# Analysis of Risk and Remaining Life of the South Park Bridge

## Final Report

Prepared for:
King County

Prepared by:
Parsons Brinckerhoff

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This report summarizes the findings of the teleconference workshop held at King County on January 21, 2004 and subsequent analysis through February 20, 2004. The scope of work authorizing this task outlines seven areas of concern:

1. High-seismic risk
2. Poor concrete condition
3. Bascule pier movement
4. Aging mechanical/electrical systems
5. Marginal superstructure load capability
6. Scherzer rolling lift bridge characteristics
7. Maintenance and operation costs

The purpose of this analysis is to examine the deficiencies of the 74-year old South Park Bridge, evaluate the risk the existing structure poses to King County and estimate its remaining service life. The end of the useful service life of the bridge was defined by King County as: a) when the bridge's moveable span is no longer able to operate; b) when the bridge can no longer safely support a legal vehicle load used in the 1994 and 1996 load rating reports; c) when the on-going costs of maintenance and operations needed to keep the bridge functioning exceed what would be considered to be a reasonable on-going budget commitment, and d) when engineers can no longer determine the safe load carrying capacity of the bridge.

In the development of the scope of work, it was decided to conduct a teleconference/workshop to discuss and analyze these issues from known data and reports. The teleconference was held at the King Street Center on Wednesday, January 21, 2004. The participants included: Tim Lane, Trinh Truong, Ana Mondragon, and Brian Holloway from King County; Einer Handeland, Yuhe Yang, and Hans Saxer from Parsons Brinckerhoff (PB) Seattle; Donald Pearson-Kirk from PB London; Mike Elza from PB Florida; David Nyarko from PB New York; Bill Ciggelakis from PCI, Inc. in Texas; and Travis Deane and Bill Perkins from Shannon & Wilson in Seattle. During the first hour, Donald Pearson-Kirk and Bill Ciggelakis discussed the condition of the concrete and live load capabilities. The second hour focused on mechanical and electrical issues as well as historical information on Scherzer rolling lift bridges in the U.S. with Mike Elza and David Nyarko. The third hour centered on seismic issues with Travis Dean and Bill Perkins participating. The workshop concluded with Brian Holloway discussing his findings from King County's tiltmeter readings.

This report documents the approach taken to answer the following question: "What is the remaining service life of the South Park Bridge?" and outlines the discussions, conclusions, and subsequent analysis by workshop participants.

## 1. High Seismic Risk

The historical performance of the bridge provides the most direct means of assessing the probability of damage occurring in the near future. The characteristics of the three similar seismic events during the 74-year life of the South Park Bridge are as illustrated in the table below.

| Earthquake Year | Location/Name | Magnitude | Epicenter Distance (km) | Hypocenter Depth (km) |
|---|---|---|---|---|
| 1949 | near Olympia | 7.1 | 56 | 54 |
| 1965 | Tacoma-Seattle | 6.5 | 14 | 57 |
| 2001 | Nisqually | 6.8 | 52 | 52 |

Shannon & Wilson's 1991 report estimated a surface peak ground acceleration (PGA) of about 0.15g for the 1949 and 1965 earthquake. Boeing field recorded a PGA 0.19g in 2001 near the site. The depth of the hypocenters (underground source of the earthquake) of these earthquakes was 50 km (about 30 miles) or greater.

There is no specific information available for the 1949 earthquake damaging the bridge. Pier damage was reported in 1965 from the U.S. Geological Survey reports and information gathered from bridge maintenance records. There was no further mention of details of the damage, but Shannon & Wilson's 1991 report suggests liquefaction would have occurred in 1949 and 1965 based on ground motions.

In the time frame between 1930 and the present, there have been three significant earthquakes that potentially damaged (1949), or did damage the bridge. Of those three earthquakes, we have recorded damage from two earthquakes (1965 and 2001). Averaging these three earthquakes over 75 years, the recurrence interval is about 25 years for a damaging earthquake. Using a probability formula, the probability of a damaging earthquake in the next 10 years is 33%.

The Nisqually earthquake in 2001 caused well documented damage to the bridge. Previous studies indicated that another earthquake with the same or greater ground motions as recorded in 2001 could further damage the weakened bridge structure to the point of requiring closure.

As a comparison to estimates used in seismic design of new structures, the threshold for an earthquake damaging the existing South Park Bridge is much less than for a new design (typically 10% in 50 years or 2% for the 10 year time period of this report).

Another Nisqually-type earthquake will likely result in liquefaction at the site with corresponding damage to the bridge. Liquefaction of the site would result in vertical settlement of the underlying soil and possible lateral spreading of the riverbank that would impact the bridge foundations. This type of damage was observed in 2001, and damaging movements of the bridge were recorded on the main bascule piers from existing tiltmeter data monitoring by King County.

From a geotechnical perspective, the most vulnerable areas of the bridge are the timber pile foundations supporting the bascule piers and the approaches. Liquefaction-induced vertical settlement would exert downdrag forces on the existing timber piles. Lateral spreading would also impose significant horizontal forces on the bridge foundation elements. These movements would likely initiate new cracking as well as accelerate existing cracking activity in the piers. For the north bascule, the piles do not have sufficient end bearing to resist this downdrag force resulting in settlement of this foundation pier. Liquefaction is likely to occur at both bascule locations based on soil conditions observed during recent subsurface exploration at the bridge site.

## Substandard Pile Capacity – North Bascule Pier

Results of geotechnical investigations completed by Shannon & Wilson in 1991 and 2003 and further analysis indicate that the vertical load capacity of the north bascule pier piles is only slightly greater than the original design loads. The 315 68-foot long piles that support the north pier were set in pre-jetted holes and were driven only the final 13 feet. The average pile tip elevation is approximately 7 to 15 feet above the top of the dense glacial till. The end bearing capacity of these piles is significantly less than the south bascule pier piles, which were driven to refusal in the dense glacial soils. Based on calculations made on the as-built information, the estimated allowable pile capacities would range from about 9 to 12 tons. This is much less than the original required design loads of 22 to 30 tons to fully comply with design standards or to support loads. This would result in a factor of safety for static conditions of one or less compared to allowable design loads. Typical designs during the 1920s and today would have a factor of safety of 2.5 or more to provide a safety margin for uncertain load conditions as well as material properties. It is likely that the piles settled within some time period following construction until the capacity of the pile equaled the bridge loads under normal conditions. This is far below current design standards and possibly accounts for the movement and foundation cracking associated with this pier.

A factor of safety is a ratio of demand and capacity. For a factor of safety = 1.0, the demand equals the capacity (i.e., equilibrium). As an example, a single pile that has a capacity of 25 tons and is only loaded to 10 tons has a factor of safety of 2.5. However, if the load demand were to increase to 25 tons due to an earthquake or other loading change, the pile would then have a factor of safety of 1.0. If the load demand were to increase beyond 25 tons for the pile, the pile would experience "failure" which would likely result in excessive settlement (typically, greater than 1 inch as determined by the structural engineer).

Due to this condition it is our opinion that if an earthquake occurs within the next 10 years creating ground motions at the site equal to or greater than observed at the site during the 2001 earthquake, the bridge would likely be closed due to excessive movement from liquefaction.

## 2. Poor Concrete Condition

Two internationally recognized concrete experts participated in this exercise. Dr. Donald Pearson-Kirk from PB in London and Bill Ciggelakis from PSI, Inc. in Texas reviewed reports and photographs dating from 1986. They concluded that over the last 18-year period, information from previous investigations is not enough to determine the fundamental causes of concrete deterioration and the progression of deterioration. The reports confirm that the bascule and steel approach piers are in poor condition as indicated by extensive cracking and spalling of concrete with efflorescence and corroding reinforcement. Even with all possible causes not known, it would not be possible to estimate the remaining service life of the concrete and/or to determine whether any remedial actions may be effective to retard further deterioration.

Spot repairs to the piers have been ineffective in slowing overall pier deterioration because the majority of concrete surfaces of the piers continue to fail. Some spalls caused by corroding rebar are mostly around rebar at corners and faces of flat surfaces but the majority of deterioration is simply due to poor concrete that is self-destructing and peeling away inch by inch.

The deterioration to the concrete elements has been attributed to chlorides, alkali silica reactions, sulfate attack, delayed ettringite formation, and possible other chemical attack. Limited chemical testing and examination of concrete samples has been performed over the past 18 years. Concrete deficiencies are widespread, but are most apparent in the approach piers under deck expansion joints and in the splash zone of the in-water piers (the 15-foot tall region of the piers that undergo continuous wet-dry cycles due to the tidal fluctuation). Concrete is so soft at some locations in the splash zone that it can easily be crumbled and broken by hand. Spalling of concrete chunks as thick as 14 inches, as well as severely corroded reinforcing steel, can be observed at many locations. Core samples taken in 1994 indicated compressive strengths as low as 2000 psi. Chloride contamination was severe in the exterior core pieces.

Continued deterioration of the in-water piers is apparent in annual low-tide inspection records. Inspection drawings illustrating the extent of spalls and cracks show significant year-to-year advancement of existing cracks and spalls on the in-water piers as well as the formation of new cracks and spalls.

A recent crack depth inspection of concrete in the splash zone was performed by King County. Using wire probes, engineers found cracks in the bascule piers to be 4 to 5 inches deep in many locations. Cracks up to 8 inches deep in the bascule piers were identified in a 1994 underwater inspection report along with severe vertical cracks under the bridge bearings (the portions of the piers that support the large loads of the moveable spans). These cracks provide paths for deterioration mechanisms to reach the interior of the piers at a much quicker rate than the typical inward advancement of spalling from the outer pier faces. Because the interior concrete cannot be visually inspected, this phenomenon contributes to another level of uncertainty in fully assessing the overall pier condition.

Boss & Mayes Testing Engineers reported in another series of tests in 1994 that certain areas of the underside of the north approach had widespread spalling as a result of reinforcing steel corrosion. They also found that the concrete did not have an entrained air void system adequate for resisting freezing and thawing damage.

The feasibility of repairing the widespread concrete deterioration to the bascule and steel truss approach piers by applying a seal or exterior patch on the piers does not appear to be a viable repair option. There is enough moisture and chloride and sulfate contamination in the concrete that most of the deterioration mechanisms (reinforcing steel corrosion, alkali-silica reaction, and sulfate attack) would continue or may even be exacerbated due to entrapped moisture. The piers would continue to deteriorate and their structural integrity would be questionable. From this data, concrete substructure repairs are deemed not practical..

## 3. Bascule Pier Movement

King County has monitored the movement of the bascule piers for several years. Each bascule pier has four tilt meters that measure the degree of structure tilt over time. Two tilt meters are located on the inside face of the waterward wall and the other two meters are placed within the counterweight pit. The north pier primarily experiences transverse tilt towards the west and has experienced very little longitudinal tilt compared to the south pier. In February 2002, the east and west portions of the north pier were moving in opposite directions. That pattern changed around mid-May of 2002 when two tilt meters changed directions and began a westward movement in line with the other two meters. This may contribute to a lateral misalignment at the centerlocks at the tips of the moveable spans. The reason behind this pattern change is not clearly understood at this time.

The south pier has much more erratic movements compared to the north pier. Each tilt meter moves independently of each other. The south pier movement is predominantly rotating. During the February 28, 2001 seismic event, the rotation was clockwise. However, over the years of observation, the south bascule leaf overall has rotated counterclockwise.

Further complicating the bridge movement is the fact that Scherzer rolling lift bascule bridges have historically wandered on their steel bearing tracks after years of service and guide track wear. This complicates the leaf rotation because it is difficult to single out the leading cause of the leaf misalignment at the centerlocks at the tips of the moveable spans. King County survey crews performed a location survey of the track supports and tracks of both the north and south bascule piers relative to the bridge centerline in February 1991. A review of the location survey results indicated that the track supports and racks for both the north and south bascule piers are not parallel with the centerline of the bridge. The track supports are also not in alignment or parallel with each other for both the north and south bascule piers. The tracks are out of alignment at the front end by approximately 3/16-inch for the north bascule pier and approximately 7/8-inch for the south bascule pier. In addition, the track supports and racks are not in alignment or parallel to the north bascule pier. The total misalignment is approximately

1-1/2 inches horizontally. Vertically, the track supports and racks for the north and south bascule piers are not level with the tracks and racks sloping down towards the waterway channel. The slope of the track supports and racks are not equal resulting in a maximum vertical difference of ½-inch between the track supports and racks for the north bascule pier and maximum vertical difference of 3/8-inch between the track supports and racks for the south bascule pier.

Several repairs have been performed in efforts to mitigate the negative effects due to these pier movements. In 1982, post-tensioning was added to both bascule piers to retard the piers' lateral movement. In 1985, centerlock hardware was repaired to tighten interlocking parts of the bascule leaves, and in 1987 the lugs on the guide track in the north pier were ground to reduce binding of the moveable spans. Teeth were cut back at the center span in 1997. The guide tracks, teeth, and centerlock were again modified in 2001 and 2002.

## 4. Aging Mechanical/Electrical Systems

Mike Elza from PB Florida and David Nyarko from PB New York participated in the January 21 teleconference call for this portion of the workshop. Mike subsequently made a site visit with Tim Lane on January 28.

Based on a cursory review, the bridge machinery would likely require repairs in the next ten years, including replacement of various portions of the open gearing and bearings. An accurate estimate of the remaining service life of the machinery would require a detailed on-site inspection. However, these repairs do not meet King County's definition for the end of service life since drive system components would likely be repaired or replaced in lieu of closing the bridge.

The more imminent impact to bridge operation appears to be from the drifting of the piers. The centerlocks, rack-and-pinion sets and guide tracks all exhibit alignment issues. Numerous repairs have been performed to eliminate interferences and free up these machinery elements for operation. Precisely how long these repairs can continue to perform is difficult to estimate. The alignment of the machinery appears to be mainly a structural issue related to the movement of the bascule piers. To determine how much the piers can continue to drift before the centerlock features are misaligned beyond repair would require further investigation.

The electrical systems are not a determinant factor when considering the remaining life of this bridge. The electrical power distribution and controls can be repaired and components can be replaced piece by piece indefinitely. While there are no exact one-for-one replacement parts for the control relays and contactors, the system is basic enough that commercially available components for similar functions can be substituted with a few exceptions where parts would need to be custom fabricated or machined. The drive motors have been refurbished in the past five years and can also be repaired and rebuilt indefinitely. However, the economic reality of continuing to make such repairs versus a major rehabilitation over a period of ten years is that the cost to make such repairs will likely be equal to the cost of a system-wide replacement. Recently

completed electrical rehabilitations of movable bridges similar to the South Park Bridge in the Seattle area have been costing approximately $1.2 to $2 million.

The bridge has been inoperable 16 times during the past ten years due to electrical malfunctions. The bridge electrical systems are already overdue for a complete rehabilitation or replacement. Many electrical conduits were cast within the cracked concrete structure and have been subject to water intrusion and cannot be repaired. Without a complete rehabilitation, preventative and breakdown maintenance, costs will continue to rise as the electrical and controls systems are kept operational. The present electrical system is very antiquated and poses certain concerns to maintenance personnel. The most serious concern is an electrocution hazard present with the exposed high voltage panelboards.

## 5. Marginal Superstructure Load Capability

In addition to the load capability of the bascule pier piling (substructure) already discussed, the most recent load rating reports were examined. The concrete approach spans and cross beams were rated in 1994 and the steel truss spans and bascule spans were rated in 1996. The load ratings were calculated for four lanes of vehicle travel. Only the superstructure (deck and trusses) was rated. The design life of the substructure and foundations was not considered.

In the 1994 report, the flat slabs and crossbeams of the concrete approaches were load-rated in two different ways. In both analyses the crossbeams and flat slabs were found to be marginally adequate but deteriorating with a rating factor of 1.0. Immediate repairs were recommended. Future concrete deterioration could lower the rating to less than 1.0, limiting truck traffic on this important freight route.

The floor beams in the steel truss approaches are the most critical members for the bascule and truss spans. The 1996 load rating for the bascule and truss spans showed AASHTO load rating trucks at a 1.1 rating factor. The vehicles specified in the AASHTO Guide Specifications for Strength Evaluation of Existing Steel and Concrete Bridges represent legal weights and are used to determine posting limits. The adequacy or inadequacy of a structural element to carry a specified truck load will be indicated by the value of its rating factor, that is, whether it is greater or smaller than 1.0. As a comparison to the South Park Bridge, a new bridge usually has a rating factor greater than 2.

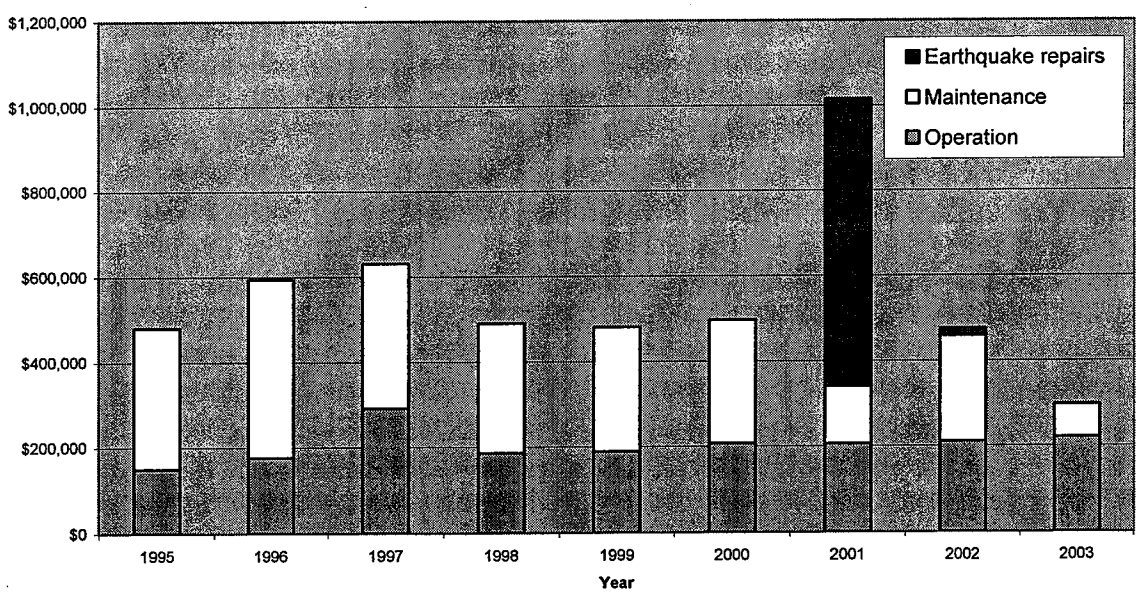
## 6. Scherzer Rolling Lift Bridge Characteristics

The South Park Bridge was built in 1930. It is a double leaf rolling lift bridge, designed and built by the Scherzer Bridge Company of Chicago, IL. William Scherzer patented the first rolling leaf bascule bridge in 1893. It was a single leaf bridge. From the founding of the Scherzer Bridge Company to present, hundreds of Scherzer rolling lift Bascule bridges have been built. Most of the Scherzer bridges were railroad bridges and most were single leaf design. The South Park Bridge is an original Scherzer Bascule Bridge and one of the last to be built by Scherzer Bridge Company.

A unique feature of a Scherzer design is the shear lock between the bascule leaves. There are no motor driven centerlocks or tail locks, instead the leaf tips are designed to interlock as the leaves close. These bridges characteristically rotate towards the waterway over time because the load is not symmetrically situated on the pier when the bridge is in the down position. A 2-inch inward movement on the South Park Bridge has occurred. The tips of the center locks and center break teeth have been trimmed to allow continued operation of the bridge.

## 7. High Maintenance and Operation Costs

Operations and maintenance records for the last nine years indicate an average of $543K being spent annually (all figures in 2004 dollars unless otherwise noted). In 2001, an additional $741K (2001 dollars) was spent on repairs for damage caused by the Nisqually earthquake. Repair work over the past nine years has annually ranged from $80K to $500K. In the near future, over $800K of major repair work is anticipated for one-time work items and $350K for recurring annual costs. Bridge tenders and utilities alone account for $230K per year. King County has deferred $14 million of major repairs to the existing bridge due to the uncertainty of its future. Although the




repairs would alleviate several major problems with the bridge, they would not correct the pier deterioration and stability problems of the bascule piers.

## Summary

The assessment of the remaining life of the South Park Bridge turned into an analysis of the current risk of the existing facility. This report outlined the discussions, conclusions, and subsequent analysis by workshop participants.

The most important issue is the very high seismic risk of this facility. Three significant seismic events have occurred over the 74 year life of this bridge. With each event more damage is recorded. Shannon & Wilson has calculated a 33% probability that a similar damaging earthquake such as the Nisqually earthquake could occur in the next 10 years. Current design standards would allow no more than a 2% probability within a 10-year time period. It is very likely that the bridge would no longer be operational after such an event.

One of the reasons that the bridge would likely fail in the next significant earthquake is the fact that the north bascule pier has a substandard pile capacity. For unknown reasons, the north bascule pier piles were set in pre-jetted holes and driven only the final 13 feet. The pile tips however, were driven 7 to 15 feet short of the dense glacial till stratum. As a result, the factor of safety for the normal day to day vertical load capacity is near 1.0. Typical design standards during the 1920s and today would have a factor of safety of 2.5 or more.

The third significant factor impacting the condition of the existing bridge is the continuing deterioration of the concrete. Over the last 18 years, several investigations have been carried out to assess the condition of the concrete, determine the reasons for deterioration, and the progression of the deterioration. All reports confirm that the bascule and approach piers are in poor condition. Extensive cracking and spalling with efflorescence and corroding reinforcement are evident. The deterioration of the concrete elements have been attributed to possible chlorides, alkali silica reactions, sulfate attack, and delayed effringite formation. Recent wire probe examinations show many cracks to be 4" to 5" in depth. Concrete experts have concluded that these chemical conditions cannot be stopped and may even be exacerbated by applying a seal or exterior patch on the piers. They would continue to deteriorate and their structural integrity would be questionable. Repairs to the concrete substructure are deemed not practical.

Over the life of the bridge, the bascule piers have moved unpredictably. Some of this movement can be attributed to the above conditions and others to the nature of a Scherzer rolling lift bridge itself. These bridges rotate towards the waterway over time because the load is not symmetrically situated on the pier. The South Park Bridge has moved inward 2 inches. Further complicating the bridge's movement is the fact that Scherzer rolling lift bascule bridges have historically wandered on their steel guide tracks after years of service and guide track wear. At some point in time it may not be possible to continue to keep the bridge in an operational alignment.

Even though the mechanical and electrical systems are aging, they are not a determinate factor when considering the remaining life of this bridge. Without a complete rehabilitation, preventative and breakdown maintenance costs will continue to rise as the electrical and controls systems are kept operational. The present electrical system is very antiquated and poses certain concerns to maintenance personnel. A serious concern is an electrocution hazard present with the exposed high voltage panel boards.

The most recent (1994 and 1996) load rating calculations indicate that the superstructure had an AASHTO load rating of 1.0. The analysis indicated that concrete crossbeams and flat slabs were found to be marginally adequate and continue to deteriorate. The floor beams in the steel truss approaches are among the most critical members for bascule and truss spans. A new bridge designed per standards would have a rating greater than 2.

Operations and maintenance records for the last nine years indicate an average of $543K being spent annually. An additional $741K was spent on repairs for the damage caused by the Nisqually earthquake. These O&M costs will continue to escalate. King County has deferred $14 million of major repairs due to the uncertainty of its future.

## Conclusions

Although the remaining life of the bridge cannot be pinpointed to a specific year, we do know that the abundance of major deficiencies severely limits the time it can remain operating in a reliable manner.

- The bridge is not likely to remain open (operational) after another seismic event equivalent to the Nisqually earthquake occurs. There is a 33% probability of this occurring in the next ten years.
- The bridge foundation is in poor condition. It has a factor of safety of 1.0 or less due to timber piles being driven too short.
- Foundation repairs are not practical. Concrete will continue to chemically deteriorate due to the inherent composition of the concrete.
- Concrete piers are cracked and they are moving and can't be repaired.
- The bridge superstructure has a marginal load capacity. There is no reserve capacity.
- Operation and maintenance costs are high and will continue to go higher.
- Fourteen million dollars of deferred maintenance is needed, but none of this maintenance will stabilize the foundations nor stop the concrete deteriation.
- The sufficiency rating (6 out of 100) of the South Park Bridge is among the lowest of major bridges in the Seattle area.
- The cost to the community if this bridge is out of service would be significant to South Park and to the region.

From what we know about the above facts, we believe the remaining service life of the South Park Bridge is very limited. We recommend that serious consideration be given to close or severely limit bridge operations within the next five years. We also recommend that the design/environmental process be accelerated. A contingency plan for closure should be developed as soon as possible. We also recommend continued frequent inspections to monitor the failing bridge condition.