NUMERICAL SIMULATION OF FLOW IN INCISED AND COMPOUND CHANNELS FOR EVALUATION OF RIVER RESTORATION DESIGN

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Abstract

Compound channels are often constructed in restoration projects on rivers and streams that have been channelized or are deeply incised. This design allows for flow over a wider cross-sectional area during high flows and is expected to reduce both flow velocities and bed shear stresses in the channel during high flows. Compound channels provide environmental benefits, by providing better habitat for fish and other wildlife at low flows, and restoring the function of the floodplain for storage and conveyance during high flows. A compound channel design was used on a restoration project on Tassajara Creek in Dublin, CA.

Our study evaluates the effectiveness of a constructed compound channel in reducing channel velocities and bed shear stresses during high flow events using both the one-dimensional model, HEC-RAS (U.S. Army Corps of Engineers, 2002) and the three-dimensional numerical model, UnTRIM (Casulli and Zanolli, 2002). Although compound channel designs for channel restoration projects are often based on one-dimensional models, our results demonstrate the advantages of using a three-dimensional model and make a strong case for the implementation of more detailed hydrodynamic modeling in evaluating the suitability of restoration alternatives to improve the planning and design of river restoration projects.

Introduction

Incised channels are characterized by a lowering of the stream bed due to an increase in erosion, such that the stream is no longer hydraulically connected to its previous floodplain (Fischenich and Morrow, 2000). Channel incision can result from steepening of the stream gradient through channelization, increased flood peaks, decreased sediment load, or from decreased erosional resistance. Compound channels, which are often constructed in restoration projects on streams that are deeply incised, incorporate a constructed floodplain within the incised channel margin and thereby reconnect the channel to a new floodplain. This design allows for flow over a wider cross-sectional area during high flows and is supposed to reduce flow velocities and bed shear stresses in the channel during high flow events. This approach was used on a stream restoration project on Tassajara Creek, located in Alameda County, CA.

Rivers are typically modeled using one-dimensional numerical models, e.g., HEC-RAS. To assess the effectiveness of the HEC-RAS model for restoration design, HEC-RAS was applied to the Tassajara Creek restoration project, implemented by Alameda County to restore about one mile of the channel upstream from Interstate-580. The restoration plan included the construction of a two-stage compound channel, restoring meanders to some reaches, and extensive re-vegetation of the constructed floodplain (S. Cook, Alameda County, personal communication, 1999). The ultimate project goals were channel stabilization to reduce further incision, improved flood control, and improved community access. Figure 1 shows a typical cross-section of the incised condition with the same

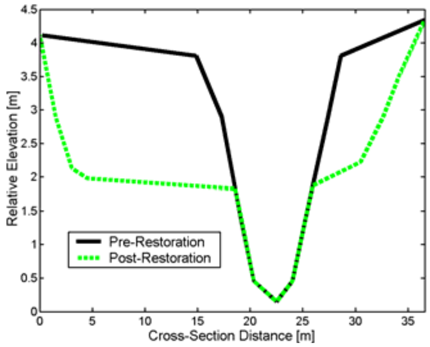

Figure 1. Pre-restoration and post-restoration cross-section geometry used in HEC-RAS and UnTRIM.

Figure 2. Pre-restoration incised channel (left) and post-restoration compound channel (right) in Tassajara Creek restoration project reach.

section after the banks were cutback to create a compound channel. The objective of this approach is to create a two-stage compound channel in which a low flow is contained within the main channel, and larger flows are spread onto the reconstructed floodplain.

Based on the Tassajara Creek project, we evaluated two major issues that are essential to the success of river restoration projects. First, the effectiveness of the compound channel design was evaluated in terms of its ability to reduce flow velocities and bed shear stresses in the channel under high flow conditions using HEC-RAS. Second, the ability of the one-dimensional model to quantify flow and shear stress modifications was assessed by comparing the HEC-RAS results to those of a three-dimensional hydrodynamic model, UnTRIM, for an idealized channel configuration.

Methods

Surveyed Channel

Figure 2 shows the incised pre-restoration condition in the upper reach and the post-restoration condition on the lower reach of the Tassajara Creek restoration project. Brian Kangas Foulk (BKF) developed the restoration design and their HEC-RAS models were obtained through the authorization of Alameda County. A survey was conducted on the upper reach following project construction (MacWilliams and Harrison, 1999).

HEC-RAS was used to model three different channel configurations: pre-restoration, restoration design, and post-restoration. The pre-restoration model is based on the pre-restoration survey and HEC-RAS model developed by BKF. In the pre-restoration model, the stream was deeply incised and the majority of the cross-sections were not subdivided into channel and overbank areas; however, at a small number of cross-sections, the channel was still connected to the floodplain for the 100-year flow event. We subdivided the cross-sections in the pre-restoration model to account for the natural floodplain that still existed for extremely high flows by adding bank stations at the edge of the channel for the cross-sections in the study reach. This modification did not noticeably change the overall flow profile, but provided a more accurate comparison between channel parameters in the pre-restoration and post-restoration models for the 100-year flow.

The restoration design HEC-RAS model used is essentially identical to the restoration design model obtained from BKF. The modeled reach in the restoration design extended above and below the restoration project. The post-restoration model was developed for our analysis based on the post-construction survey (MacWilliams and Harrison, 1999). For the post-restoration HEC-RAS model, the water surface elevations for the downstream boundary conditions were obtained from a coinciding cross-section the restoration design model which extended further downstream to ensure similar flow characteristics between the post-restoration and restoration design models. In the restoration design and post-restoration HEC-RAS models, each cross-section was subdivided into a main channel, a left overbank, and a right overbank. The channel roughness was specified using Manning's *n*. Channel roughness was estimated by BKF to be 0.03 for the pre-restoration channel and 0.04 for the restoration design channel. In the restoration design model, a value of 0.06 was applied to the overbank areas to account for the effects of vegetation which will be established on the floodplain. The same roughness values used in the restoration design model were applied in the post-restoration model.

Our analysis focuses only on the flow in the upper reach of the project, even though the pre-restoration and restoration design models evaluated the entire project. Only model results from the cross-sections within the reaches which coincide with the reach surveyed for the post-restoration model were extracted for comparison. For each of the three models, HEC-RAS was used to compute water surface profiles for 2-year, 25-year, and 100-year recurrence-interval flows. The corresponding flow events were estimated by BKF to be 18.4, 58.0, and 121.8 m^3/s, respectively. These flows were selected because they represent the range of potential flows that the reach will experience, and range from frequent return-interval flows to large floods.

Prismatic Channel

Based on the pre-restoration and post-restoration cross-sections shown in Figure 1, straight-prismatic incised and compound channels were developed. The use of straight prismatic channels eliminates any component of flow complexity resulting from channel curvature or irregular topography. On both the incised and compound prismatic channels the 58 m^3/s flow rate, corresponding to a 25-year recurrence interval flow on Tassajara Creek, was simulated using the one-dimensional HEC-RAS, and the three-dimensional UnTRIM model (described in Casulli and Zanolli, 2002, with additional enhancements as described in MacWilliams, 2004).

The modeled channel reach for the prismatic pre-restoration incised and post-restoration compound channels is 61 m long, and both channels were designed to have a uniform slope of 0.003, based on the average slope of the reach from which the cross-sections shown in Figure 1 were selected. The HEC-RAS model consists of 20 cross-sections at 3.05 m intervals. The pre-restoration channel was modeled as a single channel, while the post-restoration case was subdivided into a main channel, right-overbank, and left-overbank. The three-dimensional model grids used a uniform horizontal grid consisting of square grid cells with a side length of 0.61 m. The incised channel grid consists of

3000 horizontal grid cells and had a vertical grid resolution of 0.15 m. The compound channel grid consists of 6000 cells and had a vertical grid resolution of 0.15 m.

In order to facilitate comparison between the models, a uniform flow was simulated on both channels by setting the downstream water surface elevations to be the normal depths. For the one-dimensional model, Manning's n was 0.03 for both the incised and compound channel simulations. For the three-dimensional model, the appropriate bed roughness was determined by calibrating the water surface in each of the channels to match the water surface slope from the one-dimensional model. Additionally the advective acceleration terms were removed from the three-dimensional equations to eliminate any artificial numerical dissipation from the three-dimensional simulations. This ensured that identical flows were being compared between the one-dimensional and three-dimensional simulations and that the total energy losses due to bed friction for both the one-dimensional and three-dimensional simulations would be nearly identical.

Results

Surveyed Channel

The mean cross-sectional average values of channel velocity and channel shear stress for the upper reach of the project predicted using HEC-RAS are given in Table 1. The restoration design HEC-RAS model and post-restoration HEC-RAS model predict lower mean channel velocities than the pre-restoration HEC-RAS model for all three the flow rates. In general the results from the restoration design model produced similar results to the model based on the post-restoration channel survey. The predicted mean channel bed shear stress in the restoration design and post-restoration simulations is greater than the predicted mean channel shear stress in the pre-restoration incised channel for all three flow rates (Table 1). Thus, while HEC-RAS predicted a decrease in mean channel velocity from project construction, the HEC-RAS models exhibit an increase in bed shear stress resulting from project construction relative to the pre-restoration condition.

Channel Configuration	*Flow Rate (m^3/s)*	*Mean Channel Velocity (m/s)*	*Mean Channel Shear Stress (N/m^2)*
Pre-Restoration	18.4	2.17	49.8
	58.0	2.92	76.1
	121.8	3.40	84.7
Restoration Design	18.4	1.80	61.8
	58.0	2.55	96.2
	121.8	3.26	135.5
Post-Restoration	18.4	1.62	50.3
	58.0	2.39	85.2
	121.8	3.22	136.0

Table 1. Summary of HEC-RAS results for design flows on upper reach of Tassajara Creek restoration project.

Channel Configuration	*Model*	*Mean Velocity (m/s)*			*Mean Bed Shear Stress (N/m²)*		
		Channel	*Left Overbank*	*Right Overbank*	*Channel*	*Left Overbank*	*Right Overbank*
Pre-Restoration	HEC-RAS	2.53	-	-	47.9		
	UnTRIM	2.44	-	-	56.0		
Post-Restoration	HEC-RAS	2.61	1.46	1.18	50.3	21.1	15.3
	UnTRIM	2.67	1.37	1.14	52.7	19.2	13.4

Table 2. Summary of predicted mean velocity and mean bed shear stress from HEC-RAS and UnTRIM simulations of pre-restoration and post-restoration prismatic channel.

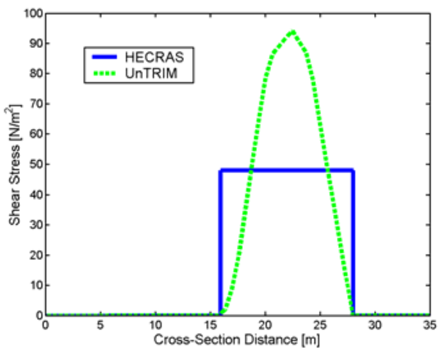

Figure 3. Predicted bed shear stress for pre-restoration channel from HEC-RAS and UnTRIM.

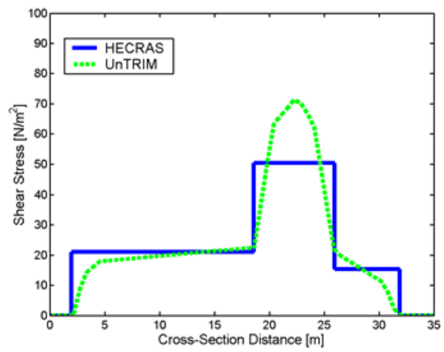

Figure 4. Predicted bed shear stress for post-restoration channel from HEC-RAS and UnTRIM.

Prismatic Channel

Average downstream velocities and bed shear stress computed on the prismatic channels using UnTRIM and HEC-RAS are compared in Table 2. For the pre-restoration channel, the average channel velocity predicted using HEC-RAS differs from the average downstream velocity computed by UnTRIM by less than 4 percent. For the post-restoration channel, the difference is approximately 2.6 percent. The average values of the left and right overbank velocities differ by 6.2 percent and 3.4 percent, respectively. The discrepancy between the models in predicting the channel and overbank velocities is the result of a different routing of the flow through the channel and floodplain in the two models. UnTRIM predicts slightly more flow in the main channel and slightly less flow in the overbank areas.

The predicted bed shear stresses for the pre-restoration incised channel simulations are shown in Figure 3. For the HEC-RAS simulation, a single average value of the bed shear stress is predicted for the entire channel. In the UnTRIM simulation, the bed shear stress is calculated for each horizontal grid cell using the near-bed velocities. The predicted bed shear stresses for the post-restoration compound channel simulations are shown in Figure 4. For the HEC-RAS simulation, separate values of the bed shear stress are predicted for the channel and overbank areas based on the channel subdivisions specified in the model. In the UnTRIM simulation, no separate channel subdivisions are made. The mean bed shear stress values for UnTRIM were obtained by averaging the shear stresses over the same regions that are used to subdivide the channel in HEC-RAS. As seen in Table 2, HEC-RAS predicts a 5% increase in mean channel shear stress in the compound channel relative to the incised channel, while UnTRIM predicts a 7% reduction in mean shear stress and a 24% reduction in maximum shear stress.

Discussion

The results from HEC-RAS model shown in Table 1 indicate that the compound channel design was successful in reducing mean channel velocity, while it was not successful at reducing the mean channel shear stress for any of the modeled flow rates. This result is contrary to the design assumptions, namely, that the construction of a compound channel will lead to lower channel shear stresses during high flows. An analysis of the method used in HEC-RAS to calculate the channel and overbank shear stresses in subdivided channels suggests that the increase in channel shear stress in the compound channel relative to the incised channel may result from the method used rather than a shortcoming in the restoration design (for details, see MacWilliams, 2004). Based on this analysis, the prediction of increased channel shear stress in the compound channel is not accurate.

The results shown in Table 1 are based on surveyed pre-restoration and post-restoration conditions. These results include effects due to channel curvature or changes in cross-section shape between sections. By modeling a straight prismatic channel using both HEC-RAS and UnTRIM, we removed any of these potential effects and thus provided a best-case scenario for modeling compound channel flow using a one-dimensional model.

The average shear stress results shown in Table 2 for the prismatic incised and compound channels show a similar trend to the results from HEC-RAS for the actual project topography. On the prismatic channels, HEC-RAS also predicted a slight increase in mean channel shear stress in the compound channel relative to the incised channel. In contrast, the UnTRIM mean shear stresses show a decrease in mean channel shear stress in the compound channel relative to the incised channel. However, in the evaluation of channel stability, the maximum shear stress is a much better indicator of the potential for erosion than the mean shear stress. In UnTRIM, the bed shear stress is calculated at each flux face in the domain from the near-bed velocity by using a log-law drag coefficient formulation (MacWilliams, 2004). Accordingly, a distribution of shear stress across the cross-section can be obtained, yielding a more accurate estimate of the actual bed shear stress than either one-dimensional or two-dimensional depth-averaged models.

The UnTRIM results in Figures 3 and 4 show that there is significant variability in the bed shear stress across the channel that can not be captured by a one-dimensional model such as HEC-RAS. This variability occurs even in a straight prismatic channel; the variability would be even more pronounced if there were significant bends or variations in geometry within the reach modeled. In the pre-restoration channel, the maximum bed shear stress in the channel predicted by UnTRIM exceeds the mean value predicted by HEC-RAS by 97%. In the post-restoration channel, the maximum bed shear stress in the channel predicted by UnTRIM exceeds the mean value predicted by HEC-RAS by 42%. Because sediment transport is a nonlinear function of bed sear stress, these large differences between the maximum and mean shear stress have significant implications on the potential for erosion and on channel stability. In contrast to the HEC-RAS results which show an increase in mean shear stress in the compound channel, the results from the UnTRIM simulations show a 24% reduction in maximum shear stress in the compound channel relative to the incised channel; these results are much more useful in predicting future channel stability than estimates of mean shear stress.

Conclusions

Many restoration projects have failed because of channel instability or attempts to create habitat features which were not compatible with the prevailing channel form. Accurate calculation of the maximum bed shear stress and the shear stress distribution in the channel is essential to obtain a reliable estimation of channel stability. As seen in the above analysis, the estimates of mean channel shear stress from HEC-RAS show an increase in mean channel shear stress in the compound channel relative to the incised channel, while the UnTRIM results show a significant decrease in maximum shear stress. The results from UnTRIM demonstrate the capacity of three-dimensional modeling to assess changes in flow velocity and bed shear stress resulting from the construction of complex cross-section designs. The shear stresses and velocities predicted in the UnTRIM simulations indicate that the design and construction of the Tassajara Creek restoration project was successful at reducing the maximum bed shear stresses in the channel. These results indicate that more detailed modeling may be warranted in the assessment of channel restoration designs.

Acknowledgments

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References

Casulli, V., and P. Zanolli (2002), “Semi-implicit numerical modeling of non-hydrostatic free-surface flows for environmental problems,” *Mathematical and Computer Modeling*, 36, 1131-1149.

Fischenich, C. and J. V. Morrow, Jr. (2000), “Reconnection of Floodplains with Incised Channels,” U.S. Army Corps of Eng. Ecosystem Management and Restoration Program, Technical Note EMRRP SR-09.

Mac Williams, M. L., and D. T. Harrison (1999), “The Role of Numerical Modeling in River Restoration: An Analysis of 1-D and 3-D Flow Modeling on Tassajara Creek, CA,” G. Mathias Kondolf LA227 Term Projects Collection, MS 96/2, Water Resources Center Archives, University of California, Berkeley.

MacWilliams, M. L. (2004), “Three-dimensional Hydrodynamic Simulation of River Channels and Floodplains,” Ph.D. Dissertation, Stanford University, 222 p.

U.S. Army Corps of Engineers (2002), “HEC-RAS River Analysis System Hydraulic Reference Manual Version, 3.1,” The Hydrologic Engineering Center, Davis, CA.