Root cause failure assessment of a water retention reservoir at a mining industry Site

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Abstract. This paper reports on an investigation into the failure of a double HDPE geomembrane lined retention reservoir constructed in 2018 that failed in 2021, only 3 years after construction. Several technical and non-technical factors contributed to the failure, and these are examined systematically. The primary failure occurred at the outlet pipe penetration, where the design detail had been modified due to constructability issues. Several administrative failures were also identified during the investigation, the most significant of which was the absence of a comprehensive construction report with a concluding statement from the engineer of record verifying the structure was constructed in accordance with the design and specifications and is fit for purpose. The failure highlights the need to better integrate design and construction teams and to keep impeccable records of all technical decisions.

1 Introduction

WSP Canada Inc. (WSP) was contracted by a confidential client to conduct a root cause failure assessment on a geomembrane lined water retention reservoir (the reservoir) that had failed in 2021, only three years after construction. WSP brought in Dr. Kerry Rowe as a subconsultant to participate in the investigation.

1.1 Design Overview

The design of the reservoir included the following components:

- Prepared subgrade;
- Secondary 2.0 mm (80 mil) thick smooth white High Density Polyethylene (HDPE) geomembrane;
- Leak detection layer consisting of a geonet made of HDPE;
- Primary 2.0 mm (80 mil) thick smooth white conductive HDPE geomembrane; and
- HDPE inlet and outlet pipes that penetrate the geomembranes at the ends of the reservoir.

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In July 2021, it was discovered that liquid was leaking from the reservoir. The reservoir was drained in order to allow for inspections, and it was determined that the penetration detail for the outlet pipe had failed and that liquids were being lost to the ground surrounding the reservoir outlet.

1.2 Liner Penetration Overview

The initial design of the penetration detail for the outlet line from the reservoir included the following general concepts:

- a secondary pipe sleeve secured to the HDPE outlet pipe with stainless steel pipe band clamps and neoprene gasket and caulking;
- a secondary liner apron welded to the secondary geomembrane and welded to the secondary pipe sleeve all around;
- a primary pipe sleeve secured to the HDPE pipe with stainless steel pipe band clamps and neoprene gasket and caulking; and
- a primary liner apron welded to the primary geomembrane and welded to the primary pipe sleeve all around.

Following a failure of the stainless steel pipe banding around the HDPE pipe (thought to be due to thermal expansion of the pipe) in June 2018, shortly after construction, several alternative designs were put forward by the liner installer. Available documentation was limited regarding the decision that followed, however the pipe was eventually cut flush to the slope and a single 13 mm (0.5 inch) "poly board" plate was installed in the field. This plate was welded to the pipe and both the primary and secondary geomembranes were welded to the plate.

1.3 Construction Overview

The review of photographs and information provided by the owner indicated that voids and oversize material existed in the bedding material around the outlet pipe. It is noted that the void from June 2018 looked very similar to a void visible in photographs taken during the August 12, 2021 inspection completed by the first author. There was no evidence in the project documentation that the voids were filled with any kind of materials. Photographs collected in 2021 showed voids in the same location (although they could have been created or expanded by leakage and piping). Photographs also show relationship between the void present in 2021 and the crack on left side of pipe. Compaction of the native soils in the vicinity of the outlet pipe appears to have been with a roller. There was no indication provided of the methods used for compacting the backfill immediately adjacent to the pipe and particularly below the spring line of the pipe but the use of the roller would not have provided good compaction below the spring line of the pipe and the critical zone between the spring line and the invert of the pipe where the void is apparent. Compaction test records were not available for backfill below and around the outlet pipe. It is not known if the material in these areas was tested although a photograph of compaction equipment working in this area was provided. The native material into which the retention reservoir was constructed contained some large diameter materials. It is not certain how the oversize material came to be so close to the pipe.

2 Review of Failure

Following the second failure, all of the available design and construction information was reviewed, and a site inspection conducted as part of the failure assessment reported in this paper.

2.1 Liner Penetration

Following a review of information, the following observations were made.

1. The pipe and plate connection as constructed relied on a single extrusion weld and hence did not provide for double containment or leak detection.
2. The outlet penetration area was not designed to manage leakage in the unexpected event that it occurred. Thus, the design left the soil-pipe contact susceptible to soil piping, loss and erosion along the length of the outside walls of the outlet pipe that penetrated the embankment. Soil loss was observed to have occurred locally in the failure area after the liner and plate was removed for inspection.
3. The loss of soil due to piping along the side of the outlet pipe could have lead to a lack of support to the plate material used in the connection detail. The hydrostatic pressure resulting from the liquid contained within the reservoir would push against the plate causing it to bend and could have resulted in cracking of the plate.
4. The plate material is specified on the shop drawings as “Poly Board” which is assumed to mean High Density Polyethylene (HDPE), but this could not be confirmed with the available data. The same term can be used to describe recycled Linear Low Density Polyethylene (LLDPE) and Polyvinyl Chloride (PVC). No documentation of the properties of the “Poly Board” or the geomembrane was provided. This information should have been part of the quality control and quality assurance information.
5. The plate was white in color, where most HDPE plate stock material is black.
6. Liner installation QC records state that a spark test was performed on the outlet penetration, however there was no evidence of a wire or filament observed (during investigation disassembly) that would have been used for spark testing the extrusion weld of the pipe to the plate.
7. Two cracks were noted on either side of the pipe commencing at approximately the spring line of the pipe and extended diagonally to the bottom edge of the plate.
8. One crack was noted in the plate material at the crown of the pipe and extending to the left side of the pipe.
9. The plate was welded to the pipe with a single extrusion weld all around. There was indication of poor bonding or adhesion of the extrudate to the plate around more than half of the circumference of the pipe indicating that the plate-weld interface failed.
10. The plate had been pulled away from the weld around the perimeter of the pipe from above the start of the diagonal cracks emanating from at or near the spring lines.
11. The extrudate material used in the weld appeared to be well bonded to the pipe and there were no obvious signs of failure in this weld to the pipe, although there were a few very localized cases of failure of the weld or in the plate where the bonding to the plate was good, this was the exception rather than the rule.

12. No construction quality assurance or quality control data such as conformance testing was available regarding the geomembrane properties, the properties of the welding rod, or the properties of the plate. Further, no information was provided regarding the stress crack resistance of the geomembrane or plate that was used.
13. Based on the significant cracking that was observed in the plate and the absence of any cracking in the geomembrane it would appear that the stress crack resistance of the plate was low relative to that of the geomembrane.
14. There was no evidence of any consideration being given to the compatibility of the welding rod with the plate. Based on the fairly robust adherence of the extrudate to the geomembrane it would appear that these two products were reasonably compatible. Based on the poor bonding of the extrudate to the plate it would appear that either (a) the welding rod and plate were not compatible, or (b) the surface of the plate was not properly prepared for welding, or (c) both incompatible rod and poor surface preparation. It is considered that a more detailed investigation into the materials used would provide more insight to the mechanism of the failure. In particular, an analysis of the melt characteristics of the geomembrane, the plate, and the welding extrudate would provide insight. In addition, it could be possible to evaluate the stress crack resistance of the materials.

2.2 Construction Quality Assurance and Quality Control

The following comments are provided related to the QC and QA activities associated with the construction of the penetration and outlet pipe.

1. There was no evidence that the plate material or fill material met the specification and except at particular times and locations that construction was in accordance with design and specifications. This information is notably lacking at the location of the failure.
2. The QC report prepared by liner installer was dated 11 May 2018. It provided a summary of the QC activities related to the installation of the primary and secondary liners in the reservoir, but no information was included for the construction of the penetration as this was completed in June 2018 after the report was submitted and no additional QC report was produced.
3. The email correspondence from the liner installer that outlined the steps completed to construct the penetration stated that a wire or filament was to have been installed in the weld of the plate to the pipe. There was no evidence of a wire or filament in the weld noted during the inspections completed in August 2021 or disassembly of the pipe penetration.
4. As built drawings of the penetration detail were not prepared.
5. The construction review report produced by the design engineer did not include a concluding statement on construction, made unusual references to "paid" and "unpaid" visits, and did not clearly identify what the responsibilities of each of the parties involved in the design and construction were and whether or not they executed those responsibilities.
6. There appears to be limited and difficult to follow documentation of quality control for the compaction testing or why multiple parties were conducting tests, and there was no post construction report summarizing geotechnical QA/QC with a concluding statement on construction produced by the geotechnical engineer.

3 Conclusions and Lessons Learned

The following items outline the conclusions and the lessons learned from the review of the available documentation.

1. The failure was attributed to multiple problems, each of which individually may not have caused the failure but when compounded resulted in a failure.
2. Double containment within the lining system is not double containment unless it also exists at the liner penetrations.
3. Liner and pipe penetrations should be designed with leakage in mind, so they are not susceptible to soil loss, erosion or soil piping in the event that leakage occurs.
4. Field extrusion welds can be difficult to test adequately using vacuum box testing methods and are a common source for leaks found during electrical leak location surveys. Consideration should be given to the use of imbedded copper wire or conductive geomembrane in critical areas.
5. Compatible materials must be used in penetration detail construction including geomembrane, extrusion rod and plate (i.e., welding rod and geomembrane are often made from the same resin material, but plate may be fabricated from a different resin).
6. Construction quality control (CQC) should be the responsibility of those contracted for the construction/installation and it should be verified by the owner.
7. Construction quality assurance (CQA) should be conducted by, or on behalf of, the owner, typically in partnership with the engineer or designer of record. Things usually go wrong and remain uncorrected when no one is checking or watching. An adage to bear in mind is: "you get what you inspect not what you expect". Resources committed to good full time CQA provide a good return.
8. Detailed CQC testing and CQA procedures are required for the installation of geomembranes, but additional steps and procedures are required for the construction of penetrations.
9. The use of shop fabricated components for penetration details such as pipe to plate connections allows for better access for welding all around, including both sides of the plate, and can offer a higher degree of QC inspection and testing than field manufactured components, which can be suspect due to conditions in the field and limited clearance for welding equipment.
10. Proper support of pipe penetration plate materials is critical to their structural integrity and performance.
11. Compaction required around a pipe and below the spring line generally requires use of smaller equipment such as plate tampers or jumping jack compactors and is necessary in critical areas such as embankment penetrations.
12. Testing of compaction is required for bedding material of pipes in critical locations, including below base of pipe and up to the spring line.

4 Recommendations

The following items outline the recommendations to be included in future designs.

1. Incorporate the lessons learned above for future designs.

2. Avoid penetrations in dam embankments, if possible. If they cannot be avoided, ensure that penetrations provide an equivalent (or better) level of protection than the overall lining system, including leak detection.
3. Avoid field welds on plate to pipe connections for penetrations. These should be completed in a shop in controlled conditions where they can be welded on both sides and can be spark tested and witnessed.
4. Provide full time third-party CQA during geomembrane installation.
5. Ensure that critical infrastructure elements, especially for sealing penetrations, or backfill of pipes or infrastructure in dam embankments, have full time CQC by the responsible party and CQA by or on behalf of the owner, in consultation with the engineer or designer of record.
6. Use of conductive geomembrane for the upper or primary geomembrane is recommended in double containment systems to allow for electric leak location testing to be completed.
7. Any voids near penetrations should be filled with a non-yielding material such as concrete but must be installed with appropriate procedures including tamping or vibration to prevent voids being created in this backfill material.
8. Installing a water stop or low permeability barrier on/around any pipe penetrations to create a longer flow path for liquid in similar situations should be considered as a means to minimize the risk of piping.
9. Plan and design for leakage in the area of any critical penetrations (i.e., filter compatibility of embankment materials, leakage collection, etc.).
10. Require comprehensive CQA documentation and post construction reporting including identifying clear responsibilities for each company involved and ensuring concluding statements on quality of construction are provided.