Experimental and field observations of breach dynamics accompanying erosion of Marmot cofferdam, Sandy River, Oregon

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Abstract

A key issue faced in dam removal is the rate and timing of remobilization and discharge of stored reservoir sediments following the removal. Different removal strategies can result in different trajectories of upstream sediment transport and knickpoint migration. We examine this issue of for the Marmot Dam removal in Sandy River, Oregon, USA using both physical experiments and field studies accompanying removal of the dam in October 2007. The physical experiment was designed to provide insights on how and if the position of a cofferdam notch will affect how reservoir sediments are remobilized, with the goal of minimizing the volume of sediment stranded in terraces. Data and observations indicate that at lower failure discharges, notch position impacts the location of cofferdam failure as well as the location of the first major knickpoint and its trajectory. In particular, notch positions that force the river to migrate laterally in order to adjust to natural valley orientation and morphology were most effective in removing larger volumes of sediment and reducing terrace heights. Actual cofferdam notching to maximize erosion produced extremely rapid and significant erosion of reservoir sediments. Comparison of model results with field observations suggests that the physical experiments provided solid predictions of rates of erosion and overall knickpoint trajectory.

Introduction

Over the past ten years, the issue of dam removal has evolved from a speculative and radical idea, to a recognized approach to restoring or improving geomorphic and ecologic function of rivers. In spite of this, there are only a handful of well-documented examples of fluvial response to dam removal. In 2007, Marmot Dam, a 15 m concrete hydroelectric diversion dam on the Sandy River near Portland, Oregon, USA, was removed to improve fish passage on the river. This removal involved the largest sediment release associated with a planned dam removal in history, and provided an unparalleled opportunity to examine key geomorphic processes associated with dam removal (O'Connor et al., in press). Studies surrounding the Marmot Dam removal have included numerical and physical modeling as well as field studies. Removal of Marmot Dam occurred in two stages. The concrete structure was removed in July 2007, after the construction of an earthen cofferdam upstream diverted flow around the main structure. The cofferdam was then allowed to fail during an overtopping flow in October 2007. Breaching and erosion of the cofferdam initiated incision and transport of stored reservoir sediment and subsequent downstream redeposition (Major et al., in press). Ongoing monitoring is following channel evolution and sediment transport as the channel adjusts to the new sediment regime.

In this paper we focus on one of the key engineering issues associated with the cofferdam breach: whether and where to notch the cofferdam to direct initial incision and knickpoint retreat. This question arose due to two potential outcomes of the breaching. First, that the upstream-migrating knickpoint might stall, creating a barrier to fish passage that would require an active intervention by the dam's owner to mitigate. Second, that the sediment stored behind the dam be eroded and transported quickly, thereby reducing the size and volume of potentially unstable remnant terraces. Consequently, a scaled physical model of the Marmot cofferdam and adjacent reaches of the Sandy River was constructed. A series of experiments were carried out with this model to investigate implications of alternative notch locations and flow conditions that might optimize post-breach reservoir erosion and rate of knickpoint retreat. In this paper we describe the results of these experiments and the associated predictions and recommendations that were made for the ensuing dam removal. We then qualitatively compare these predictions with the dynamics that accompanied the actual breach. From this we identify the strengths and limitations of the physical model and suggest implications for future dam removals.

Marmot Dam and its geographic setting

The Sandy River drains 1300 km^2 of the southwest flank of Mount Hood and the western Cascade Range in northwest Oregon, before joining the Columbia River 20 km east of Portland. The river has a gravel-cobble bed with abundant sand, and flows through alternating narrow bedrock gorges and wider alluvial sections. High natural rates of bedload transport, largely sand, are due to late Quaternary glaciation and volcanism producing abundant sediment in the river's Mount Hood headwaters.

Marmot Dam was originally completed in 1913 as a rock and timber crib structure, and replaced by a concrete dam in 1989. Located 45 km upstream from the Sandy River confluence with the Columbia River, the 14.3-m-high and 50-m-wide diversion dam impounded a pool nearly 2 km long that was completely filled with 750,000 m^3 of sand and gravel. The dam was owned and operated by Portland General Electric (PGE) as part of their Bull Run Hydropower Project. With an expiring Federal Energy Regulatory Commission (FERC) license and facing substantial fish-passage upgrades and future maintenance costs, PGE opted to surrender its license and remove Marmot Dam and associated facilities.

Physical Model Construction

The physical model of the Sandy River and Marmot Dam was constructed at the National Center for Earth Surface Dynamics (NCED), which is located at the St. Anthony Falls Laboratory. It is a distorted geometrically scaled model of the real system. The scaling factors for this concrete and wood model were 1:150 in the horizontal and 1:70 in the vertical. The size and shape of the model, flow rates, grain size distributions and time are all scaled based on modeling similarity in Froude and Shields numbers (see Marr et al., 2007, Appendix A).

Topographic data from airborne LIDAR and endpoint surveys was used to shape the model. Locations of twenty-nine cross sections were strategically chosen to capture important geometric characteristics of the river basin. Once converted into model scale, templates of each cross section were placed in the model basin. This form that was then filled with lightweight concrete, sealed and painted to complete the model. Mississippi River water was routed through the model and discharge was carefully monitored. The grain size distribution of model sediment (coarse and fine sand) was determined based on scaling the grain size from core samples taken in the reservoir (Marr et al., 2007). The sediment was introduced into the experiment with mechanical volumetric sediment feeders.

Experimental Methods

Eight dam removal scenarios were modeled during this study (Table 1). For each scenario, the dammed basin was filled by sediment and water supplied at the upstream end of the model. Once filled, the water and sediment flow were turned off and a model cofferdam was constructed using erodible modeling clay (Figure 1a). During cofferdam construction, drain tiles were activated, simulating the dewatering of reservoir deposits. A shallow notch was constructed in the cofferdam crest, at river right, river center, or river left, located 55 ft, 112 ft, 168 ft, (prototype units) at center from river left bank. The dam structure was removed and flow was re-introduced at a constant laboratory discharge representing 70.8 m^3s in the field (or 155.7 m^3s for run #5). Immediately after flow reached the cofferdam, a plug was placed in the bypass canal to block flow and force upstream pool elevations to rise, initiating failure. After cofferdam failure, the knickpoint was allowed to erode and migrate to a position just upstream of topographic profile H, at which point flow was stopped and a mid-

Table 1. Summary of sediment eroded from reservoir for eight dam removal scenarios.

Removal Run #	**Model Discharge**	**Cofferdam Notch Position**	**Reservoir Sediment Eroded**	
			(cm^3)	**(%)**
1	70.8 m^3/s	river right	29699	30.8
2	70.8 m^3/s	river right	29186	34.4
3	70.8 m^3/s	river left	31046	36.5
4	70.8 m^3/s	river left	27662	34.3
5*	155.7 m^3/s	river right	34875	40.2
6	70.8 m^3/s	river center	25574	33.1
7	70.8 m^3/s	river left	31256	38.9
8	70.8 m^3/s	river right	26415	30.9

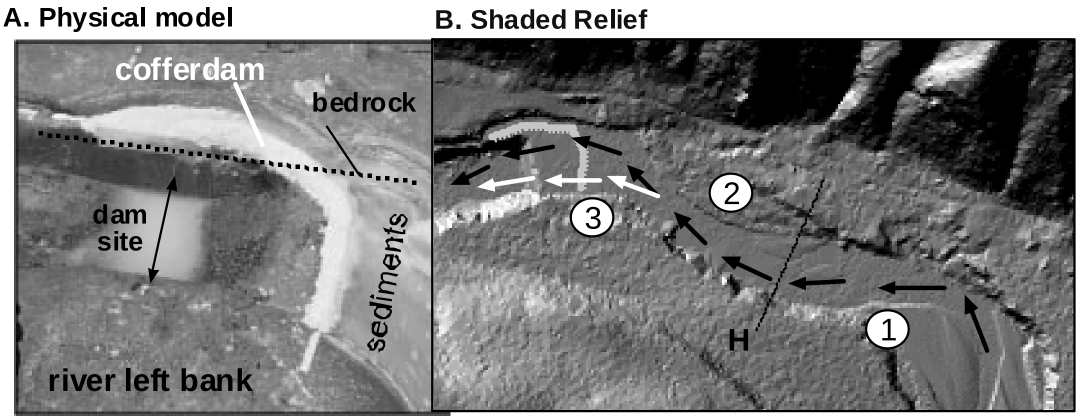

Figure 1. Sandy River at Marmot Dam A. Physical model with dam removed and cofferdam in place, indicating confining bedrock and reservoir sediments. B. Shaded relief map of Sandy River upstream of Marmot Dam annotated with cofferdam (light gray), natural river flow (black arrows), flow with river left notch (white arrows) and location of profile H. Numbers are locations discussed in the text.

removal topographic image was taken for analysis. Flow was immediately brought back to the desired discharge and held constant for an additional 9 hours (prototype equivalent time), at which point another topographic image was taken.

Data collected from several sources were used to analyze characteristics of the dam removal and cofferdam failure. Eight sheet lasers were mounted parallel to each other directly above the model with 120 ft (prototype scale units) spacing and were used to document elevation changes post-removal. Laser topographic images were taken using a high resolution Nikon D70 digital camera mounted at an oblique angle to the dam and upstream river section. Topographic images for each removal scenario were taken before cofferdam failure, after knickpoint migration to a position just upstream of topographic profile H (Figure 1b), and at the end of each removal scenario. Additional digital still images and video (DVR) were also obtained during each run.

DVR videos and timelapse images were used to qualitatively describe cofferdam failure, knickpoint migration, and channel characteristics for each removal scenario. Topographic images taken before cofferdam failure, after knickpoint migration to a position just upstream of topographic profile H (Figure 1b), and at the end of each removal scenario were combined with bedrock valley wall topography to describe erosive patterns and quantify estimates of sediment volumes and percent reservoir sediment eroded during each removal scenario (Table 1).

Model results and observations:

The model simulations suggest that, at a sustained failure discharge of 70.8 m^3/s, the location of cofferdam failure and trajectory of the knickpoint migration through the reservoir sediments depend largely on the position of the notch in the cofferdam. The data also suggest that notch position can also affect erosional patterns and rates. Sediment terraces formed and ultimately abandoned by the down-cutting river are larger and higher for a river right notch location than a river left notch position.

Knickpoint Trajectory

The failure of the cofferdam through a notch focuses flow and sediment scour, and quickly leads to formation of an upstream migrating waterfall or knickpoint. A knickpoint is a steep break in the longitudinal profile and a zone of intense hydraulics (hydraulic jumps and standing waves) and sediment scour, which migrates upstream by eroding sediment. In all runs with a notch, the first knickpoint formed at the notch location. The initial difference in knickpoint trajectory observed between a river right notch and river left notch position, had distinct implications for resulting erosion of stored sediments.

This appears to be due to the unique river valley (bedrock) alignment immediately upstream of the Marmot Dam site (Figure 1a). As the river approaches Marmot Dam it encounters a sinuous bedrock reach (Figure 1b). The river bends left at 1, the right at 2, and then back left just upstream of the dam at 3. According to the bathymetry, the river valley is actually narrower than the current water surface width at the dam. In actuality, the length of the north-south dam crest is the width of the valley and the east-west wing wall crest is the approximate alignment of the northern bedrock river bank that extends to the east from the dam crest and attaches to the bank upstream of the dam. Once failure occurs at this site and river incision begins, we predict that the river will quickly drop back inside this narrow bedrock valley.

The model simulations suggest that the notch position determines where the knickpoint begins, but after it passes into the narrow bedrock reach, it is directed by the sinuous bedrock walls and showed little difference between runs. The model predicts that the post-removal primary flow path of the Sandy River will be along the outside of bends and against the north valley wall, as indicated by the black arrows in Figure 1b. A common characteristic of laterally migrating alluvial rivers is that they often become fixed in position or “hung up” when they impinge on bedrock valley walls. Low resistance and high shear stresses at the valley wall tend to maintain the thalweg, which no longer avulses laterally toward the river center.

In model runs for a river right cofferdam notch, the knickpoint formed near the north bedrock river bank and, because of the unique flow alignment entering this reach, the river stuck against this wall. The effect is a narrower, yet deeper incision, with minimal lateral migration of the flow. The simulations of notches located on river left (Figure 1b, white arrows) force the failure at the south bedrock bank and, because of the location of upstream river bends and tendency for the river to flow along the outside bank, much more lateral migration. This results in a more uniform grade adjustment across the valley width, and more extensive erosion of reservoir deposits.

Abandoned Sediment Terraces

Of primary concern was the volume of abandoned sediment terraces that could result from rapid down cutting through the stored sediment after the collapse of the cofferdam. Once the river stage was lowered due to upstream knickpoint migration and grade adjustments, it was anticipated that it would be difficult for the river to further erode abandoned terraces. Erosion that does occur will likely be in the form of undercutting and could result in unstable cliffs and cause high banks to slough off into the river. Because of this concern, we focused our observations on these terraces and the surrounding valley morphology after each removal scenario.

Analysis of pre- and post-removal topographic profiles provide quantitative estimates of volumes eroded during model studies (Table 1). Volume estimates indicate that a river left notch, on average, eroded larger quantities of reservoir sediments, both in terms of volumes and percent valley fill. A river right or river center notch typically failed to erode large volumes. Due to a higher shear stress resulting from a much larger discharge, the removal scenario simulating 155.7 m^3/s resulted in the highest quantity of sediment removal and redistribution. Only one scenario was simulated with this high discharge, so it was not possible to ascertain which notch position would be most effective in promoting erosion. The high discharge that resulted in erosion and knickpoint retreat across the entire width of the channel, and therefore knickpoint retreat, is likely to be much less sensitive to notch location.

During the experiments, rapid incision occurred as the knickpoint migrated upstream and redistributed reservoir sediments. Occasionally patches of perched sediment and terraces remained at the end of removal scenarios. Topographic profiles showed the possibilities for large abandoned terraces to remain after incision of the river; terraces could range up to several meters high. Projected prototypical abandoned terrace heights ranged from 1 to 4 m following river left notch position scenarios and 3 to 6 m following river right notch position scenarios.

Rate of knickpoint retreat and erosion

Field time can be scaled from model results by considering the units of velocity U as a length, L, over time T, such that:

$$U = \frac{L}{T}$$

Using continuity, $Q=U*L*H$, we can get the following general expression for time:

$$T = \frac{L^2 H}{Q}$$

Writing the above equation for both the prototype and the model we derive the following scaling relationship for time:

$$\frac{T_p}{T_m} = \frac{\alpha_h}{\sqrt{\alpha_v}} = 17.9$$

For the Marmot model the time scale is such that about 1.3 hrs in the model is equivalent to 24 hrs in the field.

In the model runs, knickpoint retreat was extremely rapid and migrated upstream at rates of meters per minute. In all runs the knickpoint had migrated upstream past the first bend within 30 to 60 minutes after cofferdam failure. By the scaling relationship above, this suggested that in the field the knickpoint would migrate that same distance very rapidly – in a day or less.

Summary of Model Results

Notch location affects knickpoint trajectory and migration rate at lower discharges but less so at higher flows. At lower flows, a notch position that is located counter to the natural hydraulic tendency of the river, as defined by valley wall morphology will tend to force the river to migrate laterally, thereby sweeping more sediment out from the reach immediately upstream of the cofferdam, resulting in higher rates of sediment transport and a smaller volume of remaining sediment. Conversely, a notch located on the right or north side of the river will tend to maintain the intrinsic location of the thalweg, reducing lateral migration and resulting in deeper incision and a larger volume of sediment left as remnant terraces. Notch position will not affect the trajectory of knickpoint retreat above the short, narrow bedrock gorge located immediately upstream of the dam. This gorge, in effect, acts as a filter that limits upstream propagation of a preffered notch location. Upstream migration of the knickpoint was predicted to be extremely rapid (hours to days). Based on these findings coupled with the management objective to maximize sediment erosion and knickpoint retreat, the cofferdam was notched on the south side (river left).

Comparison with field results following cofferdam failure:

A comparison of modeling results to initial field observations offers insight into the degree to which physical models can be used to predict geomorphic response and guide future dam removals. Work analyzing these data is on-going, and these results should be considered preliminary.

Observations of cofferdam breaching and failure and initial knickpoint retreat

The cofferdam notch was initiated on October 19, 2007 around 5:00 pm by scraping cofferdam crest on river left approximately 9 m from left bank using forklift tongs. Water spilled over crest of dam shortly after 5:00 pm, but the initial channel was only 2-3 m wide and less than 1 m deep. By this time, major seepage areas had opened up across the dam face and were causing small debris flows that deposited small debris fans at the base of the dam. The initial notched channel did not appear to carry much sediment and was quite small, so the forklift operator continued to work to enlarge and deepen the channel. By 5:15 pm, the volume of flow in the notch channel had increased noticeably, and the channel began to incise up the face of the dam, with rapidly increasing volume and incision of several meters. By 5:20 pm, the notch was 3-4 m wide and 1-2 m deep; no knickpoint was observed at the dam crest. Within several minutes, flow became increasingly violent, with large steps (2-3 m) and hydraulic jumps forming along the channel down the dam face; these migrated upstream at rates of meters per minute. Bank material began to calve off, and areas of the dam appeared to be liquefying as they sloughed into the channel. By 5:45 pm a knickpoint had formed at the notch location, and migrated approximately 2-3 m upstream of the cofferdam crest; this knickpoint immediately separated into two arcuate knicks, with the arch pointing upstream (Figure 2).

This double knickpoint began migrating upstream very rapidly (meters per minute), with river right knick moving laterally towards north shore, and the river left (RL) knick moving longitudinally upstream. The lateral knick quickly stalled because the longitudinal knick incised more rapidly, thereby starving the lateral knick of flow. As the longitudinal knick moved upstream, it established a straight thalweg along the south bank. Darkness fell at around 6:30 pm, limiting further observations. By the following morning (approximately 10 am), the entire cofferdam had been eroded, as had much of the sediment in first 0.5 km above the dam. The knickpoint had eroded backward to a location over 400 meters above the former dam site (Figure 3). The rate of retreat was extremely rapid, averaging 3 meters per min of retreat during the first hour following knickpoint formation.

Figure 2. Knickpoint migration after cofferdam notch. The lateral (river right) and longitudinal (river left) arcuate knickpoints have migrated several meters from the cofferdam notch (located just out of the picture on the left). *photo credit: J. Rose Wallick*

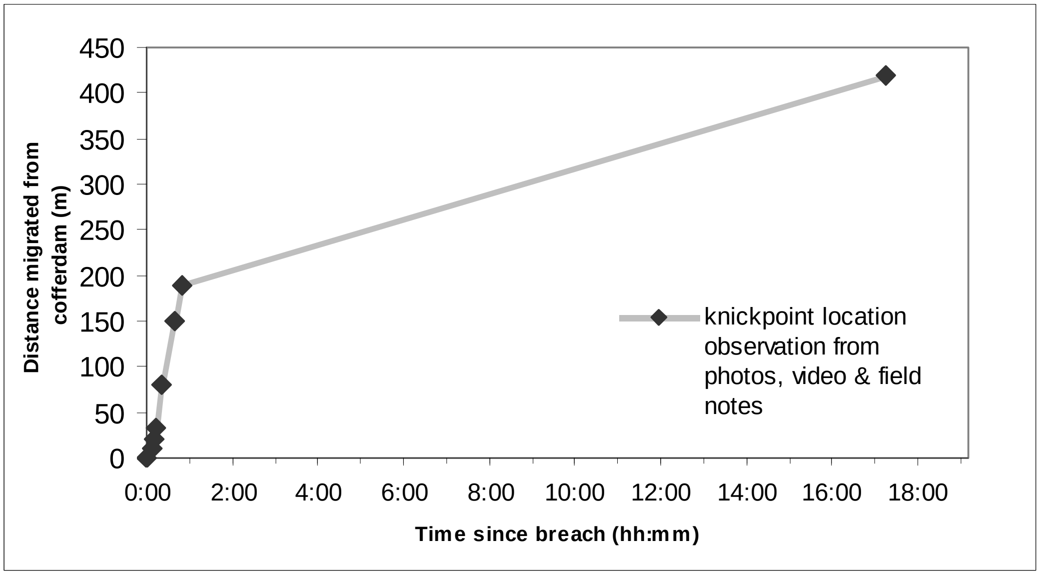

Figure 3. Preliminary observations of knickpoint migration upstream of cofferdam on October 19 and 20, 2007.

Comparison of modeled and field results

The cofferdam breaching was a natural experiment with no replication; hence we can only describe the one instantiation that occurred and can only speculate on how other scenarios may have played out. The observations do strongly support some of the model results while other predictions are weakly supported or not supported at all. The model predicted a very rapid knickpoint retreat and erosion of sediment. Despite this, all observers were surprised at how rapidly and effectively the river eroded the dam and a substantial quantity of stored sediment. Accurate measurements of the fraction of sediment eroded in the first hours following breaching must await further analysis, but we estimate that at least 10-15% of the stored sediment was eroded in the first 24-48 hours. The rate of knickpoint retreat in the field closely matched the predicted rate from the flume experiments.

The location of the knickpoint in relation to the notch location was more problematic. Despite the prediction that locating the notch on river left would force the river to erode laterally to the right, the knickpoint migrated rapidly up the left (south bank). The initial development of two competing knickpoints, including one that did move laterally to the right (Figure 2), however, suggests that the model was not entirely wrong. Instead, what we observed was that most of the river's flow was essentially captured by incision accompanying development of the left knickpoint, and that this effectively starved the right knickpoint of flow. This dynamic interaction between competing knickpoints was not captured in the model, perhaps because erosion was proceeding too rapidly. A finer grain size that better reflected the silty topset of the reservoir beds, may have allowed this interaction to occur.

In spite of this, the knickpoint trajectory upstream of the narrow bedrock gorge precisely followed the path indicated by the experiments. This suggests that overarching valley wall controls on channel hydraulics and location may trump the position of notches where the initial downcutting is localized. As it turned out, erosion of reservoir sediments was so vigorous and rapid that the difference between a left and right notch location was probably insignificant. The Sandy River was so efficient at attacking and removing stored sediment that little sediment remained in the immediate upstream vicinity of the dam. Again, imperfect scaling of grain sizes of the modeled stored sediment in relation to flow competence may have been a factor, particularly in terms of rates of bank and lateral erosion.

Conclusions

The removal of Marmot Dam offered a unique opportunity to measure and record geomorphic processes that are rarely observed in nature. We anticipate that the datasets gathered will represent a treasure trove of information useful for both understanding fundamental fluvial processes and guiding future dam removals. The preliminary results presented here provide the basis for evaluating the efficacy of physical models for predicting uncertain outcomes in dam removals. On balance, the physical experiments provided solid predictions of rates of erosion and overall knickpoint trajectory. Some details were missed, but these were insignificant in the greater scheme of things. Future analyses will sharpen our understanding of the extent to which predictions from physical models can be trusted in the complex and dynamic fluvial environment accompanying dam removals. We believe, however, that results presented here highlight the promise of these models, particularly when used in conjunction with a well orchestrated pre-removal field program.

Acknowledgements

This work was supported by the STC program of the National Science Foundation via the National Center for Earth-surface Dynamics under the agreement Number EAR-0120914, and by Portland General Electric, U.S.D.A. Forest Service, U.S. Geological Survey, Oregon State University and St. Anthony Falls Laboratory, Institute of Technology, University of Minnesota.

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