A Geomembrane Liner Failure: Design, Installation, and Communication Lessons Learned

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ABSTRACT: The world's largest single cell HDPE-lined pond, at the time of its installation in 1987, failed soon after being placed in service due to a series of installation, construction quality assurance, and material related problems. The field and laboratory analyses that identified these problems are described, together with remedial actions taken to effect repairs.

1 INTRODUCTION

The Palo Verde Nuclear Generating Station is located in the desert 80 km west of Phoenix, Arizona. After several cycles of cooling and treatment the unusable cooling water is pumped to one of two large evaporation ponds. Problems associated with the commissioning of Evaporation Pond #2 are described.

2 THE LINER DESIGN

Pond #2 has dimensions of approximately 1100 x 900m and depths from 7.5 m at one end to 11 m at the other.

At the time of its construction in 1987, it was the world's largest single cell geomembrane lined pond. The single uncovered HDPE geomembrane was laid directly on a compacted sandy soil subgrade.

French drains were provided under the geomembrane on all four sides of the pond at the toe of the slopes. The geomembrane panels on the slopes were oriented up and down the slope. Geomembrane on the bottom of the pond was designed as a series of large panels, each of which consisted of five rolls seamed together making a single large panel approximately 52 m wide. One edge of each large panel was placed in a v-notch anchor trench for ballasting. The panels and ballast trenches were oriented down slope to allow free flow of fluids beneath the liner. The unballasted edge of each large panel was seamed to the top of the geomembrane at the ballasted edge of the adjacent panel. The seams at the toes of the slopes were also ballasted in trenches, inside the peripheral drains.

3 INSTALLATION OF THE GEOMEMBRANE

The geomembrane, manufactured from a medium density polyethylene resin, was 2 mm thick and was predominantly seamed using the lap extrusion technique. It was installed between May and November 1987, mostly at night, when temperatures were more tolerable and winds were lightest. The pond remained empty over the winter and was filled between March and August 1988.

During construction, to facilitate ease of installation, the HDPE panels were laid across the floor of the basin which was normal to the designed orientation. To permit the flow of fluids beneath the liner, from one side of the ballast flap to the other, 25 mm diameter holes with a spacing of 3 m were placed close to the seam. Figure 1 is a schematic cross section of the ballasted seam. Seams were nondestructively tested by vacuum box, and destructive samples were removed each 110 m of seam for peel and shear testing at an independent laboratory. Shear and peel strengths were measured. Typical on-site Construction Quality Assurance (CQA) was performed by the owner's team of approximately 10 monitors.

4 SITE INVESTIGATION

During the winter of 1987/1988 temperatures dropped to -10°C. Short stress cracks appeared in the upper half of side slope seams as typically reported (Peggs &

Carlson, 1988). The cracks were in the lower geomembrane at the edge of the extruded seam. Many were within grinding gouges and also at the tops of the

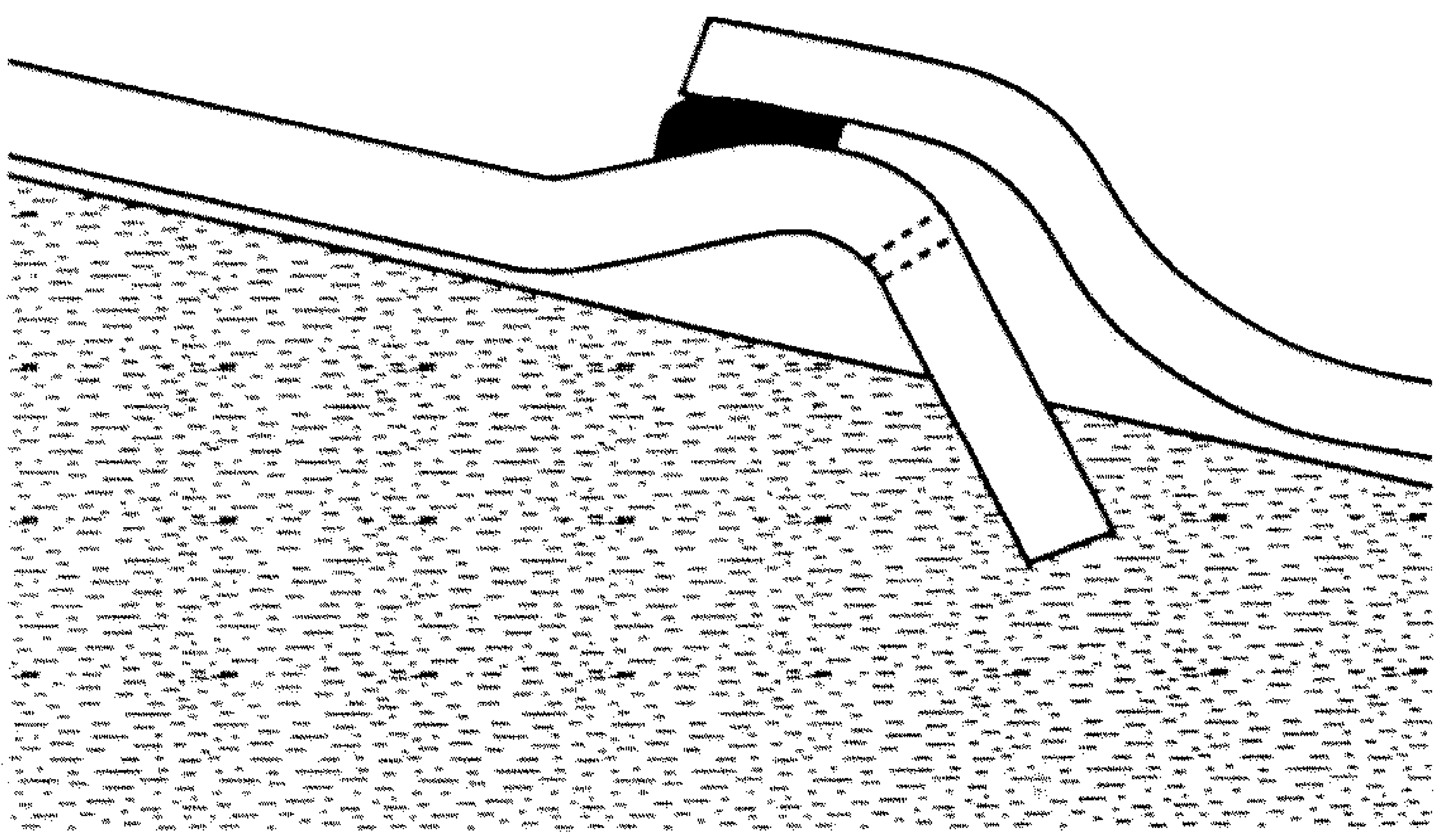

Fig. 1 Cross section of installed ballast seam

slopes where fillet extrusion beads had been laid on top of the lap extrusion seams. As the winter progressed trampolining developed at the toe of the slope at the shallow end of the pond.

The pond was filled slowly. When it was about 60 cm deep at the shallow end "whales" developed and a strip of liner was observed to be floating. A geoelectric leak survey was performed on the liner to determine the locations and extent of leaks. Short (1 cm) and long (36 m) cracks were found along seams, primarily those seams that had been ballasted (Figure 2). The whales occurred on the low side of ballasted seams and the floating section of liner occurred between adjacent ballasted seams.

Fig. 2 Stress crack along edge of ballasted seam

The water level was lowered to expose the cracks. In general the liner profile at the ballast seams was as shown in Figure 3 - the liner had been raised on the low side of the seam and/or had been pulled toward the bottom of the slope. The resultant peeling force on the liner had caused some seams to peel apart, but most of the leaks were quasi-brittle cracks (no ductile deformation) along the edge of the seam in the upper sheet, the sheet in which the peeling force had been applied to the seam.

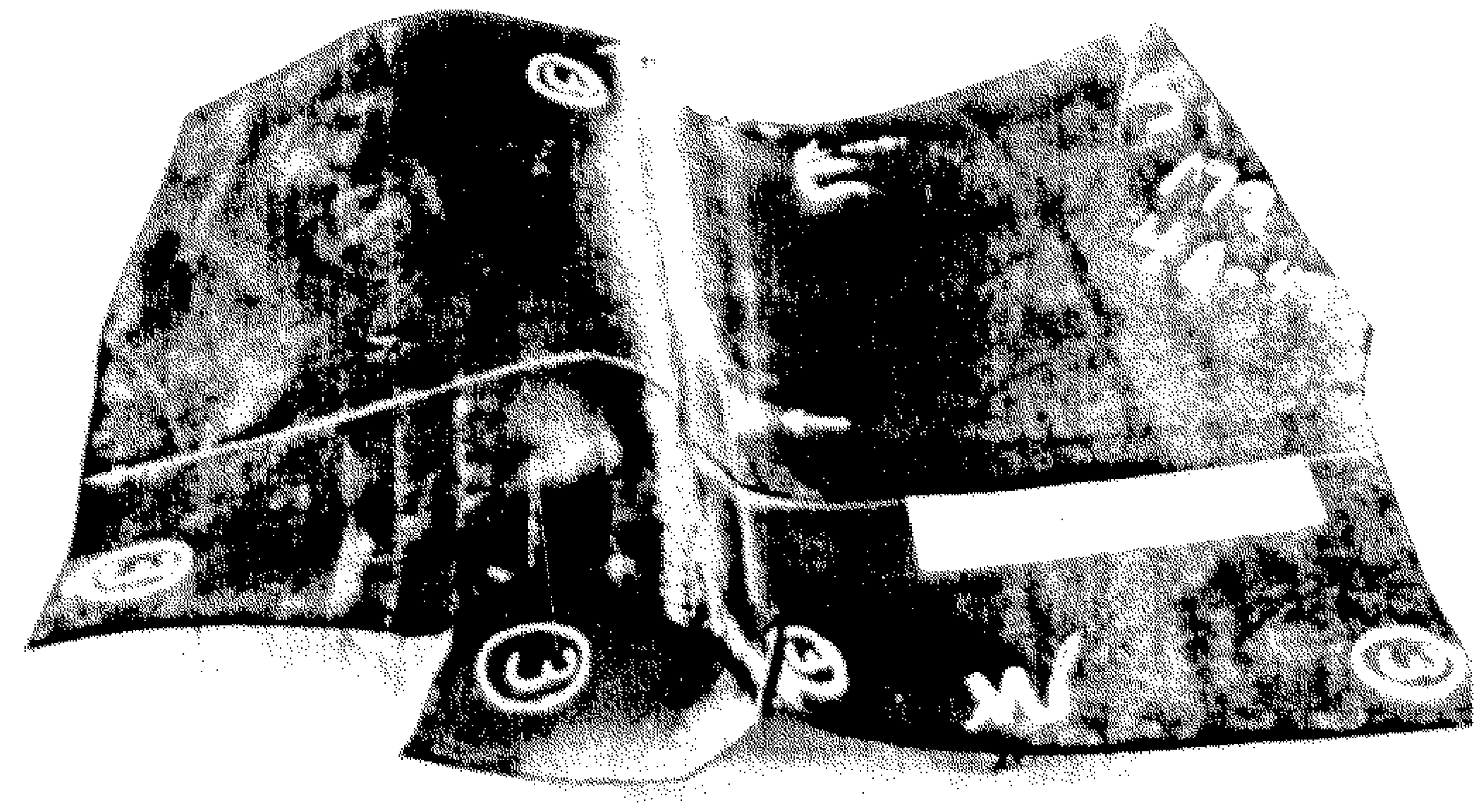

Fig. 3 Cross section at failed ballast seam. Crack is arrowed.

5 LABORATORY INVESTIGATION

At most locations there were no "breathing" holes in the buried flap, and in other places the holes had obviously been buried in the trench, preventing passage of fluids. Many samples were removed for laboratory examination and testing.

The three basic components of the laboratory investigation were: 1) conformance testing, 2) microscopy of fracture faces, and 3) thermal expansion/dimensional measurements. The conformance testing revealed that the HDPE geomembrane probably met all project and manufacturer's specifications at the time of installation. Seam peel testing showed that in a limited number of areas seam bond strength was inadequate, thus explaining those few areas where the seam had separated completely.

Fractography and transmitted light microscopy of thin (15 μm) microsections across the fractures showed that the cracks had occurred with little apparent ductility. The fracture face morphology showed that the fractures were generally initiated on the underside of the top geomembrane and propagated through the geomembrane thickness by a process of slow crack growth, and then propagated along the geomembrane by a moderate speed rapid crack propagation. Some cracking on the slopes had been initiated in deep grinding gouges oriented parallel to the seam on the top surface of the top sheet. Many of the seams that had been stressed, but that had not failed, displayed crazing, the precursors of slow crack growth. It was clear that the predominant failure mechanism was stress cracking - apparent brittle fracture due to the application of a constant stress below the yield stress of the material. If the geomembrane had simply been overstressed it would have failed in a yielding ductile mode.

It is well known that organic polymers, including HDPE, have relatively high coefficients of linear thermal expansion (CTE) compared to conventional construction materials. Geomembranes wrinkle and contract as temperature increases and decreases respectively. The CTE of HDPE at 0°C, or between -30 and +30°C is approximately 1.2 x 10^{-4}/°C and differs with test direction and increases as the temperature increases (Peggs et al., 1990). Laboratory measurements showed that if a stress of 5 MPa (a strain of 2%) was applied to an HDPE specimen at room temperature, the stress would drop to 1.7 MPa with a temperature increase of 65°C. Conversely if an HDPE geomembrane was installed without wrinkles at an elevated temperature (80°C has been measured in summer sunshine) a significant restrained contraction stress could develop at winter temperatures of -10°C. Figure 4 shows the effects of time under stress at elevated temperatures (stress relaxation) and the effects of cyclic temperature changes such as would have occurred on the installed geomembrane: a temperature decrease of only 40°C almost doubled the stress in the geomembrane.

The dimensional stability of the geomembrane was measured according to ASTM Standard Test Method D1204 for several hundred hours. While the 1 hr dimensional stability was well within the project specifications, after initially expanding in the cross-roll direction and contracting in the roll direction, over the long term the material contracted, and continued to contract, in both directions, without any indications of reaching an equilibrium dimension.

6 DISCUSSION

Hemispherical radiating crack growth patterns on the fracture faces surrounded by smooth fracture faces, with no local deformation of the geomembrane, identified the fracture process as being stress cracking - essentially a monotonic fatigue process. It was determined that the basic geomembrane resin was quite susceptible to stress cracking, as were a number of resins in the early to mid eighties. Significant improvements have since been made. Excessively deep (>10% thickness) grinding gouges oriented parallel to the seam (normal to the applied stresses) acted as stress concentrating crack initiation sites, which, together with some areas of overheating during seaming, increased the susceptibility of the geomembrane to stress cracking adjacent to the seam.

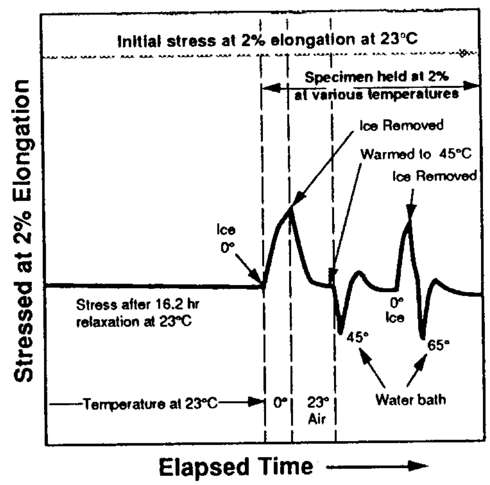

Fig. 4 Effect of temperature on stress in HDPE strip maintained at 2% elongation.

The stress necessary to initiate and propagate cracking was provided by two sources - restrained thermal contraction of the geomembrane at low temperatures, and uplift of the geomembrane caused by air trapped against the ballasted seam flap as the pond was filled. If the orientation of the panels had not been changed during installation, or if the breathing holes had been correctly placed in all flaps, and those that had been placed had not been buried, this latter stressing mode would not have occurred. However, the stresses due to thermal contraction would still have occurred and the liner would likely still have failed - recollect that cracks did appear in the side slopes.

There was lack of forethought in changing the orientation of the panels, inadequate care in preparing and burying the ballast flaps, inefficient CQA in not identifying these changes and inadequacies, and ineffective control by the designer/project engineering staff. The CQA team should have identified the problem and, through the project engineer, should have ensured that a satisfactory solution was found. Insufficient thought was given by all parties to the thermal contraction stresses that would be generated, and the need for compensation, as the temperature of the exposed liner decreased over the first winter. If there had been water in the pond there would only have been concern for the exposed side slopes.

From the first buried flap at the toe of the shallow end slope the downhill edge of each large panel was buried, and the downhill panel was seamed to the top of the uphill panel (see Figure 1). The liner was thus anchored in the ballast trench at the deep end. On cooling, the liner would contract towards the anchoring trench thus pulling the seam at the first uphill ballasted trench downhill, possibly by 1% of the distance between the two ballasted seams. The actual distance will depend upon the temperature drop, the CTE over that temperature range, and the geomembrane/soil interface shear resistance. Some of this displacement will be extended to all uphill ballasted seams. In simplistic terms, each uphill seam will also experience an additional 1% displacement due to the same thermal contraction of its adjacent downhill panel. The downhill displacement of each panel will, therefore, increase towards the shallow end, thereby increasing the peeling stress imposed on each ballasted seam and tending to pull each ballasted flap out of the trench, and finally causing trampolining at the toe of the shallow end slope, all of which were observed. Thus, the contraction problems were most evident at the shallow end and were aggravated by the underliner air pressure build-up during the filling of the pond. In hindsight, the ballasting should have been done with both edges of each panel being buried, or both edges being seamed to the top of each large adjacent panel. In this way contraction problems would not have been accumulative but would have been limited to each individual panel.

The seam stressing problem was aggravated by the change in orientation of the geomembrane panels. In these geomembrane rolls the CTE is higher in the cross roll direction than in the roll direction. In the original layout plan the major thermal contraction would have occurred across the bottom slope, not up and down the slope. The contraction stresses would still have occurred but they would not have been assisted by the slope nor would they have been augmented by the air underpressure stresses. It is possible (but unlikely) that the contraction stress alone may not have been sufficient to cause failure, but needed the additional stresses from the underpressure.

7 REMEDIATION

Compensation panels were added and damaged seams were removed and capped, both on the bottom and at the tops of the slopes. All ballast seams were cut free allowing unimpeded fluid movement under the liner, and allowing liner to expand and contract without developing major peeling stress concentrations on the seams. Since the repair was made in the winter of 1989/90 only one or two additional stress cracks have appeared at the tops of slope seams. They will continue to appear, but at a decreasing rate.

8 LESSONS LEARNED

Only the most stress rupture resistant HDPE geomembranes should be used for exposed applications in locations where temperatures vary over a wide range. Stresses in HDPE lining systems should be minimized. Overgrinding and overheating at seams be avoided. Designers must not only consider in-service conditions, but also those interim conditions between final construction and initial service. The designer is responsible for the ultimate performance of the lining system, therefore, changes such as panel orientations should not be made without his/her approval after input from all involved parties. Effective CQA, to produce maximum lifetime lining systems, requires a comprehensive knowledge of polymer performance and durability.

9 ACKNOWLEDGEMENTS

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