately $534,000. The Colorado State Engineer's Office granted acceptance of construction on 10 January 2003. **Photo 2** shows the reservoir full and in service today.

Lessons learned

The failure and subsequent redesign of this reservoir points out several important lessons to designers:

- Build earthen reservoirs on stable foundation soils and with suitable materials.
- If construction materials do not meet filter criteria, than engineered seepage control measures must be incorporated into the design such that the controls will not damage the system or the underlying soil support for the system.
- Avoid the use of steel battening liner terminations below liquid levels. If steel battening must be used below the liquid level, provide encasement of the batten strip or use double batten strips to allow pressure testing of the seal.

With the surface impoundment placed back in service the only remaining activity is the inevitable litigation that follows a failure. It is unfortunate that so many of our best lessons must come at such expense. **GFR**

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Designer's Forum

By Jean E. Bierwirth, P.E. and
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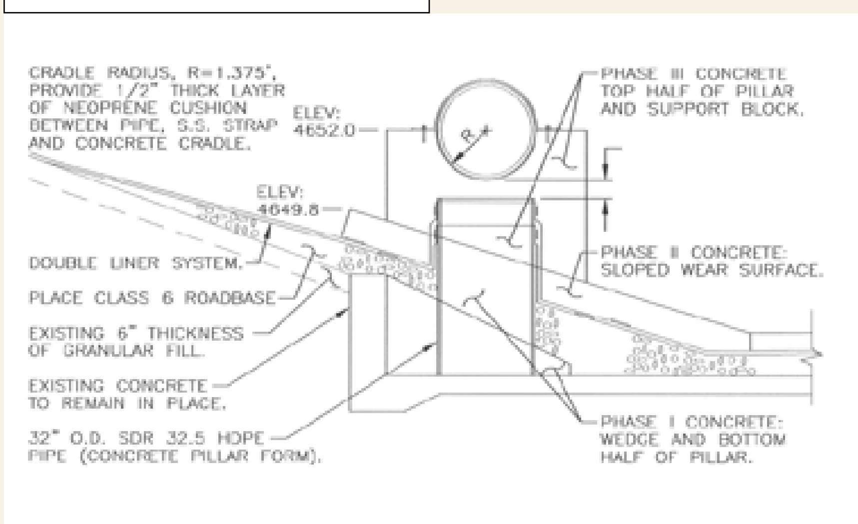

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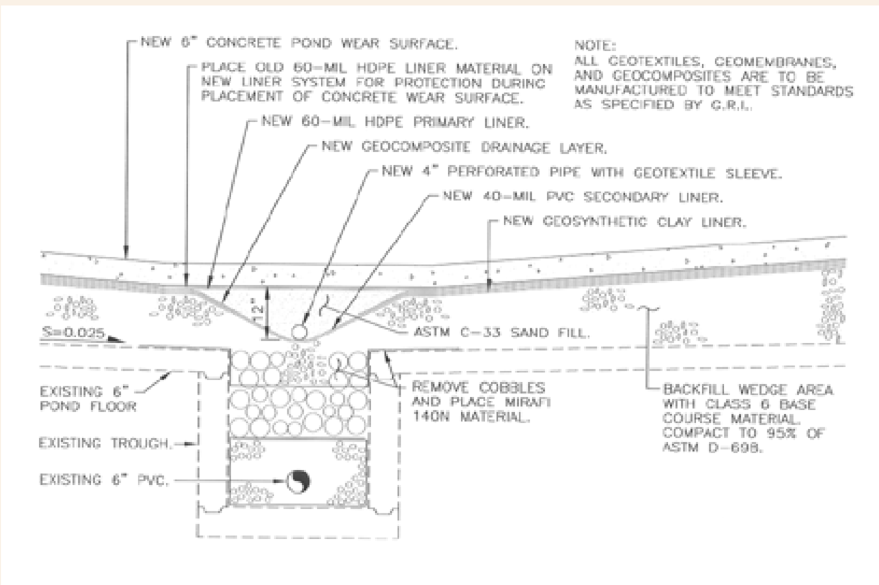

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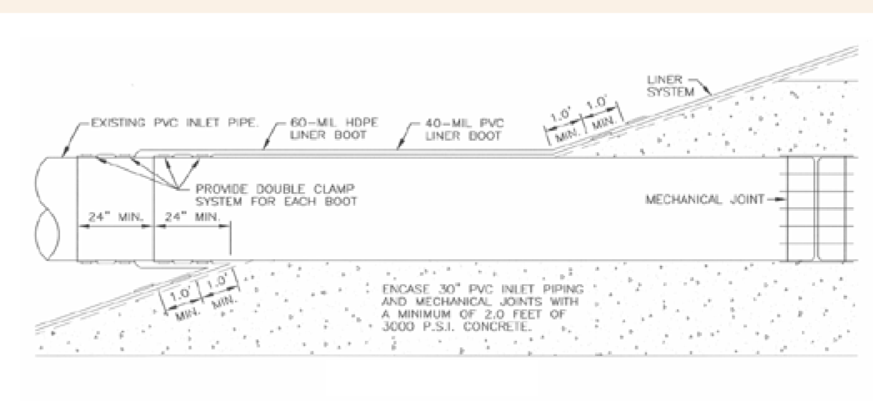

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