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Continuing Sediment Management at Mount St. Helens: Raising the Spillway of the Sediment Retention Structure

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ABSTRACT

The Sediment Retention Structure (SRS) was constructed by the U.S. Army Corps of Engineers (USACE) from 1987 to 1989 to trap sediment eroding from the Mount St. Helens debris avalanche, for the purpose of maintaining flood risk levels downstream in the Cowlitz River. In 1998, the operation of the SRS changed, and the sediment trapping efficiency decreased. The USACE began studies and an alternatives analysis to identify a long-term plan given the current conditions. The studies and alternatives analysis led to a preferred adaptive-management plan including up to three incremental SRS spillway raises to trap more sediment. The first spillway raise was constructed in 2012. The 2.1-m-high structure was constructed using 8,700 cubic meters of Roller Compacted Concrete (RCC). The RCC structure was set back from the original spillway crest to allow room for the subsequent two raises. The primary hydraulic design goals were downstream fish passage and the promotion of a separated and vegetated floodplain terrace in the flat sediment plain above the spillway. The main features of the spillway raise included the RCC structure, a plunge pool, and a channel excavated in rock connecting to the original spillway crest. The RCC structure was designed with a three-tiered crest, and angled RCC sills were constructed on the downstream face to collect and concentrate low flows and to dissipate energy at high flows. The spillway raise has increased the trapping efficiency of the SRS and maintained flood risk levels in the Cowlitz River downstream.

Keywords: *Mount St. Helens, Sediment Retention Structure, spillway raise, Roller Compacted Concrete, fish passage.*

1. BACKGROUND AND PURPOSE

The 18 May 1980 eruption of Mount St. Helens in Washington State resulted in a debris avalanche of approximately 2.3 billion cubic meters (3 billion cubic yards). Sediments eroding from the avalanche and depositing downstream in the lower Cowlitz River decrease the capacity of the river and increase flood risk for communities with a population of 50,000. In 1985, the U.S. Army Corps of Engineers (USACE), Portland District developed a 50-year plan to manage the sediment and maintain authorized flood risk levels along the Cowlitz River. The main feature of the plan was the Sediment Retention Structure (SRS) on the North Fork Toutle River. The SRS was constructed from 1987 to 1989 for the single purpose of trapping sediment eroding from the Mount St. Helens debris avalanche.

The SRS consists of an earth- and rock-fill embankment dam, an outlet works, and an un-gated spillway excavated in rock. The outlet works is a concrete structure containing six rows of pipes. When all flow passed through the outlet works, the sediment trapping efficiency was about 80 – 90%. The rows of pipes were closed from the bottom up as sediment filled behind the SRS. In 1998, the outlet works pipes were all closed, and all flow passed over the spillway. In this condition, the sediment trapping efficiency dropped to about 30 – 40% and more sediment began to deposit in the Cowlitz River.

The 1985 plan identified dredging in the Cowlitz River as the means to maintain flood risk levels once the SRS became run-of-river (all flow over spillway). Dredging is not as easy today due to development along the river and Endangered Species Act listings. In the late 2000s, the Portland District began studies and an alternatives analysis to identify a new long-term plan.

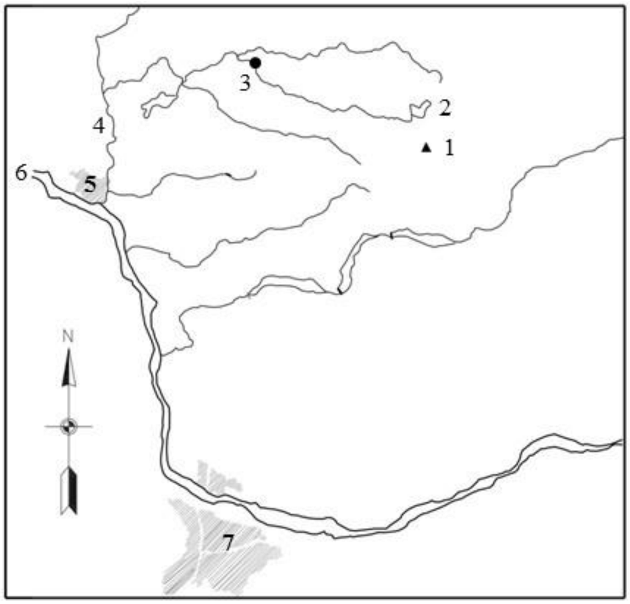

Figure 1. Map of Region (Washington and Oregon, USA)

The purpose of this paper is to describe the design, construction, and performance of the 2012 SRS spillway raise, which was the first implemented action of the new long-term plan for maintaining the authorized flood risk levels in the Cowlitz River. The main purpose of the spillway raise was to trap sediment and reduce sedimentation in the Cowlitz River. Hydraulic design goals for the structure included downstream fish passage and promotion of a separated and vegetated floodplain terrace in the flat sediment plain upstream.

2. A NEW LONG-TERM PLAN

2.1. STUDIES

Five studies played major roles in the alternatives analysis: sediment budget study, debris avalanche erosion rate study, Future Expected Deposition Scenario (FEDS) analysis, mudflows study, and probable maximum flood study.

In the onset of the current planning study for the new long-term plan, The Biedenharn Group, LLC was retained under contract with the Portland District to develop a comprehensive sediment budget for the Toutle River basin. The purpose of the Biedenharn study (Biedenharn Group, LLC 2010) was to present a sediment budget for the basin that identifies the existing watershed sediment sources, pathways of sediment transport, and sinks of temporary sediment storage based on all available data at the time as well as existing basin conditions. The results from this study were used to forecast sediment loads out to 2035.

The sediment budget relies heavily on U.S. Geological Survey (USGS) gages in the Cowlitz River and Toutle River basins, which provide a long-term estimate of the suspended sediment loads. An unbroken data record extends from the present to, in some cases, the early years immediately after the eruption. More recently, hydrosurvey in the lower 32 km (20 mi) of the Cowlitz River has provided a record of sediment deposition since 2009. Light Detection and Ranging (LiDAR) data has added to this information by providing sediment plain deposition and essential information to characterize the persistent sediment loads coming from the debris avalanche.

A relatively high degree of uncertainty still exists regarding future sediment yield from the debris avalanche, both in terms of total yield and variability of yield. The best available scientific analyses of future yield have widely varying conclusions: a near future of persistent high load (Major 2004 and Meadows 2014) or one of continued decay (USDA 2012). Data collection into the future will be the best (any maybe the only) way to know with certainty how sediment yields from large volcanic debris avalanches mature.

To apply a measure of conservatism in the estimate of future sediment loading, the no-decay assumption was applied to the forecast of future sediment loads from the debris avalanche. However, to respond to the inherent uncertainty in the primary driver of sedimentation in the Cowlitz River (sediment yield from the debris avalanche), an adaptive approach is desirable. Any feasible management strategy should be able to accommodate the conservative sediment input of the adopted approach but would be scalable if significant decay does occur.

The FEDS analysis and report (USACE 2011b) introduced the hydraulic and sediment transport tools used to evaluate performance of alternatives for development of the new long-term sediment management plan. The FEDS approach and models rely on sediment budget inputs to forecast performance into the future. With the suite of models described in the FEDS analysis, it is possible to produce a probabilistic Cowlitz River flood risk performance metric for future conditions with and without alternatives. This probabilistic future performance metric was used to determine if a proposed measure or suite of measures (alternative) is viable in protecting the communities.

Two of the potential measures involved modifying the SRS are raising the entire structure or raising the spillway only. A mudflows study and probable maximum flood (PMF) study were done in order to evaluate these measures.

For design of the SRS in the 1980s, the requirement to pass the Operating Basis Mudflow (OBM) without overtopping the dam was the critical criterion for sizing the spillway and resulted in a height difference between the spillway crest and the dam crest of 18 m (60 ft). The OBM was based on an “intra-episode” eruptive event roughly the size of the June 1980 eruption (a smaller eruption following the main eruption on May 18) occurring at a time of maximum snowpack, as this event represented the largest mudflow event that was considered realistic during the project lifetime. The volume of the OBM was assumed to be 57 million cubic meters (75 million cubic yards). The Portland District now believes that the most appropriate OBM would be a smaller-volume event (USACE 2013). The USGS Cascades Volcano Observatory modeled two new mudflow scenarios: a mudflow caused by failure of the debris avalanche blockage forming Castle Lake (56 million cubic meters) and a mudflow originating in the crater of Mount St. Helens (25 million cubic meters). For both scenarios, the mudflows never reach the SRS (Denlinger 2012). As the mudflows progress downslope, the flows spread out over the sediment plain and into embayments. With this result, the OBM was no longer the controlling criterion for determining the height of the dam above the spillway crest. The controlling criterion was now the PMF.

The recalculation of the PMF is documented in USACE (2011a). The primary reason for reinvestigation was to update the PMF to reflect the most recent hydrometeorological report, HMR No. 57 (Hansen et al. 1994). The HMR is used to calculate the probable maximum precipitation (PMP), which forms the basis of the PMF. During the course of the reinvestigation, all aspects of the PMF calculation were revisited and updated, including the PMP, unit hydrograph, and bulking assumption. The 2011, PMF recalculation effectively reduced the design PMF from 6,030 cubic meters per second (cms) (213,000 cubic feet per second, cfs) to 3,400 cms (120,200 cfs), a 44% reduction in peak flow.

2.2. ALTERNATIVES

The Portland District evaluated several measures for managing sediment. Three alternatives proved capable of maintaining the authorized flood risk levels along the Cowlitz River (USACE 2011b): 1) a single large raise of the SRS, 2) a dredging program in the Cowlitz River, and 3) a phased approach involving three incremental SRS spillway raises followed by the construction of dikes in the sediment plain above the SRS, with dredging in the Cowlitz River on an as-needed basis only. The phased approach was selected as the least costly, most adaptable alternative. The reductions in the OBM and PMF allowed for the SRS spillway to be raised up to 9.1 m (30 ft) without needing to raise the dam crest. Three incremental 3-m (10-ft) spillway raises, built as needed, are desirable to 1) limit the pool above the SRS to optimize sediment trapping efficiency (large pools unnecessarily trap fine sediment that would not deposit in the Cowlitz River) and 2) respond to the remaining uncertainty in future sediment erosion and deposition rates.

The remainder of this paper describes the design, construction, and performance of the first SRS spillway raise.

3. 2012 SEDIMENT RETENTION STRUCTURE SPILLWAY RAISE

The first spillway raise was planned for 2012. A limitation in funding meant that the first spillway raise height could only be 2.1 m (7 ft) instead of the originally planned 3 m (10 ft).

Roller-Compacted Concrete (RCC) was selected for the spillway raises due to its proven performance in the environment and the need for rapid construction. The first flows over the spillway, in the winter of 1995 to 1996, eroded weak/highly fractured rock in the spillway. RCC was used to fill and repair the eroded areas. The RCC has performed well. It has not eroded significantly under the continuous sediment-laden flow over the spillway since 1998. In addition, an advantage of RCC is that it can be placed rapidly. The in-water work window for the North Fork Toutle River was limited to July 1 through October 7.

Figure 2 shows the planned outlines of the three spillway raise increments. The intent is for the slope of the final raise to match the slope of the original spillway (7%). The first two raises have overall downstream slopes of 10% and are positioned such that all three raises share a common upstream face.

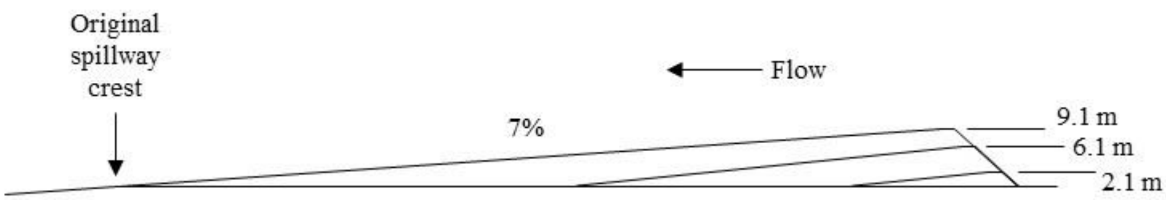

Figure 2. Outlines of three spillway raise increments

3.1. HYDRAULIC GOALS, CRITERIA, AND DESIGN

An advantage of using small, incremental spillway raises is the ability to optimize the sediment trapping efficiency. In terms of downstream sedimentation, equilibrium can be achieved with SRS trapping efficiencies in the 45 to 60% range at current sediment inflow rates. The SRS spillway raise approach increases the spillway elevation approximately 3 m at a time in successive raises. The maximum pool depth is limited by these spillway raises and results in a trapping efficiency close to the desired equilibrium condition. Immediately after construction of the first raise, the observed trapping efficiency was between 60 and 70%. As the small pool fills and the upstream valley slope begins to steepen, the trapping efficiency will to drop toward the pre-raise conditions (approximately 35%). Monitoring of debris avalanche sediment loading and downstream sedimentation trends will inform if an additional spillway raise is needed to maintain flood risk levels.

The progressive drop in overall SRS trapping efficiency expected with incremental spillway raises may take as many as 10 years depending on hydrology and incoming sediment load. Furthermore, if significant decay in avalanche erosion occurs in the intervening period, the trapping efficiency of the SRS required for downstream equilibrium may decrease as well. Monitoring of the hydrology, hydraulics, and sediment trends in the system is critical in making decisions that optimize the performance of the phased construction approach.

One of the design goals of the spillway raise and downstream channel was to provide safe passage of downstream migrating juvenile fish (primarily steelhead and Coho salmon). The chief intent of the juvenile fisheries criteria was to prevent the occurrence of harmful sheet flow and stranding of fish within a 90% duration of the historic discharges during the juvenile fish passage season (primarily April through May). Hydrologic analyses were conducted over a 25-year record (1986-2011). For the two month migration period, a daily flow rate of 15.4 cms (545 cfs) was estimated to be exceeded 95% of the time and defined the low design discharge. The high design discharge was defined as the 5% exceedance discharge for a full twelve-month period and was determined to be 47.3 cms (1,670 cfs).

Design criteria for the low design discharge required a minimum flow depth of 0.3 m (1 ft) at the thalweg. The low flow channel on the spillway raise was delineated by notch openings between the lowest sills on the crest and between the sills on the 10%-sloped section down to original grade.

Design criteria for the high design discharge required the containment of flow within a channel excavated through the original flat grade that would connect the notched channel from the raised spillway section on the upstream side to the brink of the original 7% spillway grade on the downstream side (Figure 3). This is to prevent overland sheet flow and stranding of fish over the flat grade between the spillway raise section and the 7% grade break at high design discharge.

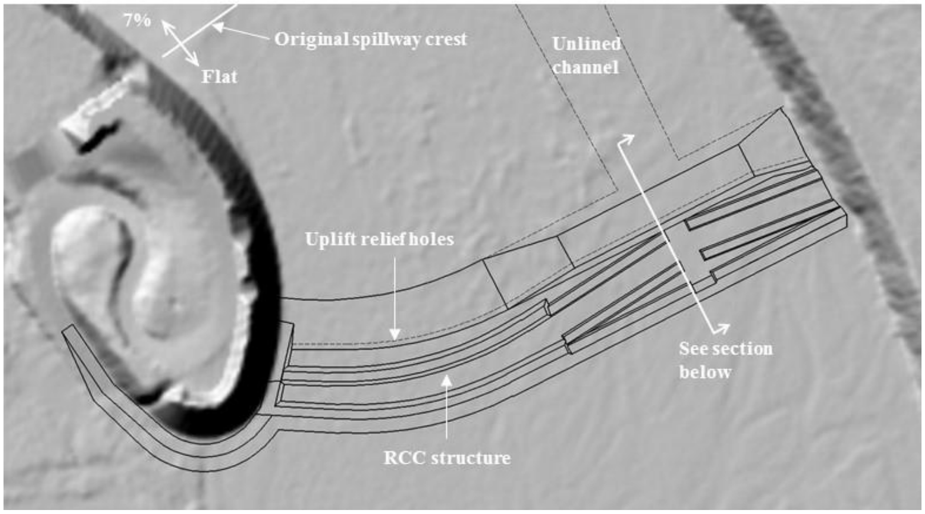

Figure 3. Spillway raise plan

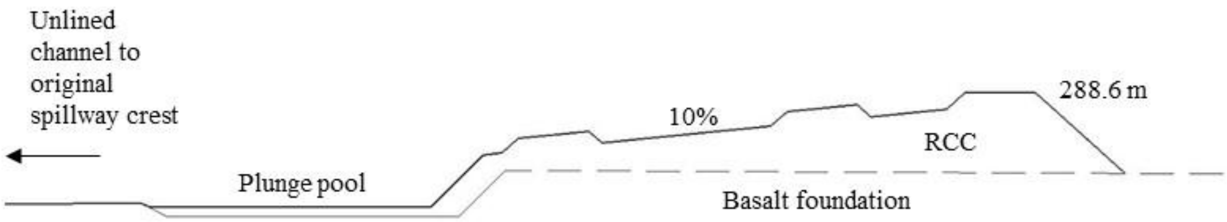

Figure 4. Spillway raise section

The shape of the spillway raise influences the geomorphic response of the sediment plain immediately upstream of the structure. The historic spillway was a flat weir crest approximately 122 m (400 ft) wide. Construction tolerances and surface erosion resulted in flow concentration during low flows, but the overall effect was a very flat flow-stage rating curve between low flow and the 50% annual exceedance probability channel forming flows. This near sheet flow resulted in an upstream morphology with no concentrated flow or deep channel and little opportunity for fluvial deposition that could create distinct floodplain terraces. The resulting landscape in the 500 m upstream of the spillway was an unvegetated, rapidly shifting, and dense network of small braided channels.

The 2012 design increases the relative stage between low and channel forming flow from 1.3 m in the historic condition to 1.9 m in the with-project condition. This was done in an attempt to differentiate between the summer low flow and flood event sediment regimes and promote the development of a separated and vegetated floodplain terrace. Field evidence from the summer of 2013 (Figure 5) shows the development of proto floodplain and emergence of grasses. While encouraging for long-term revegetation and associated floodplain roughness in the sediment plain, grasses did not emerge in the summer of 2014 for unknown reasons. The USACE will continue to monitor the system for the primary performance metric but will also look for opportunities to improve basic designs like the weir crest shape.

Figure 5. Conditions upstream of SRS spillway raise in summer 2013

The convergence of design concerns regarding upstream geomorphology and downstream juvenile fish passage led to a three-tiered crest. The lower two levels are intended to pass fish within the design juvenile range of low and high flow rates. The crest was shaped to contain the high design juvenile discharge and to assure the flow depth will be at least 0.3 m at low design juvenile discharge. The invert of the 6.1 m (20 ft) wide opening of the low flow channel represents the bottom tier on the crest, which is 1.7 m (5.5 ft) higher than the original crest. The second level is 2.1 m (7 ft) higher than original crest and represents nominal height of the spillway crest raise. The combined opening width of the first and second levels is 76 m (250 ft), which defines the maximum extent of the low flow channel through the crest. The third level is 2.7 m (9 ft) higher than original grade and is set strictly on the left side of the crest to reduce the concentration of unit discharge adjacent to the dam abutment. The low flow channel is on the right side of the crest to draw the concentrated flow away from the abutment. The full width of the raised spillway crest is about 165 m (540 ft). Because the raised spillway was placed upstream of the original crest, the new spillway crest is 35% wider than the original crest, which increases flow capacity. A schematic of an upstream view of the crest is shown in Figure 6 along with computed pool levels for various flow rates.

Comparative rating curves for the raised and original spillway crests are shown in Figure 7. Due to the three-tiered configuration of the raised spillway, the new rating curve is steeper than the original at lower (normal) flow rates, whereas the larger opening width leads to a flatter rating curve at the flood discharges. The rating curve for the ultimate 9.1 m (30 ft) spillway raise is also shown and illustrates that the PMF will not encroach upon freeboard in spite of the ultimate spillway raise. This is because the PMF has been revised downward, as is described above.

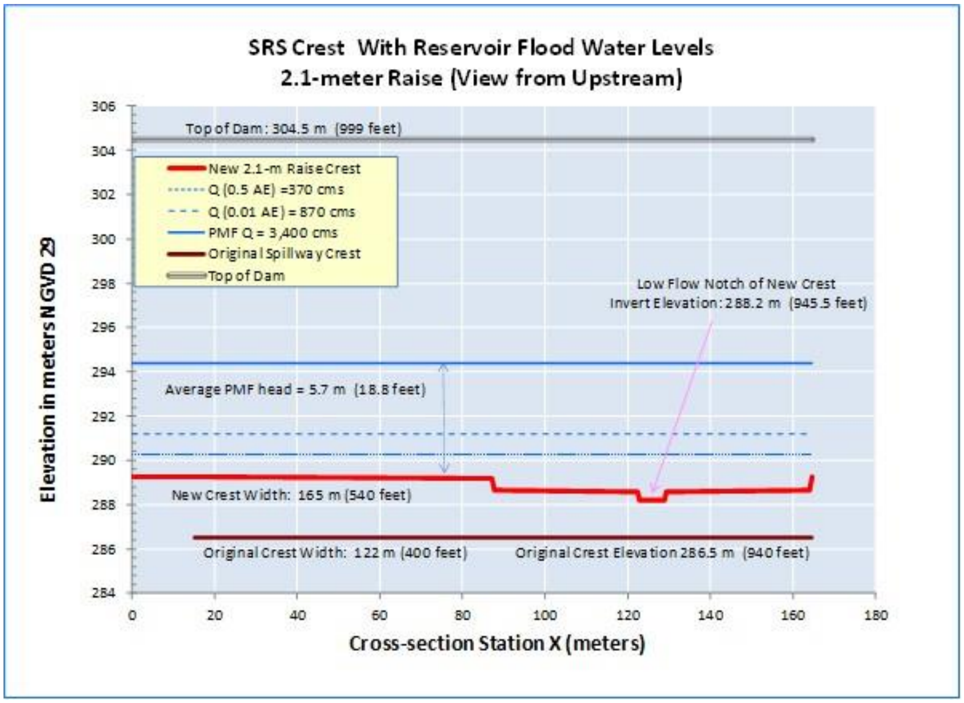

Figure 6. SRS 2.1 m spillway crest shape (exaggerated vertical scale)

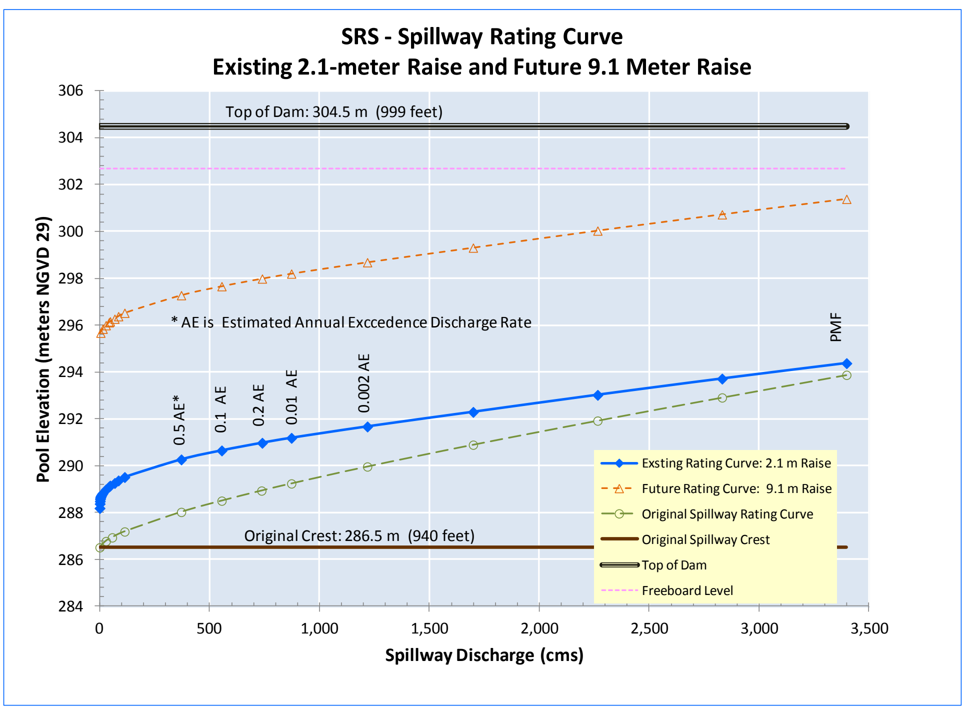

Figure 7. SRS spillway rating curves

The spillway channel downstream of the crest is comprised of three features: RCC sloped section with RCC sills, plunge pool for collecting juvenile fish, and excavated channel to the edge of the original 7% grade (Figure 4).

Downstream of the crest, the RCC slopes 10% from the crest invert elevation of the low flow channel down to the existing grade. The approximate stream length of the sloping RCC section is 26 m (85 ft.) To slow the flow during low discharges and to dissipate energy at high discharges, two rows of sills were added to the 10%-sloped surface downstream of the crest. The opening widths match the widths on the crest. The sills are angled slightly down the slope (10:1 lateral to slope distance) so that when flow subsides, any residual fish and sediment will drain along the toe of the sills towards the low flow channel. When discharge ramps up, the flow will expand from inside-out from the low flow channel. Most juvenile fish and larger sediments will remain entrained in the more concentrated flow in the center.

At the downstream end of the sloped RCC section, flow contained by the low flow channel is collected by a 91 m (300 ft) wide plunge pool. Excess discharge above high juvenile design flow will bypass the plunge pool and flow overland over unchanged horizontal original grade. The plunge pool is needed as a collector of flow below high juvenile design and as a transition to the excavated channel.

The excavated channel connects the plunge pool to the brink of the original 7% spillway grade. The purpose of the excavated channel is to safely and swiftly convey fish without stranding. The channel has a trapezoidal shape with bottom width of 12 m (40 ft) and 2:1 horizontal to vertical side slopes. The minimum excavation depth is 1.7 m (5.5 ft) at the upstream end, and the maximum excavation depth is about 3 m (10 ft), as the channel thalweg is sloped at 1% grade. The channel contains the high design juvenile discharge, and the flow depth exceeds the minimum required depth at the low design discharge. Channel velocities will range between 1.2 m/s (4.0 ft/s) at low design discharge to 2.2 m/s (7.2 ft/s) at high design discharge. Where the flow reaches the edge of the original spillway crest, the channel connects to an existing natural channel that had previously been eroded into the rock during past spillway usage.

3.2. CONSTRUCTION

The spillway raise contract was awarded to LKE Corporation for $4.5 million in July 2012. River diversion was accomplished in two phases. In phase one, the river was diverted to the left side of the existing spillway—through 10 culverts beneath a temporary access road—while the right side of the RCC structure was constructed behind a cofferdam. In phase two (Figure 8), the river was diverted through the low flow channel of the RCC structure while the left side of the RCC structure was constructed behind a cofferdam. The work was performed during late summer when flows in the river are at their lowest.

The contractor placed a total of 8,700 cubic meters (11,400 cubic yards) of RCC on twelve days within a nineteen day period. The RCC 90-day strength was specified to be 31 MPa (4,500 psi) for durability against the erosive sediment-laden flows. Figure 9 shows the completed structure.

Figure 8. SRS spillway raise during construction

Figure 9. Completed spillway raise, 17 October 2012

3.3. PERFORMANCE

The 2012, the SRS spillway crest raise has proved highly effective in increasing the trapping efficiency of the SRS and preventing problematic deposition in the lower Cowlitz. The USACE has collected LiDAR data of the sediment plain as well as bathymetry in the lower Cowlitz for 2013 and 2014 following the crest raise. The USACE has further funded the USGS to collect suspended sediment samples in the Toutle River downstream of the SRS. Analysis of this data, along with field observation of the sediment plain, demonstrates performance of the project. The small, still-water pool created upstream of the spillway by the crest raise was filled with sediment during the first winter following construction. Despite the obvious loss of the pool due to filling with sediment, the crest raise effectively decreases the valley slope upstream of the spillway, decreasing sediment transport capacity in the reach. This decrease in transport capacity is the fundamental long-term action. Data shows that the trapping efficiency of the SRS has been increased to the mid 60% range following construction: 67% in water year 2013 and 63% in 2014. These are the highest two values observed in the system since post-outlet-works-shutdown data collection began in 2002 (Figure 10).

Hydrosurvey further shows that net erosion occurred in the lower 32 km (20 mi) of the Cowlitz River in both water years 2013 and 2014. These successive years of net erosion are the first years of credible data that indicate a change in the depositional trend since 2003. With deposition in the lower Cowlitz and its associated effects on flood protection as the primary driver for USACE involvement, the transition of the lower Cowlitz from depositional to erosional due to the SRS spillway crest raise is a great success for the project and USACE.

4. CONCLUSIONS

The new long-term plan for maintaining flood risk levels in the Cowlitz River is a phased approach beginning with three incremental SRS spillway raises. The purpose of the spillway raises is to trap sediment and reduce sedimentation in the Cowlitz River. The first spillway raise, constructed in 2012, was effective in increasing the trapping efficiency of the SRS and maintaining the authorized flood risk levels. RCC proved to be a viable material and should be used for the next two spillway raises. The 2012, spillway raise met the downstream fish passage design goals. More time is needed to monitor the development of a separated and vegetated floodplain terrace in the sediment plain above the spillway raise.

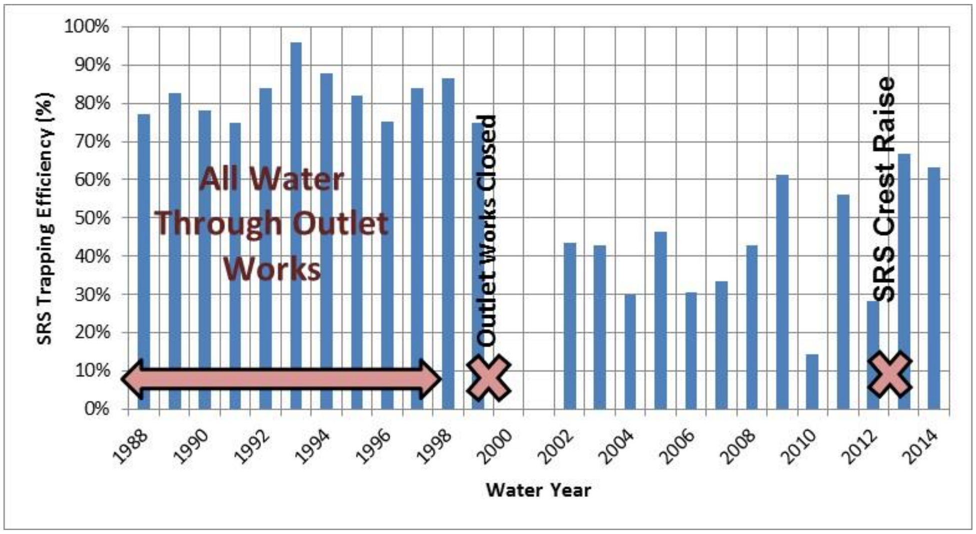

Figure 10. SRS trapping efficiency over time

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