North American Society for Trenchless Technology
2008 No-Dig Conference & Exhibition

Dallas, Texas
April 27 – May 2, 2008

BALLARD SIPHON REPLACEMENT PROJECT

Kimberlie Staheli, Ph.D., P.E.[1] and Michelle L. Ramos, P.E., L.E.G.[1]

[1] Staheli Trenchless Consultants, Seattle, WA

ABSTRACT: The Ballard Siphon consists of twin 1,365-foot long inverted wood-stave siphons that traverse under the Seattle Ship Canal, a major shipping waterway that connects Lake Washington to Puget Sound. In 2005, King County performed a sonar survey in which it appeared that the crowns of the siphons were intruding, suggesting imminent failure. This prompted King County to issue an emergency declaration to replace the twin 36-inch wood-stave siphons.

Staheli Trenchless Consultants (formerly part of Bennett-Staheli Engineers) performed a feasibility study to determine the applicability of using horizontal direction drilling (HDD) methods to replace the siphons. Concurrent with the study, King County performed additional investigations on the siphons and found that they were not in imminent danger of failing but were in need of cleaning. King County was then able to reevaluate the project and revise its scope to include increased flow capacities to reduce the number of Combined Sewer Overflows (CSO's) into the Ship Canal. King County developed a number of pipe configurations that could accommodate the increased flow. All of the options included construction of multiple pipes beneath the Canal that could be housed in two or more tunnels.

The feasibility study ruled out the use of HDD due to hydraulic requirements imposed by the gravity siphon. With the new information regarding the existing siphon conditions, Staheli Trenchless Consultants proposed slip-lining the existing 36-inch siphons with 30-inch HDPE pipe to eliminate one of the crossings beneath the canal. This approach resulted in an estimated cost savings of over $3 million. This paper presents details of the HDD feasibility study, the slip-lining feasibility study, and the analysis used to determine the preferred tunneling method beneath the canal.

1. INTRODUCTION

The Ballard Siphon was built in 1935 and conveys sewer flows from the Ballard Regulator to the North Interceptor across the Seattle Ship Canal. The existing siphon consists of two 36-inch diameter wood-stave pipes buried in the sediment on the floor of the canal. The location of the Ballard Siphon is shown in Figures 1 and 2.

A sonar survey was completed on both barrels of the Ballard Siphon in December of 2005. The sonar images seemed to indicate crown intrusion by the wood-stave pipes, which suggested that the pipes were in imminent danger of collapse. As a result, an Emergency Declaration was executed by King County and the Ballard Siphon Replacement Project was initiated.

Figure 1. Location map of the Ballard Siphon Project. The Seattle Ship Canal passes over the siphon to connect Lake Washington to Puget Sound, and is deep enough for deep draft vessels.

2. HDD REPLACEMENT OF THE SIPHON

Staheli Trenchless Consultants was tasked with evaluating the use of horizontal directional drilling (HDD) to install pipelines to replace the existing siphons. For the evaluation, the preferred site location was determined to be the site of the existing Ballard Siphon in order to minimize the ancillary sewer work which would accompany moving to a new site. To meet flow demands and hydraulic requirements, the replacement siphon needed a minimum equivalent diameter of 72 inches. This could be accomplished with a number of different siphon diameters and configurations including, but not limited to, three 42-inch diameter pipelines, two 60-inch pipelines, and two 36-inch pipelines and a 48-inch pipeline. After preliminary examination, a configuration of three 42-inch diameter bores was selected for further evaluation. The preferred product material was HDPE pipe. However, at the time of the evaluation, 42-inch diameter HDPE had not been installed using HDD at the lengths required to cross the Ship Canal. It was assumed that steel casing pipe would be installed with HDD methods and that a product pipe would be inserted into the casing.

At the time of the HDD evaluation, a geotechnical investigation had yet to take place at the crossing location. However, an extensive historical review of available existing geotechnical information was completed. The existing geotechnical information revealed that the soil conditions at the site generally consisted of fill and alluvium over glacial till. The both the fill and alluvium units were composed of loose to medium dense silty sand. The glacial till was very dense silty sand with occasional gravel.

These soils did not pose significant risk to HDD construction, and based on the geotechnical conditions, using this method was considered feasible. However, some of the fill soils identified in geotechnical reports were extremely soft, with blow counts of less than three blows per foot. Since very soft soils are particularly susceptible to settlement, there was concern that the construction of three 42-inch pipelines with HDD techniques would result in significant surface settlements if the soft soils extended down into the immediate vicinity of the crossing location. In addition, very soft soils could result in hydrofracture into the shipping canal.

Following the initial geotechnical appraisal, site reconnaissance was also performed to evaluate the feasibility of using HDD for crossing the Ship Canal at the existing location. The area surrounding the existing Ballard Siphon is highly developed with very little open space (Figure 2). Since a large drill rig would be required to install the 42-inch diameter pipelines, the required footprint for the drill rig alone was approximately 10 by 65 feet. Total additional layout area would have been approximately 200 by 100 feet to accommodate the supporting equipment. Such an area could not be identified without significant road closures and impacts to local businesses. Additional concerns were also raised regarding drilling triple 42-inch diameter pipes beneath the existing critical utilities and structures that line both sides of the Ship Canal.

Bore geometry was evaluated based on a previously completed bathymetric survey at the existing siphon location. Control benchmarks were established at the deepest points of the channel along the existing siphon alignment to determine the appropriate bore depth. Existing utilities along the roads lining the Ship Canal were then located to determine the necessary set-back distance to achieve the appropriate depth beneath the channel while accommodating bore geometry requirements.

In order to accommodate these initial site constraints, a 250 foot set-back distance was required on the south-west side of the Ship Canal, and a 390 foot set-back distance was required on the north-east side of the canal. With necessary setbacks, the total bore length to cross the siphon was 2,000 feet.

Figure 2. Ballard Siphon detail. The area is fully developed with active barge traffic accessing the docks visible in the canal. Development moving away from the waterfront is mixed industrial and commercial property.

With the bore geometry that was necessary to ensure appropriate protection of existing utilities and the current channel, and to provide sufficient layout area, the hydraulics of the pipeline were no longer acceptable to operate the Ballard Siphon with the existing regulator structure. It was the desire of King County to continue to operate with the existing regulator structure. In addition to the hydraulics, HDD posed a large risk of near-surface hydrofracture, settlement of historic structures, and binding during pull back since sufficient layout area was not available to preassemble the pipeline. HDD was therefore not recommended for replacement of the existing siphons (Staheli and Ramos, August 2006).

3. SIGNIFICANT CHANGE IN PROJECT STATUS

While King County was assessing the feasibility of using HDD, both barrels of the siphon were cleaned and another sonar inspection was completed in January 2007. Data from the subsequent inspection were in conflict with the 2005 inspection data, and did not indicate crown intrusion. Analysis of the sonar images could not resolve the discrepancies between the two inspections. One of the siphon barrels was dewatered, allowing a CCTV inspection. The visual inspection revealed that the crown intrusion shown on the 2005 sonar survey was actually grease deposits on the crown of the pipe.

This new information significantly reduced the risk assessment associated with the siphon replacement and determined that the Ballard Siphon was not in imminent danger of collapse. However, King County was still interested in increasing the capacity of the siphons to accommodate a 20-year storm event. Considering the age of the siphon, the inability to accurately asses the structural stability of the wood-stave pipes, and the benefits gained by installing additional capacity, it was determined that the project would continue to move forward.

4. PIPELINE CONFIGURATIONS

Once the emergency status was lifted, King County could focus on their desires for the new siphon. After extensive hydraulic analysis, the desired diameter equivalent was set at 84 inches. King County wanted to develop a pipeline configuration that was adequate to carry daily flows and have the capacity to handle large storm events. It was decided that dual pipelines would be installed beneath the Ship Canal to serve this function. The existing dual 36-inch siphons performed in this manner, with the normal daily flow through one siphon and storm events resulting in the use of both siphon barrels. For the new siphons, one of the siphon barrels had to be maintained at a diameter relatively close to the existing 36-inch size to maintain adequate flow velocities across the Ship Canal during normal daily flow events. However, the second barrel would have to be significantly larger to accommodate a 20-year storm event.

King County developed a myriad of pipeline diameter combinations, including two, three and four barrel alternatives that would meet their requirements for a desired equivalent of 84 inches. Table 1 presents some of the pipeline dimensions considered for the new siphons.

Table 1. Equivalent Inner Diameter [inches] Nominal Sizes.

Desired Equivalent	Low Flow Barrel	Barrel 2	Barrel 3	Barrel 4	Equivalent Diameter
60	30	30	54	0	61.5
	30	42	48	0	62.1
	36	42	42	0	60.6
	36	36	48	0	61.4
72	30	54	54	0	72.7
	30	48	60	0	73.3
	30	42	48	48	72.3
	36	54	54	0	74.2
	36	42	60	0	72.2
	36	36	48	48	71.8
84	30	66	66	0	87.5
	30	60	66	0	83.9
	30	54	72	0	85.1
	30	54	54	54	83.6
	36	66	66	0	88.6
	36	60	66	0	85.1
	36	54	72	0	86.3
	36	54	54	54	84.8

All of the configurations above assumed that a single siphon would be used for low-flow and that additional siphons would be used as flows increased. With any of the pipeline configurations listed above, it was necessary to have either multiple crossings of the Ship Canal or to construct large casings that would accommodate more than one pipe.

Since the subsequent sonar survey indicated that the existing siphons were in adequate condition, Staheli Trenchless Consultants suggested slip-lining the existing siphons with HDPE pipe. This would result in using both slip-lined siphons to accommodate low-flow, and constructing only one additional crossing that would serve as the overflow siphon. Staheli Trenchless was charged to perform a feasibility study for slip-lining the existing siphons to determine if this potentially cost-saving alternative was viable.

5. SLIP-LINING FEASIBILITY

The general factors that affect slip-lining feasibility are the number of bends and deflection angles of the host pipeline, the outer diameter of the slip-line pipe compared to the inner diameter of the host pipe, the potential for blocking debris in the pipeline, and the available area to construct access pits. These factors were evaluated in detail along with cost and schedule impacts.

A hydraulic analysis developed by King County determined that the ideal inner diameter for the new siphons was 26.5 inches. Adequate area was identified for constructing access pits for the slip-lining activities on each side of the Ship Canal, and the sonar surveys did not indicate that significant debris existed in the pipeline. Therefore, the biggest concern regarding slip-lining feasibility was the geometry of the existing pipelines.

The existing Ballard Siphon bends sharply on the south side of the Ship Canal, and is inclined at a 22.5-degree angle from horizontal. On the northern side the incline is much more gradual and is about an 8-degree angle from horizontal. The approximate radius of curvature of the existing siphon is about 600 feet on the south side and approximately 4,770 feet on the north side. A schematic of the siphon profile is shown on Figure 3.

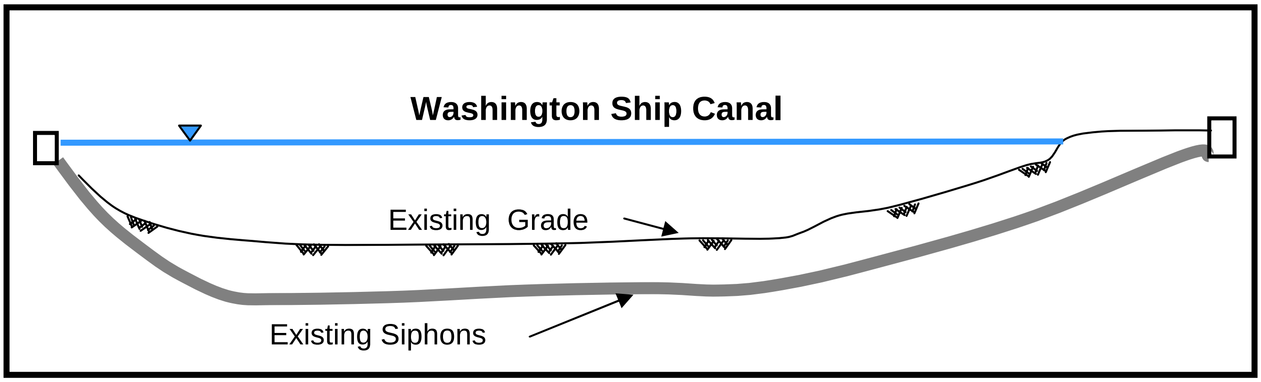

Figure 3 Siphon Profile

Curved host pipe alignments have been slip-lined; however, the curves result in substantially increased pulling forces on the pipeline. Preliminary slip-lining pulling force calculations indicated that a wall thickness corresponding to DR 17 was necessary to withstand the anticipated pulling forces for the geometry of the existing siphons. A DR 17 HDPE pipe with an inside diameter of 26.5 inches corresponds to an outside diameter of 30 inches.

The preliminary analysis indicated that slip-lining was a feasible alternative; however, in order to pursue the slip-lining alternative, the County needed some assurance that the slip-lining operations could be successful in the wood-stave pipes. To raise the confidence in the success of the method, it was decided to pig the existing siphons while carefully measuring the force required to move the pig through the pipelines. This information would then identify any areas in the existing pipes where difficulties might occur during slip-lining.

Polyethylene pigs were used to clean the siphon. The pigs were sequentially upsized after each run from 24-inch to 26-inch to 29.5-inch diameters. The cleaning pigs were inserted from the south side and pulled to the north. Careful force readings were continuously collected to evaluate the force necessary to move the pig through the pipeline. Figure 5 shows a graph of the

Figure 4 29.5-inch Pig exiting West Siphon

forces that were recorded during the pigging of the western siphon. Very low forces were recorded while using the 24-inch pig, with a maximum force of 200 pounds. There was a noticeable increase in forces when the 26-inch pig was pulled through the siphon, with a maximum force on the order of 800 pounds. There was no significant difference in pull forces when the pig was increased from a 26-inch diameter to a 29.5-inch diameter, with maximum forces near 800 pounds. The results of the pigging clearly indicated that the host pipe did not contain any significant obstructions and that slip-lining the pipe with 30-inch OD HDPE pipe was feasible.

The slip-lining alternative was further evaluated and was found to provide a potential $3.1 million cost savings over constructing multiple crossings of the Ship Canal. (Staheli and Ramos, 2007). The project was subsequently moved forward based on slip-lining the existing siphons with 26.5-inch ID pipelines and constructing a single pipeline beneath the channel using tunneling methods.

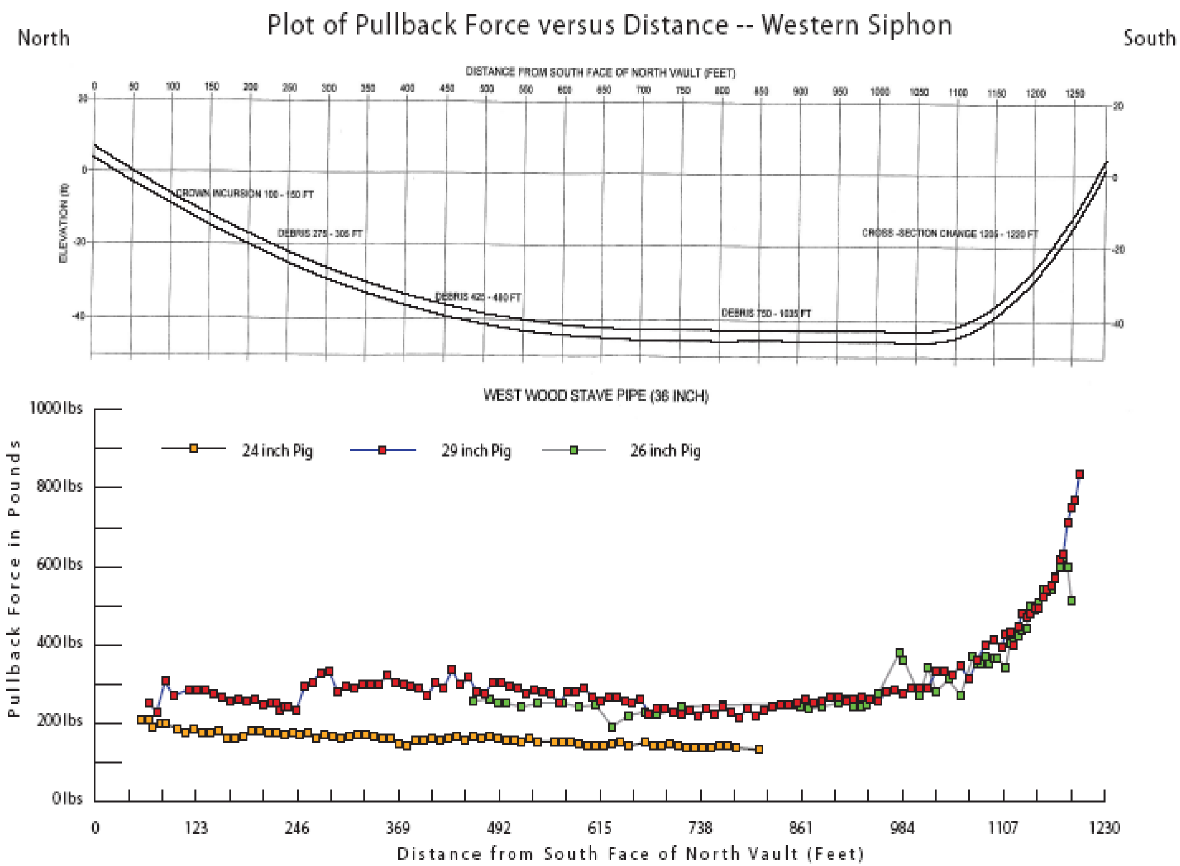

Figure 5 Pulling Forces during Successive Pigging Operations

6. TUNNELING FEASIBILITY

Site conditions were analyzed to determine the feasibility of using various tunneling methods to cross the Ship Canal. The primary factor affecting feasibility was the geotechnical condition at the preferred crossing location.

A geotechnical investigation was completed and soils adjacent to and beneath the Ship Canal were identified and tested. In agreement with the previously conducted historical geotechnical review, soil conditions along the alignment consisted of fill/alluvium over glacially consolidated silts and clays. The fill/alluvium consisted of loose to medium dense silty sand. The glacially consolidated silts and clays were very stiff to very dense clayey silt and silty clay. Very loose/soft soils (with blow counts of less than 3 blows per foot) were identified within the canal in the uppermost 10 to 30 feet. On the south side of the canal, slicken-sided clays were also identified. Groundwater was identified at approximately the elevation of the water in the Ship Canal. Figure 5 shows a geotechnical cross section of the alignment.

It was concluded that tunneling was a feasible crossing method due to the dense soils present along the alignment. However, the soft/loose soils on the canal floor present significant challenges for tunneling as they do not provide adequate bearing capacity to support the machine and will not allow steering. It was therefore necessary to choose a tunnel horizon that did not traverse these soils. In addition, it was desirable to select an alignment depth that avoided the slicken-sided clays to prevent excessive soil loading on the tunnel. Based on the soil and groundwater conditions, it was decided to further investigate microtunneling and Earth Pressure Balance (EPB) tunneling for the canal crossing.

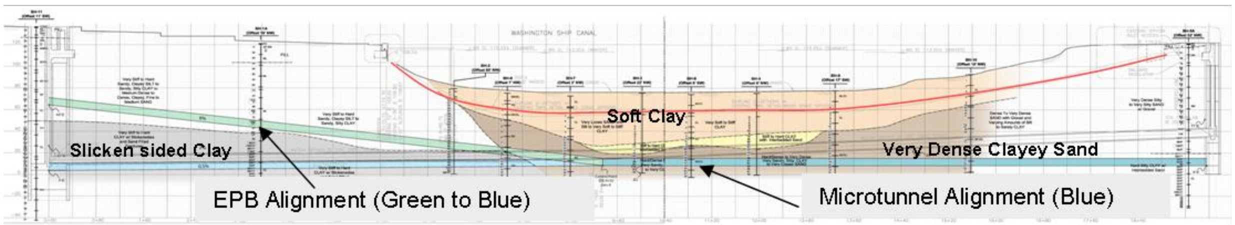

Figure 6 Generalized Cross Section

7. TUNNEL METHOD SELECTION

A number of factors were considered when determining the preferred tunneling method. These factors included geotechnical conditions, alignment and shaft locations, pipeline elevation, site constraints, shaft construction methods, available pipe materials, jacking force considerations, liner design consideration, construction risks, estimated costs, and schedule.

For the microtunneling alternative, a 1,550-foot tunnel with 84-inch flow diameter pipe (one-pass tunneling) was considered. This represented the minimum straight-line distance across the canal with the set-back necessary to avoid structures near the edge of the canal. The shafts and tunnel were placed at depths sufficient to minimize geotechnical risks, resulting in shaft depths of approximately 100 feet on each side of the canal.

For the EPB alternative, the preferred alignment was a 2,000-foot tunnel with a minimum diameter of approximately 104 inches. It was assumed that a bolted and gasketed concrete segmental liner would be used as the tunnel support in which an 84-inch flow diameter pipe would be placed upon tunnel completion. The alignment included a vertical curve that allowed a reduced number of required easements as private property could be avoided. The EPB curved alignment allowed shallower shafts than the microtunneling alternative while maintaining the vertical clearance beneath the very soft soils in the canal.

The minimum straight-line distance alignment considered for microtunneling required obtaining difficult easements on the south side of the canal due to the highly developed nature of the property and the multiple property owners. Lengthening the alignment to approximately 2,000 feet allowed the south shaft to move away from the shore and the highly developed property. However, this resulted in an extremely long microtunnel. Although lengths in excess of 1,500 feet are possible for microtunneling and have been completed outside of the United States, the number of contractors with microtunneling experience on these drive lengths is very limited. Lengthening the tunnel to 2,000 feet to avoid difficult easements was not concerning for EPB tunneling methods as tunnels well in excess of this length are commonly completed.

There was significant concern over the risk of hitting an obstruction that would require retrieval of the microtunneling machine from beneath the canal. Although it is possible to fit microtunneling machines of this diameter with an air-lock for face access, few machines have this capability and the access is limited due to size restrictions. In addition, the vast majority of microtunneling contractors do not have experience with accessing the face through an air-lock system. This was of significant concern to King County due to the ever-present risk of encountering large boulders in glacial soils and their previous experiences with microtunneling which have resulted in a number of unplanned machine retrievals. Obstructions are of much less concern for EPB machines due to the ability to access the face of the machine during tunneling.

8. RISK EVALUATION

The selection of the preferred tunneling alternative was driven by the analysis of risks. Over 50 tunneling risks were identified and considered for both tunneling methods. These included construction risks, such as encountering an obstruction that stopped the forward progress of the tunneling machine beneath the Ship Canal, settlement of the critical structures above the tunnel alignment, and long drive lengths; acquiring necessary easements; property acquisition; and permitting risks. A thorough risk evaluation was performed, identifying specific risks and quantifying those risks by assigning costs to the measures that would be necessary to mitigate each risk event. From these, a risk register was developed for each method, and relative comparisons of the two methods were developed. Based on the cost-based risk analysis, the County selected EPB tunneling as the preferred alternative. This alternative was then moved into final design.

9. CLOSING

In summary, the Ballard Siphon Replacement Project has gone through a number of different permutations over the initial three years of the design process. After HDD was eliminated as a feasible replacement method, the County chose to slip-line the existing dual wood-stave siphons to provide adequate low flow capacity, and to tunnel one supplemental crossing to provide overflow capacity for a 20-year storm event. Of the potential trenchless methods investigated for the additional crossing, EPB tunneling was chosen as the preferred alternative as the County was unwilling to accept the risks associated with microtunneling. These risks included the unusually long drive length, the extremely deep shafts required, and the high potential for unplanned machine retrieval. This project is currently in the 60% design stage, and is expected to go out to bid in late 2008.

REFERENCES

Crawford, B. and Swarner, B. (2006). Ballard Siphon Capacity and Sizing, Technical Memorandum, July 11, 2006.

Staheli, K. and Ramos, M. (2006). HDD Feasibility Study for Ballard Siphon, Technical Memorandum, August 21, 2006.

Staheli K, and Ramos, M. (2007) Sliplining Assessment for the Ballard Siphon, Technical Memorandum, February 7, 2007.

Staheli, K, and Ramos, M. (2007) Microtunneling Assessment for the Ballard Siphon, Technical Memorandum, April 27, 2007.

Staheli, K. and Ramos, M. (2007) Earth Pressure Balance Tunneling – 30% Design Recommendations, Ballard Siphon Replacement Project, Technical Memorandum, January 7, 2008.