VERIFICATION OF PCCP FAILURE MARGIN AND RISK CURVES

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ABSTRACT

Failure margin analysis of prestressed concrete cylinder pipe (PCCP) evaluates the effect of broken prestressing wires on performance of the pipe and its margin to failure using the risk curves technology. The risk curves technology is based on structural analysis calibrated and verified by hydrostatic pressure testing of pipes with broken wires to failure, nonlinear finite element analysis that simulates the behavior of distressed pipe to failure, and external inspection of pipes with broken wires. This paper compares the observed levels of distress from external inspection of failed or highly distressed pipes to those predicted using the risk curves technology with the observed number of broken wires and expected internal pressure.

INTRODUCTION

PCCP, like other pipe, deteriorates with time. The primary mode of deterioration leading to failure is breakage of prestressing wires due to corrosion and/or embrittlement. Pipes with broken prestressing wires can be identified, and the number of broken wires can be estimated, using electromagnetic inspection and other nondestructive-testing (NDT) technologies as discussed by Zarghamee et al. (forthcoming).

The vast majority of pipes with broken wires are not in immediate risk of failure, and an objective of pipeline management is to identify the relatively small number of pipes that are at an unacceptably high risk of failure and repair them before they fail. Maintaining an acceptable risk of failure of pipe with broken wires is accomplished by performing failure risk analysis to determine repair priority for each pipe and by subsequent repair of pipes with an unacceptable risk of failure. This form of proactive maintenance can result in an overall improved reliability of the pipeline and reduced cost of maintenance and repair.

Failure margin analysis using the risk curves technology evaluates the effect of broken prestressing wires on the performance of the pipe and its margin to failure using a calibrated and verified model. The failure scenario of PCCP with broken prestressing wires was originally presented by Zarghamee and Ojdrovic (2001), and a model was developed that related the number of broken wires and maximum pressure in the pipe to different limit states of serviceability, damage, and strength (rupture). As a part of the research program sponsored by the PCCP Users Group, SGH performed hydrostatic pressure testing (Figure 1), pipe external inspections, and nonlinear finite element analyses that simulate the behavior of distressed pipe to failure (Figure 2) to validate the risk curves and the failure margin analysis procedure (Zarghamee et al. 2003). Repair priorities assigned to pipes with broken prestressing wires quantify their risk of failure when subjected to the maximum internal pressure and gravity loads.

Reliability of distressed pipe depends on material and load variability and on the pipe's proximity to failure, which is influenced by the uncertainty in the estimated number and location of broken wires, the uncertainty in the maximum pressure that the pipe will be subjected to, nature of wire breakage (corrosion or hydrogen embrittlement), and the rate of increase in the number of broken wires if the pipe is not repaired immediately. Field verification of distressed pipe reduces the uncertainty in the failure margin analysis by verifying the predicted number of broken wires and confirming assumptions used in the model. Uncertainty analysis allows importance factors to be assigned to parts of the pipeline where consequence of failure is great. These uncertainties are used to calculate the effective number of broken wires and pipe repair priorities at present and at several years into the future, within which time the pipeline may be reinspected or repaired.

The purpose of this paper is to present the results of verifications of the risk curves technology based on the external inspection of the pipes with broken wires and failed pipes.

FAILURE MARGIN ANALYSIS – RISK CURVES

The first step in failure margin analysis of a pipeline is collection of pipeline data, including pipe design, maximum pressures expected in the pipeline, soil-cover heights, and any available information regarding past performance, inspections, and aggressiveness of the environment toward PCCP.

Risk curves are constructed for each pipe design class using the earth load corresponding to the actual soil-cover height (usually within ±2 ft). The serviceability limit state is based on the onset of cracking, the damage limit state is based on structural cracking of the core and on increase in wire stress adjacent to the broken wire zone (BWZ), and the strength limit state is based on the ultimate strength of the pipe with and without the confining effects of soil (Zarghamee et al. 2003).

The confining effects of soil vary around the circumference of the pipe from most effective near the invert to least effective at the top of the pipe. Although most corrosion failures occur near the pipe springline, where cracks expose the prestressing wires to the environment, we consider the confining effects of soil present at the top of the pipe. Thinning of the steel cylinder due to corrosion is accounted for in analysis of lined cylinder pipe (LCP) (Erbay et al. 2007), but is generally not included in analysis of embedded cylinder pipe (ECP) unless identified as a concern based on external inspection.

The risk curves divide the plots of pressure versus number of broken wires into Repair Priorities 1a to 4b indicating failure margin, where Repair Priority 1a is the highest and indicates imminent rupture of the pipe. Repair priorities are calculated for each distressed pipe using the maximum expected pressure in the pipe and an effective number of broken wires that accounts for the estimated number of broken wires from NDT data, uncertainties in estimation of the number of broken wires, and progression of wire breaks with time. The expected rate of wire breaks can be either calculated using historical results of condition assessment on the same pipeline or obtained from documented rates observed on other similar pipelines. The maximum expected pressure in the pipeline can be calculated from hydraulic transient analysis, determined from results of pressure monitoring, or estimated using code recommendations. The maximum pressure experienced by the pipe is more critical than the pressure at the time of failure because the pipe can fail at a lower pressure due to loss of strength caused by a previous high pressure. Each pipe with broken wires is assigned a repair priority, depending on its margin to failure.

Due to the uncertainties in the numbers of wires predicted with the nondestructive condition assessment technologies, the results of failure margin analysis are considered to be preliminary until verification of the predicted number of broken wires is performed on selected pipes through external inspection. After verification is complete, the failure margin analysis and repair prioritization are adjusted as needed and final recommendations are made regarding the future management of the pipeline.

VERIFICATION OF PCCP FAILURE RISK CURVES

We performed external inspection of distressed pipes and reviewed reports of pipe failures and compared the results of physical observations with the risk curves technology. Investigations we performed included counting the number of broken prestressing wires, documenting the mode of wire failure, measuring crack widths, and observing the condition of intact wires and the steel cylinder. In some cases, where we did not perform failure investigations, we estimated the number of broken wires from photographs provided. We plotted the observed number of broken prestressing wires and the expected pressures on the risk curves. The maximum pressure experienced by the pipe is often not known with certainty, and it can range between the working pressure and the maximum working-plus-transient pressure.

120 in. Diameter ECP, Utah. Two heavily distressed pipes were identified by internal nondestructive inspection in 2003. External inspection of the pipeline was performed under the working pressure. One distressed pipe contained two broken BWZs separated along the pipe length, one with approximately 100 broken wires on one side of the pipe and one with approximately 190 broken wires on the other side away from the first BWZ. The other pipe had nearly all prestressing wires broken along its length. Both pipes contained cracked and hollow-sounding mortar coating. Risk curves developed specifically for the pipe design of the distressed pipes are shown in Figure 3 with the approximate number of broken wires and the expected pressure range for these pipes plotted. The actual pressure in the pipe ranged between the operating pressure and the expected maximum working-plus-transient pressure.

- 100 broken wires – no cracking of the concrete core was observed in the BWZ. The BWZ is at or below the serviceability limit state curve and, as expected, displayed coating cracks but no cracking of the concrete core.

- 190 broken wires – 0.015 in. wide crack was observed. The pressure and observed number of broken wires exceed the damage limit state, but are below the ultimate strength limit state. Observations of cracked mortar coating and a 0.015 in. wide crack in the concrete core are consistent with the level of distress expected on a pipe exceeding the damage limit state.

- Nearly all wires broken – 0.060 in. wide crack was observed. The strength limit state curve passes very near to the pipe with 0.060 in. wide core crack, indicating that the strength limit state curve predicts the extreme level of distress on this pipe fairly well. This pipe did not fail, possibly due to high confining pressure of the soil.

102 in. Diameter ECP, Rhode Island: A pipe failure occurred in 1996, prior to development of the risk curves technology, and a heavily distressed pipe of the same pipe design as the failed pipe was identified by internal nondestructive inspection in 2005. The actual number of broken wires was determined as a part of 1996 failure investigation and 2005 pipeline inspection. The maximum expected operating pressure for these pipes was about 65 psi. Risk curves developed specifically for the pipe design of the failed pipe and the distressed pipe are shown in Figure 4 with the approximate number of broken wires and the expected pressure for these pipes plotted. The strength limit state curve passes very near to the failed pipe, indicating that the strength limit state curve predicts the failure well. The pressure and observed number of broken wires in the distressed pipe exceed the damage limit state, but are below the ultimate strength limit state. Observations of a 0.020 in. wide crack in the concrete core, delamination between the steel cylinder and concrete core, and minor surface rust on the steel cylinder correlate well with the level of distress expected on a pipe exceeding the damage limit state (Ojdrovic et al. 2009).

99 in. Diameter ECP, Mexico. A pipe failure occurred in November 2009 prior to failure risk analysis. The pipe contained approximately 60 broken prestressing wires based on measurements taken on the failed pipe. The pressure at the time of failure was between the working pressure of 128 psi and the maximum expected working-plus-transient pressure of 179 psi. Risk curves developed specifically for the failed pipe are shown in Figure 5 with the approximate number of broken wires and the expected range of pressures for this pipe plotted as a line. The strength limit state curve passes slightly below this line, indicating that the pipe failed at a slightly higher number of broken wires (fewer than 10) than predicted by the strength limit state curve. The number of broken wires present at the time of failure may have been lower as some wires may have broken due to rupture dynamics, the failure may have occurred at the pipe springline or invert where soil-confining pressure is greater than accounted for in the risk curves, or the material properties may have been higher than those used to generate the risk curves.

54 in. Diameter ECP, Florida. A pipe failure occurred in 2010 prior to failure risk analysis. The pipe contained between 70 and 75 broken prestressing wires based on photographs of the failed pipe and had an internal pressure between the operating pressure of 75 psi and the maximum expected working-plus-transient pressure of 115 psi. Risk curves developed specifically for the failed pipe are shown in Figure 6, with the approximate number of broken wires and the expected range of pressures for this pipe plotted as a rectangular zone. The strength limit state curve passes through this rectangular zone, indicating that the strength limit state curve predicts the failure well.

48 in. Diameter ECP, Utah. A pipe failure occurred in September 2008 prior to failure risk analysis. External inspection of the failed pipe indicated that the pipe contained approximately 32 broken prestressing wires at the time of failure and had significant thinning of the steel cylinder due to corrosion. The internal pressure of the pipe ranged between the operating pressure of 57 psi and the assumed maximum working-plus-transient pressure of 97 psi. Risk curves developed specifically for the failed pipe are shown in Figure 7, with the approximate number of broken wires and the expected range of pressures for this pipe plotted as a line. The strength limit state curve passes through the top portion of this line, indicating that pipe failed at a pressure and/or number of broken wires at or slightly less than predicted by the strength limit state curve for pipe with uncorroded steel cylinder. Corrosion of the steel cylinder was not known at the time of development of the risk curves, so no reduction in the pipe ultimate strength due to thinning of the steel cylinder was included in the analysis.

48 in. Diameter LCP, Canada: Six records of pipe leakage or rupture were documented between 1990 and 2000, prior to failure risk analysis. The number of broken wires for each pipe was based on photos of the leaked/failed pipes that were removed from the pipeline, and the maximum pressures were calculated based on the difference between the hydraulic grade line and the elevation of each pipe. The comparison of the pipe data with the generated risk curves indicate that the strength limit state curve provides a good estimate of the pressures and number of broken wires corresponding to pipe failure (Figure 8). The data for leaked pipes falls between the damage and strength limit state curves, where the pipe has cracked and exposed the wires and steel cylinder to the environment. Corrosion results in thinning and eventually perforation of the steel cylinder. Previous experience with LCP in this project showed that leakage commonly occurred prior to pipe rupture.

48 in. Diameter LCP, Canada: A pipe rupture occurred in 2007, prior to failure risk analysis. The length of the rupture zone was not reported, so we estimated the length of the failure zone as about 3.5 ft based on photographs from the inspection report. The maximum working pressure as determined by hydraulic analysis was 70 psi and the maximum working-plus-transient pressure, which was not provided by hydraulic analysis, was taken as 110 psi. Comparison of the pipe prestress loss length and the range of pressures with the generated risk curves indicate that the risk curves provide a good estimate of the pressures corresponding to pipe failure (Figure 9). The strength limit state curve passes through the range of anticipated pressures at the estimated number of broken wires.

FAILURE MARGIN ANALYSIS – WIRE-BREAK PREDICTIONS

Failure margin of PCCP is directly affected by the uncertainty of the predicted number of broken wires from inspection data and the nature of wire breakage (corrosion or hydrogen embrittlement). Field verification of the predicted number and locations of wire breaks and mode of wire failure is necessary to reduce the uncertainties in the NDT inspection results and increase the accuracy of failure margin analysis. Our field inspection experience has shown that the actual number of broken wires can differ significantly from the number of broken wires predicted by NDT inspection. In some cases, the results of NDT inspection tended to underestimate the actual number of broken wires, while in other cases, the predictions tended to overestimate the actual number of broken wires. Results of field verification can be used to revise the predicted numbers of broken wires on pipes and/or modify the uncertainties used in evaluation of the failure margin.

CONCLUSIONS

- Failure of a structure is an extremely complex process that is difficult to capture with numerical models. The risk curves technology is a simplified tool based on structural analysis that accounts for the failure process of PCCP and has been validated by hydrostatic pressure testing of pipes with broken wires to failure, nonlinear finite element analysis that simulates the behavior of distressed pipe to failure, and external inspection of pipes with broken wires.

- External inspections of failed and highly distressed pipes show that the risk curves technology accurately predicts the level of pipe distress for the observed number of broken wires and expected maximum internal pressure.

- Field verification of distressed pipe by verifying the predicted number of broken wires reduces the uncertainty of the NDT inspection results and increases the accuracy of failure margin analysis.

- Uncertainty analysis allows importance factors to be assigned to parts of the pipeline where consequence of failure is great and calculates the effective number of broken wires at present and at several years into the future, within which time the pipeline may be reinspected or repaired.

RECOMMENDATIONS

- Maintain an acceptable level of failure risk by performing failure margin analysis of distressed pipes using risk curve technology to determine their failure risk and by subsequent repair of pipes with unacceptable risk of failure.

- Verify results of NDT inspections through external inspection. Use the results of field verification to increase the accuracy of failure margin analysis and determination of repair priorities.

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Figure 1. Hydrostatic testing of PCCP with broken prestressing wires.

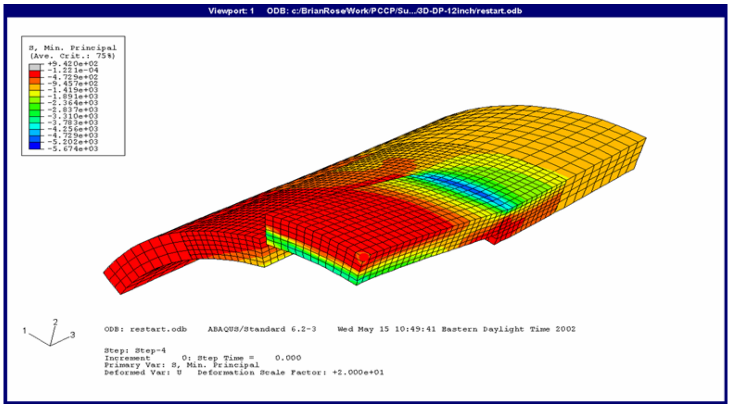


Figure 2. Strains in outer core at failure of cracked outer core.

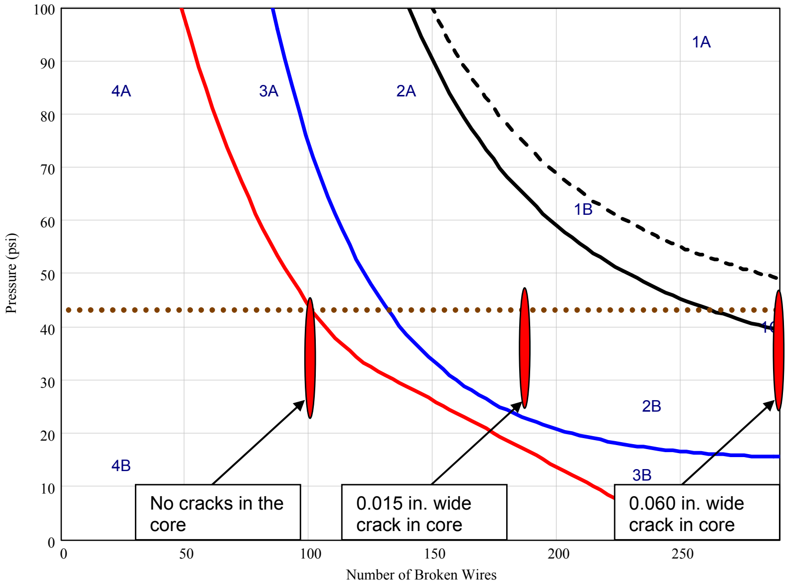
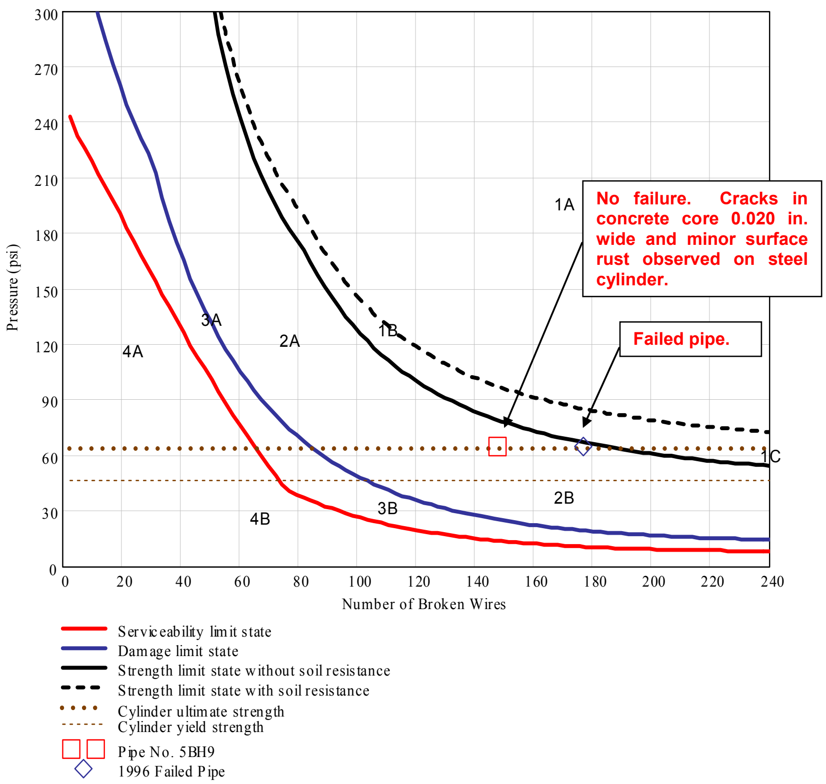


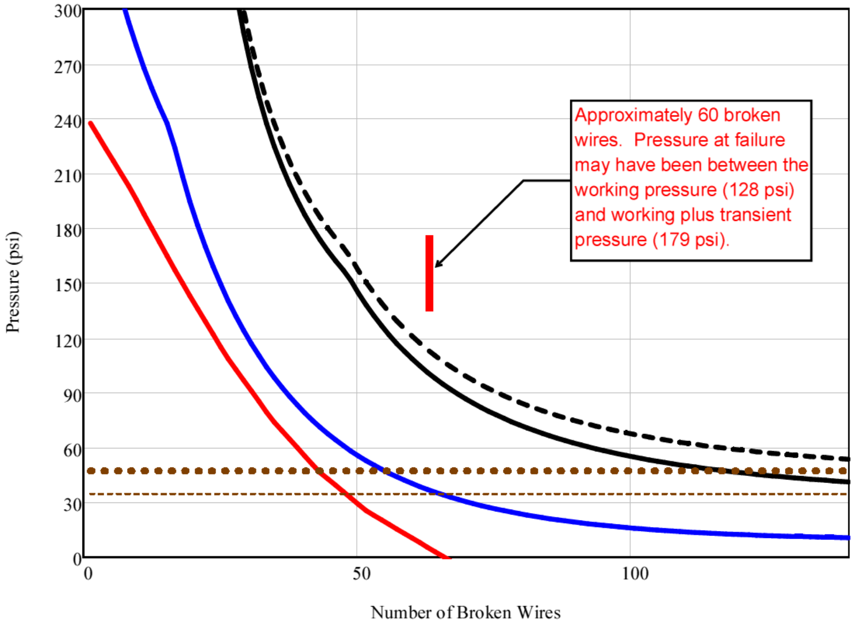
Figure 3. Risk curves for a 120 in. diameter ECP in Utah.



No failure. Cracks in concrete core 0.020 in. wide and minor surface rust observed on steel cylinder.

Failed pipe.

Figure 4. Risk curves for a 102 in. diameter ECP in Rhode Island.



Approximately 60 broken wires. Pressure at failure may have been between the working pressure (128 psi) and working plus transient pressure (179 psi).

Figure 5. Risk curves for a 99 in. diameter ECP in Mexico.

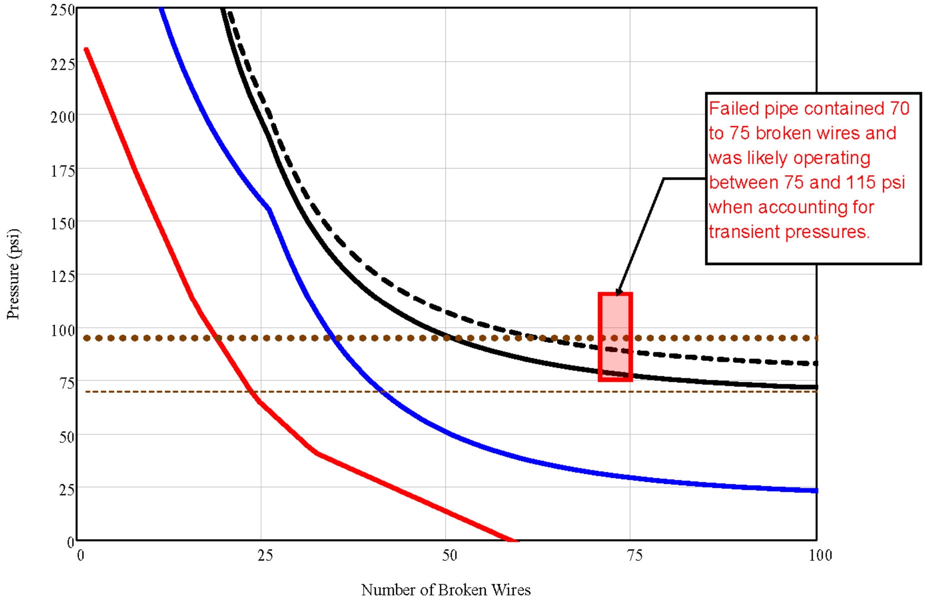


Figure 6. Risk curves for a 54 in. diameter ECP in Florida.

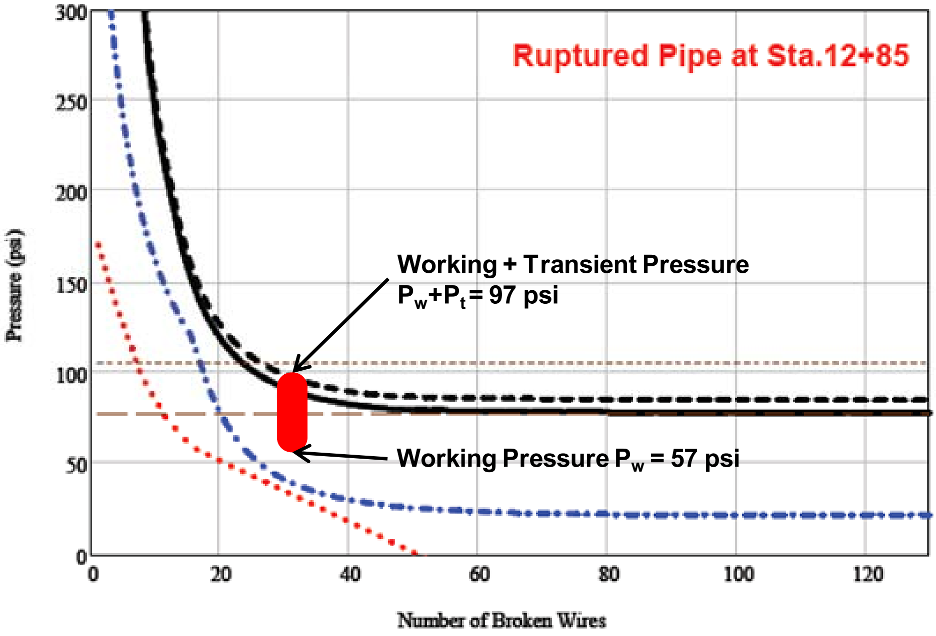


Figure 7. Risk curves for a 48 in. diameter ECP in Utah.

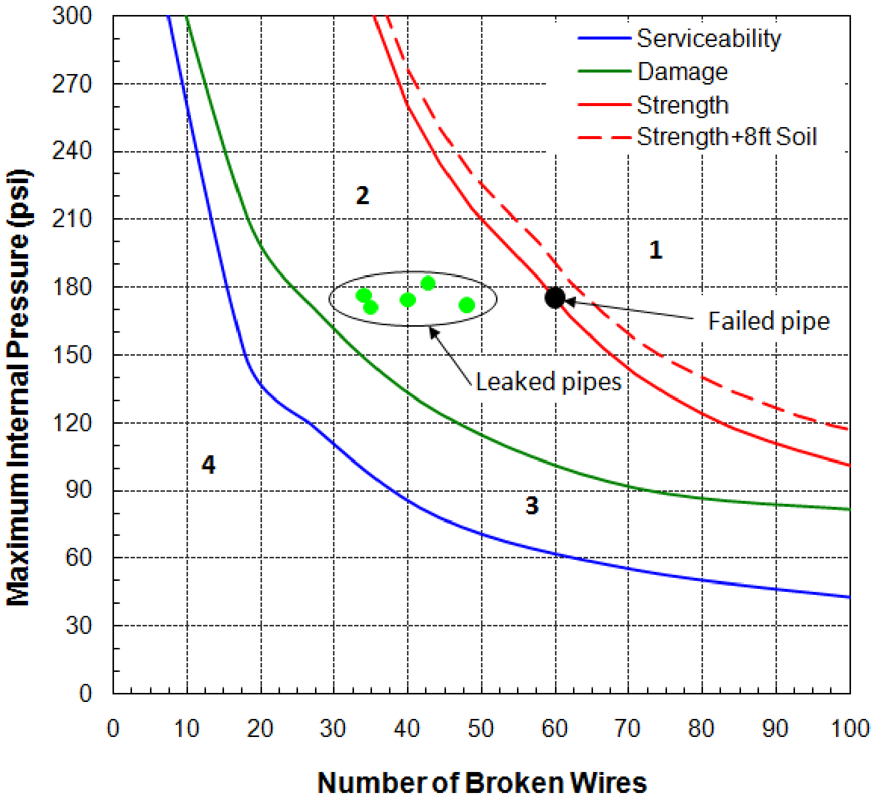


Figure 8. Risk curves for a 48 in. diameter LCP in Canada.

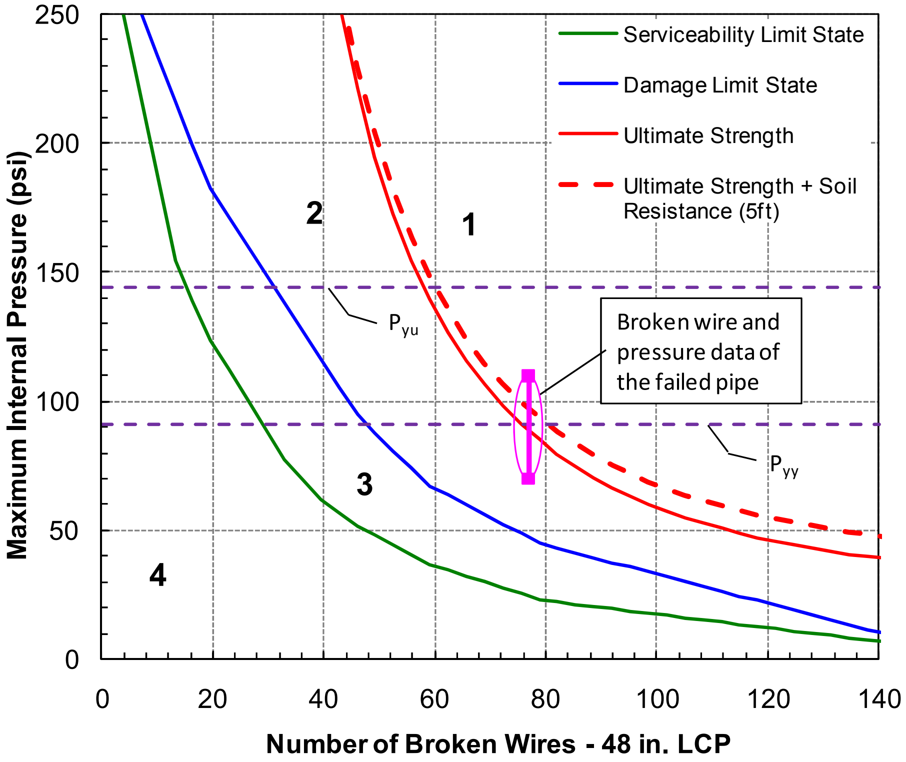


Figure 9. Risk curves for a 48 in. diameter LCP in Canada.