RECLAMATION
Managing Water in the West

PAP-1046

World Environmental and Water Resources Congress 2011:
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Flume Analysis of Engineered Large Wood Structures for Scour Development and Habitat

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ABSTRACT

Engineered large woody debris (LWD) structures are being introduced into rivers due to the many realized benefits of woody debris, particularly with respect to salmonid habitat restoration. In this study, a 1:11 Froude scale physical hydraulic model of a gravel bed river channel was constructed to observe the scour patterns and extent of erosion and deposition produced by six LWD configurations. The model represented a “typical” river in the Pacific Northwest as determined by hydraulic geometry relationships. The material size was scaled such that the median grain size (d_{50} = 8 mm) was near incipient motion for bankfull flow in order to identify bed movement occurring only as a result of interaction with the LWD structure. The scaled logs were simplified to include the trunk and rootwad; smaller branches were excluded.

The LWD configurations contained between two and seven logs that were placed in a variety of orientations such as X-shape, trapezoidal shape, or free-form shape. All other parameters (slope, bed material, log size) were kept constant. Each configuration was tested at two discharges: near bankful (90%) and mid depth (50%) flow conditions. Changes in bed topography were recorded using photogrammetry techniques. Aggradation/degradation maps were produced to compare physical changes from the different configurations. Rootwads facing upstream deflected flow around the structures producing less scour within the structure. Downstream oriented rootwads produced localized scour zones. Slower velocities downstream of the structures allowed for deposition of the scoured material. Results provide information to designers of LWD structures to assist in selecting the most effective structure(s) to meet their project objectives.

INTRODUCTION

Naturally occurring in-stream large woody debris (LWD) jams were removed from many rivers, especially in the Pacific Northwest, for flood control and navigational efforts during the 20th century (Montgomery et al., 2003). As a result, morphological chances such as incision, expansion, increased sediment loads, and habitat homogeneity have occurred. Replacement efforts are currently occurring due to the many realized benefits of in-stream woody debris such as: fish habitat restoration and habitat complexity, bank protection and stabilization, grade control, debris retention, increased hyporheic zone flow, and production of scour and deposition areas. Engineered LWD structures are installed using fallen trees, stumps, rootwads, and branches in a variety of orientations with various numbers of pieces. They have been placed in rivers as free structures meant to move during flood events and as fixed structures to reduce the risk of failure during larger flood events.

Several previous laboratory experiments have been conducted to assess the depths and extent of erosive and depositional zones resulting from individual pieces of LWD. Beschta found that scour depth generally increased with increased discharge when flows were deflected under a cylinder. The maximum scour occurred as flow began to overtop the cylinder. Once overtopping occurred, the scour depth slowed or stopped and scour holes tended to shift downstream (Beschta, 1983). A laboratory flume study by Cherry and Beschta in 1989 showed that upstream oriented dowels produced larger scour areas and deflected flows toward the streambank. Downstream oriented dowels produced less scour area, but better protected banklines. Results also showed that partially elevated individual logs produced more localized scour than logs positioned on the channel bed (Cherry and Beschta, 1989). Wallerstein et al. (2001) mapped erosion and deposition zones for four different log sizes and locations.

One major ecological benefit of LWD within rivers is the improvement of floodplain connectivity and the creation of habitat and cover for endangered fish species. Morphological changes and hydraulic conditions produced by LWD structures positively affect fish habitat suitability. Habitat suitability is based on the biological needs of the fish species of interest. Research has been ongoing at the Bureau of Reclamation to better understand how engineered LWD installations increase habitat complexity, particularly with respect to salmonid habitat restoration. Areas of the research include: 1) determining the depths and extent of erosion and/or deposition zones formed by LWD structures, 2) evaluating the variation in scour patterns produced by different LWD structure types in terms of habitat complexity, and 3) linking the morphological changes of the river to fish habitat suitability criteria using depth, velocity, velocity shear, and cover parameters.

The focus of this moveable bed hydraulic model is to evaluate differences in the shape and volume of scour produced by six LWD structure configurations with multiple logs. Under mid-depth (50%) and near-bankfull (90%) flow conditions, a comparison between the LWD structures provides insight into potential fisheries habitat produced by each structure.

MODEL DESCRIPTION

A physical model of a generic river section containing an engineered LWD structure was constructed at the Bureau of Reclamation’s Hydraulics Laboratory in Denver, Colorado. Variables considered for the design of the river model and large woody debris pieces were: river discharge, bankfull river width, channel bed slope, channel side slopes, grain size of bed material, number of wood pieces in logjam structure, length of logs, percentage of log imbedded into bank, rootwad dimensions, and orientation of wood pieces. The majority of these variables were fixed based on guidance from literature and their values are described in the following sections.

The physical model represents a “typical” river in the Pacific Northwest where LWD structures are often installed. Model parameters were determined using hydraulic geometry relationships proposed by Julien (2002) and Parker (2008). The goal of both sets of equations is to describe the hydraulic relations at bankfull flow of rivers by relating discharge and grain size to depth, width, and bed slope. Julien analyzes noncohesive alluvial channels and Parker specifically addresses alluvial gravel-bed rivers. Use of these equations allows for the prototype channel to be representative of a natural river system which links the laboratory results closer to field conditions, while not limiting the results to a single river system.

A bankfull discharge of 150 m^3/s (5,297 ft^3/s) and a median grain size (d_{50}) of 90.5 mm (3.56 in) in the small cobble size range were selected. Based on calculations from the equations by Julien (2002) and Parker (2008), a channel width of approximately 30 m (98.4 ft) and a slope of 0.004 were chosen to be representative values for the prototype channel. Normal depth calculations were used to determine the bankfull depth. Normal depth was calculated by Manning’s equation assuming the channel was trapezoidal with 3H:1V side slopes. Several equations can be used to estimate the bed roughness based on the mean particle diameter. A preliminary estimation of the bed roughness was calculated using Strickler’s relationship $n = 0.041 d_m^{1/6}$, where n = Manning’s roughness parameter and d_m = effective mean bed material size (m). The bankfull depth was calculated to be 2.0 m (6.6 ft) at the maximum discharge of 150 m^3/s (5,297 ft^3/s). These hydraulic parameters provided the foundation for the physical hydraulic model.

Similitude between the model and the prototype is achieved when the ratios of the major forces controlling the physical processes are kept equal in the model and prototype. An undistorted scale was used to represent flow patterns and sediment transport. In order to represent the desired prototype geometry in the available laboratory flume, the physical model was designed at a 1:11 Froude scale. To avoid having viscous forces affect model performance, the minimal range for turbulent flow conditions must be achieved in the model. At a 1:11 scale, the Reynolds number ($Re = vd/\nu$) was greater than 5,000 for all flow conditions of interest.

To achieve similarity of bed load transport in moveable bed models, the difference of the calculated Shield’s parameter to the critical Shield’s parameter should be the same in the model and prototype for the range of tested flow conditions. To have similarity of sediment deposition, the particle settling velocity must also scale appropriately between prototype and model. Settling velocity is a function of both particle diameter and density. Acceptable sediment scaling was achieved through geometric scaling of the gravel material. Using a 1:11 undistorted model scale, pea gravel from a local quarry with a d_{50} of 8.0 mm was chosen for the model material. With the selected geometry, the channel boundary was near the threshold of motion at high flow rates, therefore changes to the bed shape were attributed only to flow patterns around the structure.

MODEL FEATURES

The physical model included a headbox, 9 m (30 ft) of straight river bed, and a tailbox with tailgate. A rock baffle was used to calm the energetic water entering the headbox. A roughened concrete transition zone containing vertical and horizontal curves was used to transition flow from the headbox to the river channel. The trapezoidal river channel was 2.7 m (8.9 ft) wide with a 1.6 m (5.3 ft) wide bottom and 3H:1V erodible side slopes. The top of the bank was 0.2 m (0.6) ft above the bed elevation. The bed material was 1.5 ft deep to ensure that localized erosion did not scour to the model floor. The river channel was graded to a 0.004 slope with a trapezoidal template. A tailgate was placed at the downstream end of the model to maintain uniform flow conditions. A gravel trap was constructed at the end of the model to collect scoured material.

The large woody debris pieces were designed based on guidance from Montgomery et al. 2003 and the National Resources Conservation Center (NRCS) Stream Restoration Design Handbook Technical Supplement 14J (Figure 1). Montgomery et al. suggests that pieces capable of altering channel morphology have a diameter greater than half of the bankfull depth and length greater than half of the bankfull width (Montgomery et al., 2003). The NRCS handbook recommends the following guidelines for the minimum dimensions of logs and rootwads: rootwad diameter = bankfull discharge depth, trunk diameter = 0.5 times the bankfull discharge depth, and tree length = 0.25 times the bankfull discharge width (NRCS, 2007).

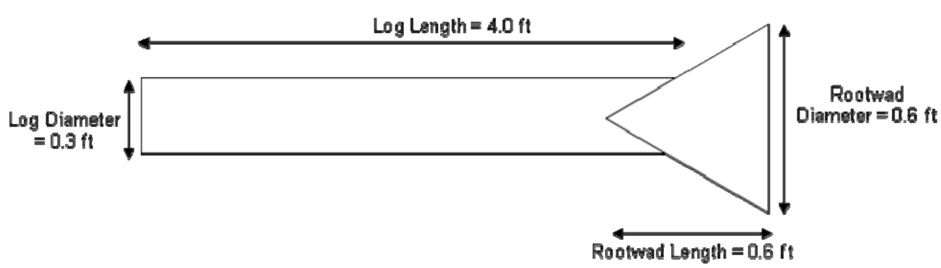

Figure 1. Design of log pieces for LWD structures.

Six simplified LWD configurations used in field restoration efforts were tested in the physical model: triangular, rectangular, cross-structure with the downstream log on top, cross-structure with the upstream log on top, free-form, and bar apex jam (Figures 2 through 7). The scaled logs were simplified to include the trunk and rootwad; other smaller branches were excluded. The log sizes were the same in every configuration. Each configuration incorporated between 2 and 7 logs with bottom logs placed halfway below grade. Each LWD structure was tested at two submergence levels, half-bankfull (50% depth) and near- bankfull (90% depth), in order to analyze morphological changes resulting from these flow events.

Figure 2. Configuration 1: Triangular LWD structure.

Figure 3. Configuration 2: Rectangular LWD structure.

Figure 4. Configuration 3: LWD Cross-structure with downstream log on top.

Figure 5. Configuration 4: LWD Cross-structure with upstream log on top.

Figure 6. Configuration 3: Free-form LWD structure.

Figure 7. Configuration 6: Bar Apex Jam LWD structure.

To simplify modeling parameters, the stability of the LWD structure was not modeled. LWD structures were fixed in place by securing the structure to the model sidewall and model floor. The log components were fastened to each other, allowing for localized scour and deposition of the bed and banks without allowing individual pieces to move laterally or vertically.

The model was designed to produce only localized sediment movement due to interactions with the LWD structure. At the highest tested discharge, the bed material was below incipient motion, this allowed for the movement caused by the LWD structure to be isolated. All model runs were clear water tests without the addition of sediment to the inflow. In a natural river channel, it is likely that continuous sediment transport would occur through a river reach. Since no sediment load was introduced into the model, the resulting topographic changes caused by the LWD structure indicate only general patterns of erosion and deposition. However, a general comparison of scour patterns and depths between various LWD structures can be useful in determining whether the LWD structure can produce suitable conditions for fish habitat or other project needs.

DATA COLLECTION

Water was supplied to the hydraulic model through an automated flow delivery and measurement system with laboratory venturi meters providing flow measurement to an accuracy of $\pm 0.25\%$. Point gages equipped with a vernier scale were used to read water surface elevations to the nearest 0.001 ft. Stationary point gages placed at the entrance and exit of the model measured water levels at the inflow and outflow to the model. A tailgate was used to control tailwater conditions.

Photogrammetry was used to document areas of erosion and deposition in the model. A 12-megapixel Nikon D700 SLR camera with a 20mm lens was mounted on top of a 12-ft-high range pole and was remotely triggered with a handheld transceiver. Photographs were taken before and after test runs to identify morphologic changes. Control points were placed at fixed locations along the model walkways. To achieve 70% overlap in photogrammetric images, photographs were collected at 4 locations to produce 2 image pairs.

Images were processed using ADAM Technology's 3D CalibCAM and 3D Analyst software. The software produced three-dimensional digital terrain models (DTM) to analyze the bed surface. DTM data points were compared to physical point gage measurements at specific points in the model to ensure that the photogrammetry accurately represented the model bed. Differences between point gage and photogrammetric measurements were within an average of 1/8 inch. Initial test runs showed that 6 hours was needed to achieve stable scour depths in the model. The majority of scour occurred within the first hour of the model run. DTM data was processed in ArcGIS software to create a map showing the difference between photographs taken before and after each model run. Terrain maps show areas of aggradation and degradation produced by each LWD structure configuration.

RESULTS AND DISCUSSION

For each of the six LWD configurations, terrain maps showing the bed elevation change at 90% bankfull flow conditions are displayed (Figures 7 through 12). The contours represent the change in bed elevation from the initial timestep (t = 0 hours) to the final timestep (t = 6 hours). Contours were produced at 0.1 ft (model units) intervals; bed elevation changes that were less than the grain size diameter (+/- 0.026 ft) were ignored in the analysis. Erosive areas are designated in black, the contour line thickness increases with erosion depth. Depositional areas are designated in white, the contour line thickness increases with deposition depth. Table 1 displays the percent of channel width obstructed for each configuration. In addition, the total volume and surface area of aggradation and degradation for the 90% bankfull simulation are displayed.

Table 1. Channel width obstructed and aggradation and degradation volume and surface area for the 90% bankfull simulation in model units.

Percent of Channel Width Obstructed (%)	35.1	47.7	35.1	35.1	47.3	44.4
Volume of Scour (ft^3)	0.78	0.88	1.76	1.35	1.94	0.52
Volume of Deposition (ft^3)	0.60	1.02	1.51	1.13	1.85	0.29
Surface Area of Scour (ft^2)	15.47	23.41	16.94	14.16	26.86	7.23
Surface Area of Deposition (ft^2)	8.06	11.87	13.56	13.32	13.89	7.93

General observations can be drawn from each configuration. In configuration 1, the upstream facing rootwads produce local scour holes and deflect flow away from the structure (Figure 7). The deflected flow creates little scour within the structure but it does impact the rootwad angled into the flow. A large erosional zone is created downstream of this rootwad. Sediment is deposited downstream of the structure due to lower velocities in this region.

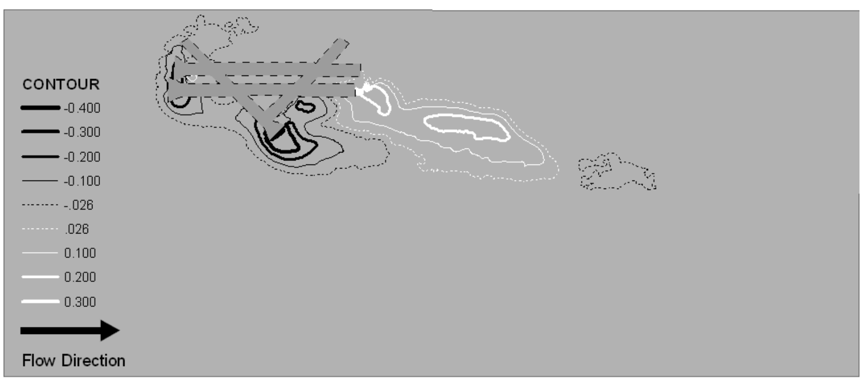

Figure 7. Configuration 1: Triangular structure contour map.

The upstream rootwads in configuration 2 cause flow to backwater (Figure 8). These rootwads deflect flow around the structure. Erosion occurs in multiple local pockets at the upstream rootwads as well as around the rootwads perpendicular to the flow. There are also small erosional zones underneath the downstream end of the streamwise logs. The majority of the deposited sediment occurs downstream of the structure. The calculated volume of scour is less than the volume of deposition for this configuration, which is due to errors in the contouring since there is no physical basis for this to occur.

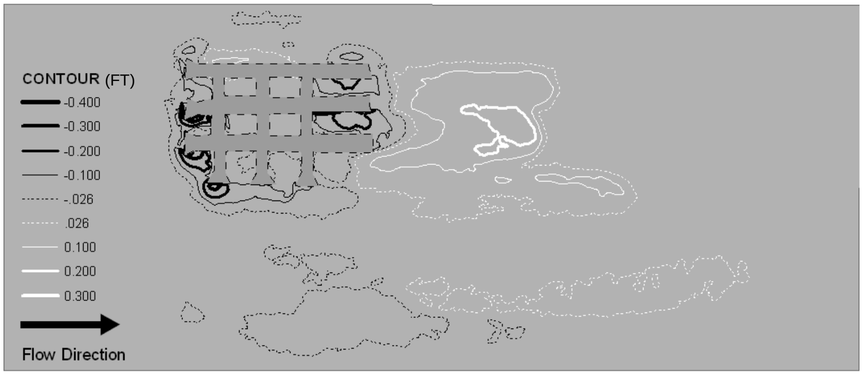

Figure 8. Configuration 2: Rectangular structure contour map.

Configuration 3 and 4 are very similar; the only difference is whether the upstream log is underneath (3) or on top of (4) the downstream log (Figures 9 and 10). In configuration 3, the water flows on top of the upstream log and underneath the downstream log producing a large erosion zone underneath the downstream log. Since the upstream rootwad is angled off of the bed only a small scour zone is created. In contrast, configuration 4 has a large scour zone to the right of the structure caused by the upstream facing rootwad at the bed. There is no major scour inside the structure. The rootwads are undercut and may have collapsed if they were not fixed. Both structures have a deposition zone downstream of the structure.

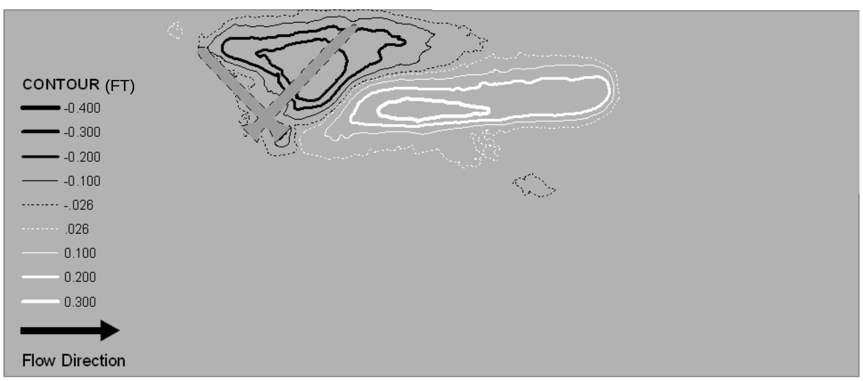

Figure 9. Configuration 3: Cross-structure (downstream log on top) contour map.

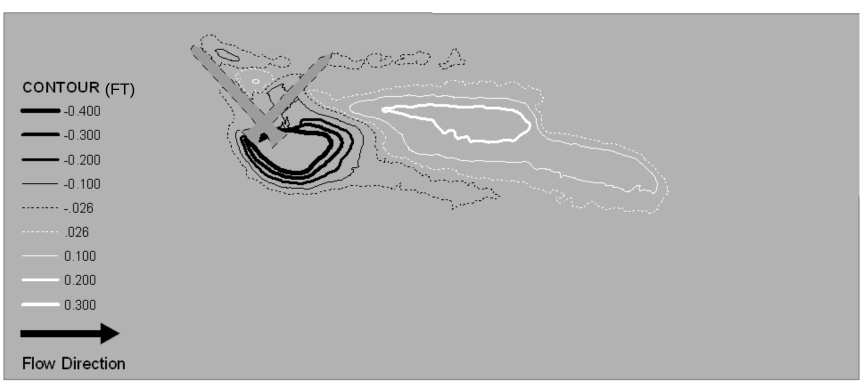

Figure 10. Configuration 4: Cross-structure (upstream log on top) contour map.

By spacing the logs further apart, configuration 5 produced multiple small scour zones primarily near each of the downstream oriented rootwads (Figure 11). There is also a large scour zone along the left bank that appears to be due to flow being directed by the upstream logs towards the downstream bank. Deposition occurs within the structure and immediately downstream.

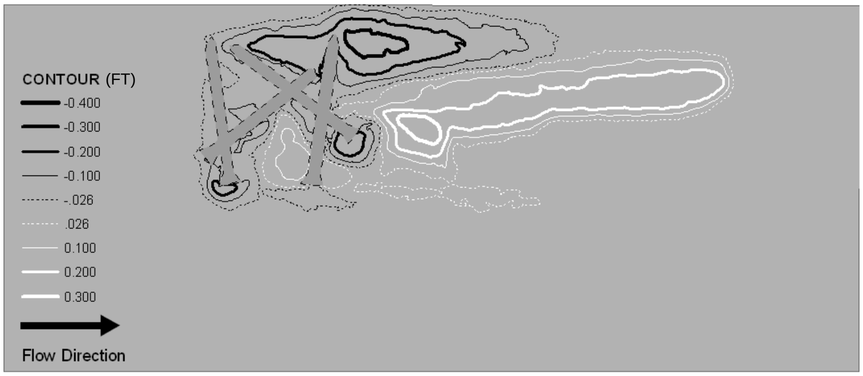

Figure 11. Configuration 5: Free-form structure contour map.

Configuration 6 produced very little scour or deposition compared to the other configurations although it had the greatest number of logs (Figure 12). The additional logs appear to block and deflect flow away from the structure, especially the upstream oriented rootwads, preventing sufficient flow through the structure to produce gravel movement. There are two scour zones: one along the left bank and one in the channel to the right of the structure. Deposition occurs downstream of the structure and extends downstream further than the other structures.

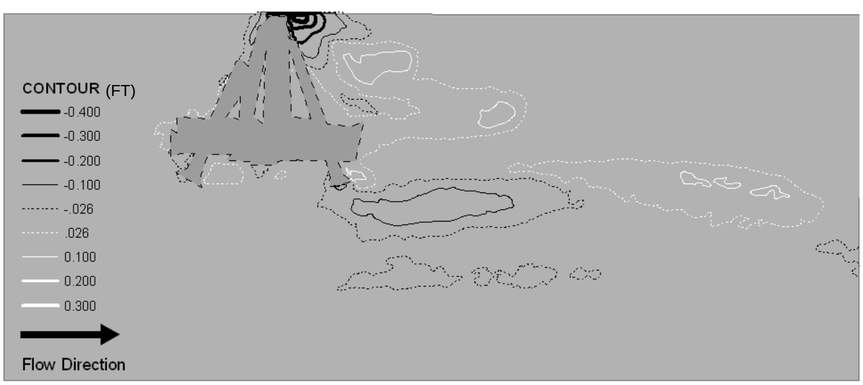

Figure 12. Configuration 6: Bar Apex Jam structure contour map.

In comparing the structures, several outcomes were noticed. Tightly placed structures, such as configuration 1 or 6, produced the least scour volume. Configurations 1, 2, and 5 produced multiple, small scour zones. In contrast configuration 3 and 4 both produced a large scour zone and a large deposition zone. Although the number of logs in the configurations was variable, the percent of channel width obstructed was similar (35 to 47%). Several configurations (1, 2, and 6) had upstream-facing rootwads. These rootwads deflected flow around the structure to the left and right producing less scour within the structure. In addition, if there were logs present along the left bank as in configuration 6, bank erosion occurred. Cherry and Beschta, 1989 noticed similar results in that upstream dowel orientation caused major flow disturbances, but they also appeared to increase the potential for bank erosion due to deflected flows. Deposition occurred downstream of all configurations due to the flow expansion and slower velocities directly downstream of the structure.

Results provide an initial view of the location and extent of scour produced by each structure and the type of LWD design that may be needed to produce desired scour patterns. Research is currently underway to link scour and flow patterns produced by LWD structures to fish habitat preference curves to give an estimate of habitat suitability as defined by water depth, velocity, velocity shear, and cover parameters.

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