Integration of Soil Bioengineering into an Erosion and Flood Protection Design on the Urbanized Sacramento River in the City of Sacramento

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Abstract

Traditional engineering approaches to assess horizontal and vertical extents of an erosion and flood protection project would normally require continuous bank protection up to the water surface elevation of the design flow. Such elevation of hard protection, mostly not inundated year round, creates permanent environmental impacts. Besides, such design does not provide aesthetic values, especially in urbanized areas such as in the Sacramento City.

With an effort to restore and sustain river environments within a bank erosion and flood protection design on the Sacramento River, a robust analysis methodology was developed to transform a design with 100% hard protection exposed almost year round to a design not only with a minimum invisible footprint of hard protection but also with the creation of a valuable riverine environment. The long term ecological uplift of the design benefits the riparian habitat for the endangered yellow billed cuckoo, the spawning and nursery habitat and shaded riverine areas for salmonids and green sturgeon, and protection and food sources for these endangered aquatic species throughout their life cycles.

This paper presents a rigorous process of deterministic, qualitative, and statistical analyses to justify the reduction of the height of the hard protection and replace it with soil bioengineering (planting of native vegetation in encapsulated soil lifts) for ecological uplift and reduction in environmental impacts. It is expected that the softening of the design still effectively provides protection against fluvial and boat wake erosion without compromising the life safety aspect of the flood protection project.

Introduction

Background

Sacramento River and the associated levee system has experienced fluvial erosion and, boat wake and wind wave induced erosion. Waves created by boat wakes cause erosion of the river bank and toe, which varies with the season. Some limitations of traditional methods of erosion assessment are that it primarily addresses fluvial erosion caused by flow depths and velocities associated with river flows, not boat wakes in particular. By supplementing a Bank Stability and Toe Erosion Model (BSTEM) with traditional erosion assessment, a robust analysis methodology was developed to estimate the components of the driving energy from fluvial and boat wakes. The partition of the components of the total driving energy allowed the design to consider a soil bioengineering alternative design on the bankline above the annual low water surface elevation with a toe rock protection below to provide protection from boat wake and fluvial erosion. The design evaluated the resisting parameters (shear strength and cohesion) of the design materials used in the proposed soil bioengineering versus the driving energy from fluvial and boat wakes. The analysis also informed potential Operations and Maintenance (O&M) requirements during the early stage of the soil bioengineering alternative.

Analysis

Scenarios Considered

A matrix of the simulation scenarios is summarized hereafter (Table 1) to represent present and future conditions of the project site.

Table 1. Inventory of BSTEM simulations

Hydraulic Inputs	Geometry input	Deterministic Simulation	Stochastic Simulation
Historical Flow (2008-2018)	2008/2018 geometry (no erosion noted in surveys)	BSTEM with no boat wave	Not performed
Synthetic Average Summer Flow	2018 existing geometry	BSTEM with boat wave	Not performed
	After construction design geometry, no toe scour	BSTEM with boat wave	BSTEM with boat wave
	5 years after construction, no toe scour	BSTEM with boat wave	BSTEM with boat wave
Synthetic High Summer Flow	2018 existing geometry	BSTEM with boat wave	Not performed
	After construction design geometry, no toe scour	BSTEM with boat wave	BSTEM with boat wave
	5 years after construction, no toe scour	BSTEM with boat wave	BSTEM with boat wave
April Runoff	2018 existing geometry	BSTEM with boat wave	Not performed
	After construction design geometry, no toe scour	BSTEM with boat wave	BSTEM with boat wave
	5 years after construction, no toe scour	BSTEM with boat wave	BSTEM with boat wave
1/325 AEP Design Flow	2018 existing geometry	Not performed	Not performed
	After construction design geometry with 15-ft deep max toe scour	BSTEM with no boat wave	BSTEM with no boat wave
	5 years after construction with 15-ft deep max toe scour	BSTEM with no boat wave	BSTEM with no boat wave

There are five flow series to represent past and future design flow regimes. They are:

1. 2008 to 2018 daily flow at Sacramento River at Freeport Gage (USGS 11447650) to validate that there was no erosion captured between the two surveys (cbec, 2019)

2. Synthetic average summer flow at Sacramento River at Freeport Gage (16k cfs to 17 k cfs, 50% percentile of daily mean values from post 1968, after the construction of Oroville Dam)
3. Synthetic high summer flow at Sacramento River at Freeport Gage (30k cfs to 33k cfs, 90% percentile of daily mean values from post 1968, after the construction Oroville Dam)
4. April runoff (storm with peak flow magnitude of 78k cfs, almost as high as a ½ Annual Exceedance Probably (AEP), 80k cfs). The ½ AEP flow event is frequently referred by natural resources agencies as a significant environmental indicator to evaluate the riverine ecosystem.
5. Design flow of 1/325 AEP (115k cfs)

Three different scenarios were considered for the bank geometry inputs: existing condition (1), soil bioengineering (above low annual water surface) with toe riprap protection design condition (2), and soil bioengineering with toe riprap protection and 15-ft scour depth condition (3). The soil bioengineering is a design configuration of encapsulated soil lifts and planted native riverine vegetation.

In scenario (2) of the design condition, there are two points in time marking the significant stages of vegetation growth. They are the stages of immediately after construction and five years after construction when vegetation would develop to a medium height for the design vegetation. The stages of vegetation growth would change the hydraulic roughness and effectiveness of the applied shear stresses to the cross section. In scenario (3) of the design condition, the launchable material in the toe rock is mobilized to cover the slope of the scour hole with a layer of riprap with a minimum thickness of 1*D100 (20-inch) (USACE, 2022c).

The models from this analysis also evaluated shear stresses generated from boat wave (with the wave module of BSTEM) when recreational boat traffic is anticipated. The highest recreational boat traffic is during the summer months (DBW, 2002). There is less boat traffic in the colder months (DBW, 2002). For the design flow of 1/325 AEP event, it was assumed that there would be no boat traffic as boaters would take extreme caution during periods with dangerously high river stages, and therefore, the wave module was not utilized for the design flow. Statistical distributions of the design materials internal strengths were simulated with BSTEM stochastic module for the design condition to describe the possible range of behaviors of the design.

The BTEM results from the simulations summarized in the simulation inventory table (Table 1) informed if a structural based (toe rock) soil bioengineering alternative design could protect the bankline above the annual low water surface elevation from boat wave and fluvial erosion during summer, winter, and design flow events.

BSTEM Results and Discussions

Typical analysis results are presented with a standard deterministic BSTEM plot (Figure 1) from one simulation. Tabular results associated with the standard deterministic plot, such as fluvial and flow shear stresses, are also available. The tabular deterministic results and the critical strengths of the design materials are subsequently arranged to provide additional perspectives (Figure 2) in the evaluation of the strengths of the design materials. And lastly, a standard stochastic BSTEM plot (Figure 3) shows a range of responses of the design from the statistically distributed ranges of the design materials.

No lateral erosion was estimated for all deterministic simulations. The low summer and high summer flows mostly did not result in lateral erosion in the stochastic simulations. Lateral erosion was estimated for all stochastic simulations for the April runoff and design flows. With the limited space for the proceedings papers, selective results and plots of the design conditions from the higher flow regimes are presented and discussed only.

Existing Condition

Traditionally, design calibration of design parameters (shear, cohesion, roughness, etc.) would occur if topographic changes were identified. There are two bathymetric surveys of the site, 2008 and 2018, however, topographic changes along the project site were not detected (cbec, 2019). Therefore, the design process could only validate that historical flows between the two surveys did not result in detectable topographic changes. During validation, adjustments of the design parameters were still performed by lowering the resisting strengths to mirror the static site conditions. By using the lowest possible critical strengths of the materials while still mirroring the static site conditions between 2008 and 2018, the validation process added conservativeness to the selection of the critical strengths that would be used in the hypothetical simulations of future design conditions.

Soil Bioengineering with Toe Riprap Condition with Seasonal Flows, immediately after Construction

At the project site, erosion potential for the soil bioengineering with bank and toe riprap design geometry condition with the seasonal flows are calculated by deterministic and stochastic analyses. The hydraulic model used for the design flow was a 1D HEC-RAS model (USACE, 2022b). Water surface elevations and shear stresses were extracted from the 1D HEC-RAS model for the hydraulic inputs in BSTEM. The soil bioengineering with bank and toe riprap condition BSTEM results for the unsteady seasonal flows, e.g. 16k-17k cfs (average summer flow), 30k-33k cfs (high summer flow), and April Runoff (28k-78k cfs) are presented and discussed below. The energy from boat traffic was also simulated simultaneously with the seasonal flows to represent the two erosion driving forces identified at the project site, fluvial and boat wake.

April Runoff:

At the project site, no lateral erosion in the soil bioengineering layer was estimated during the April runoff (Figure 1). During the April runoff, no erosion potential was calculated based on the deterministic BSTEM result. The critical strength of coir fiber from the soil bioengineering layer (resisting force) helped to prevent lateral erosion from fluvial and boat wake driving forces. The deterministic result matches most of the percentile lines of the stochastic results with a small amount of fluvial erosion at layer 2 for the 99th percentile line. Given the deterministic result for this condition (Figure 1) showing no erosion and the known shear stress used in this stochastic BSTEM model representative of the channel, not the left overbank where the soil bioengineering layer is placed, it would give more conservative BSTEM results. Since there is no erosion potential up to 95th percentile line from the stochastic results (Figure 3) and the critical shear of the fabric above elevation 7 ft is higher than the total shear (Figure 2), the risk for the erosion between elevation 7 feet and 13 feet to occur in the condition is very low. That supports the recommendation to rely on the percentile lines below the 90th percentile line (e.g. 50th and 75th percentile lines) as the likely responses of the design under the April runoff, given the distribution of the design material strengths used in the stochastic simulations.

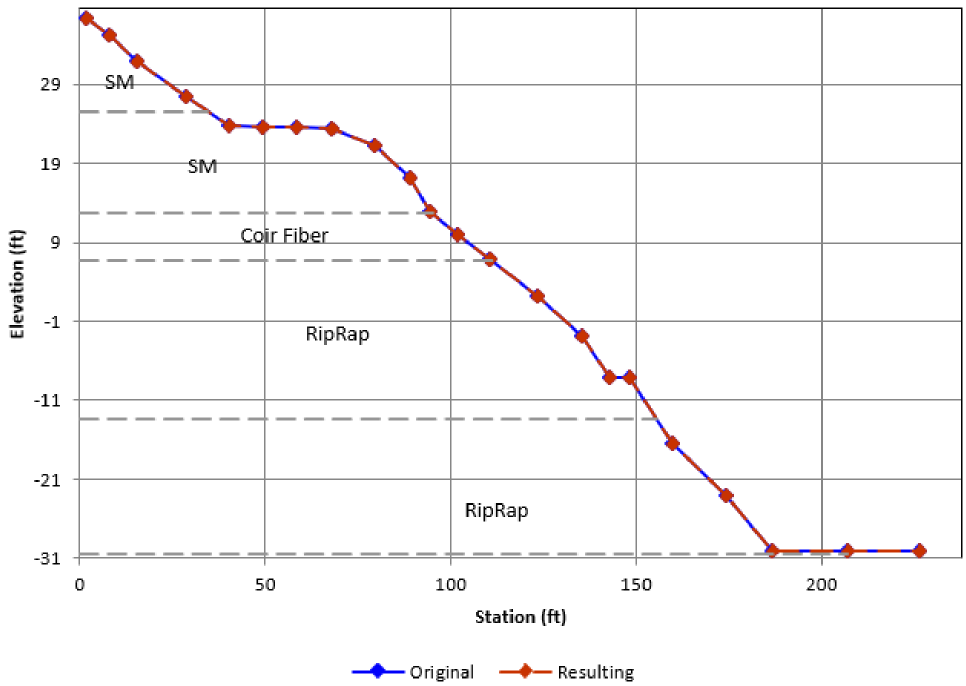

Figure 1. Soil bioengineering with toe riprap condition, unsteady seasonal flow with boat wave, deterministic results during the April Runoff (peak of 78k cfs) for just after construction scenario.

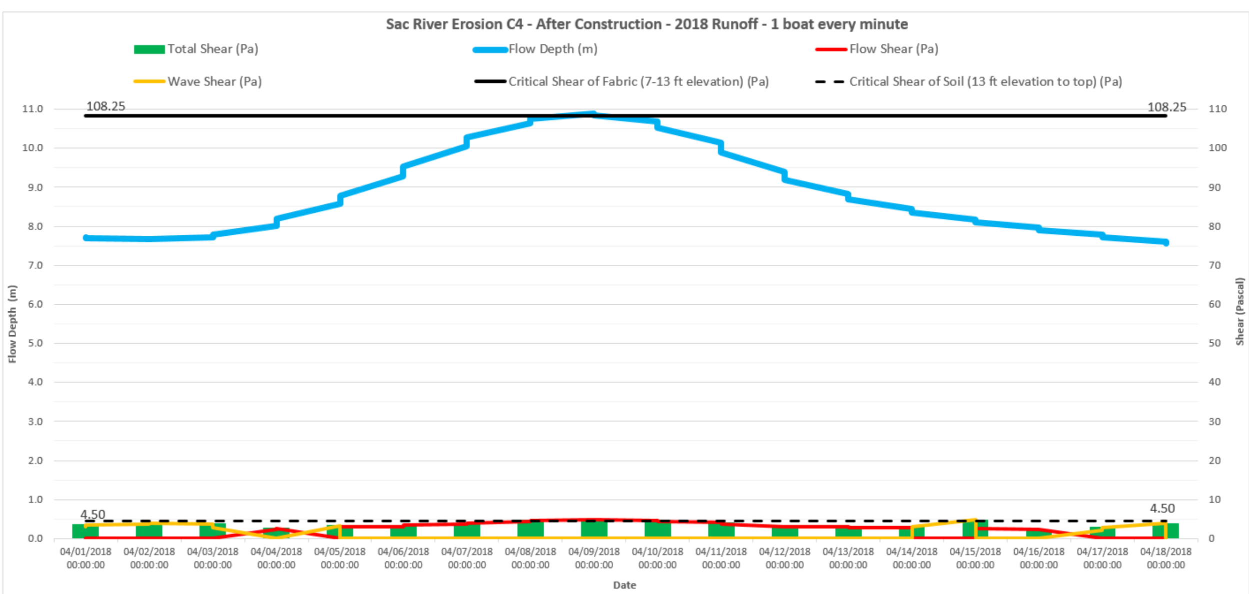

Figure 2. Components of shear stresses during simulation of BSTEM with boat module for April runoff for just after construction scenario

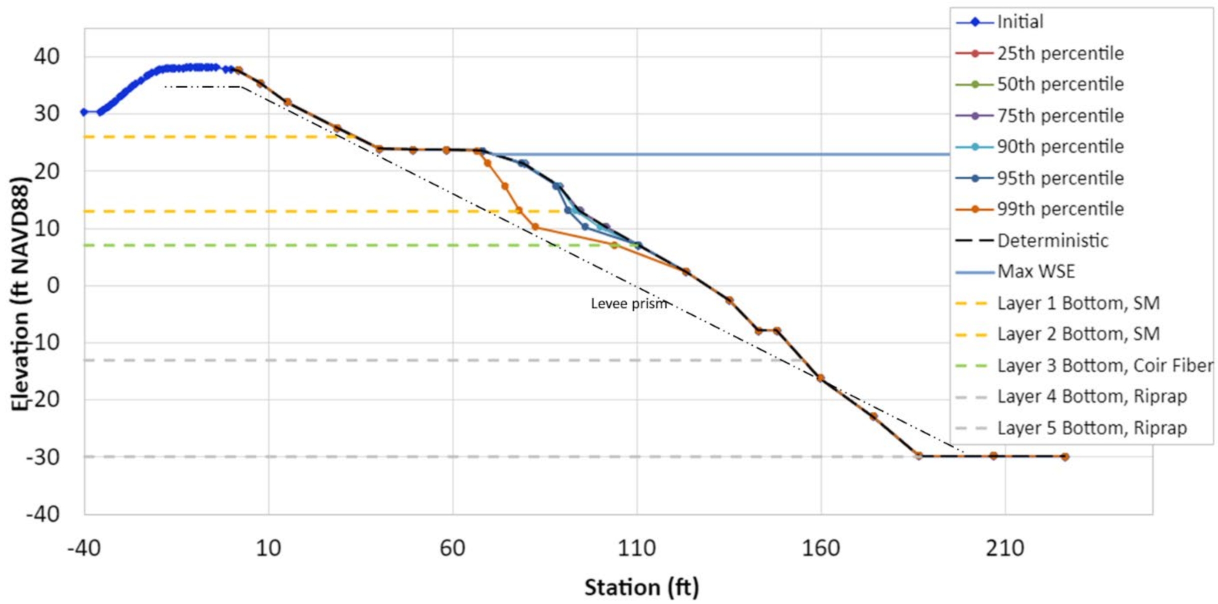

Figure 3. Soil bioengineering with toe riprap condition, unsteady seasonal flow with boat wave, stochastic results during the April runoff (peak of 78k cfs) for just after construction scenario

Soil Bioengineering with Toe Riprap Condition with Seasonal Flows, 5 Years after Construction

April Runoff:

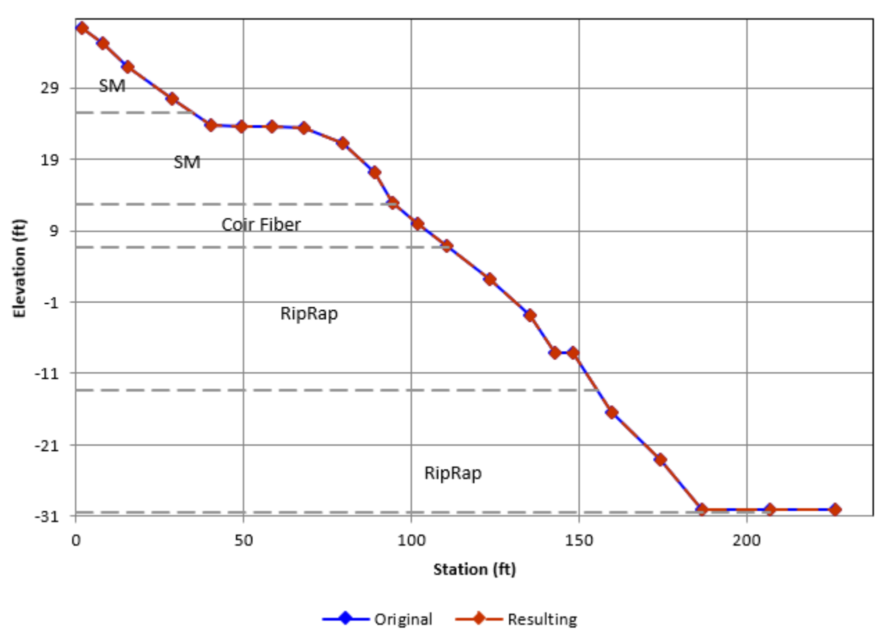

Figure 4. Soil bioengineering with bank and toe riprap condition, unsteady seasonal flow with boat wave, deterministic results during the April Runoff (peak of 78k cfs) for five years after construction scenario

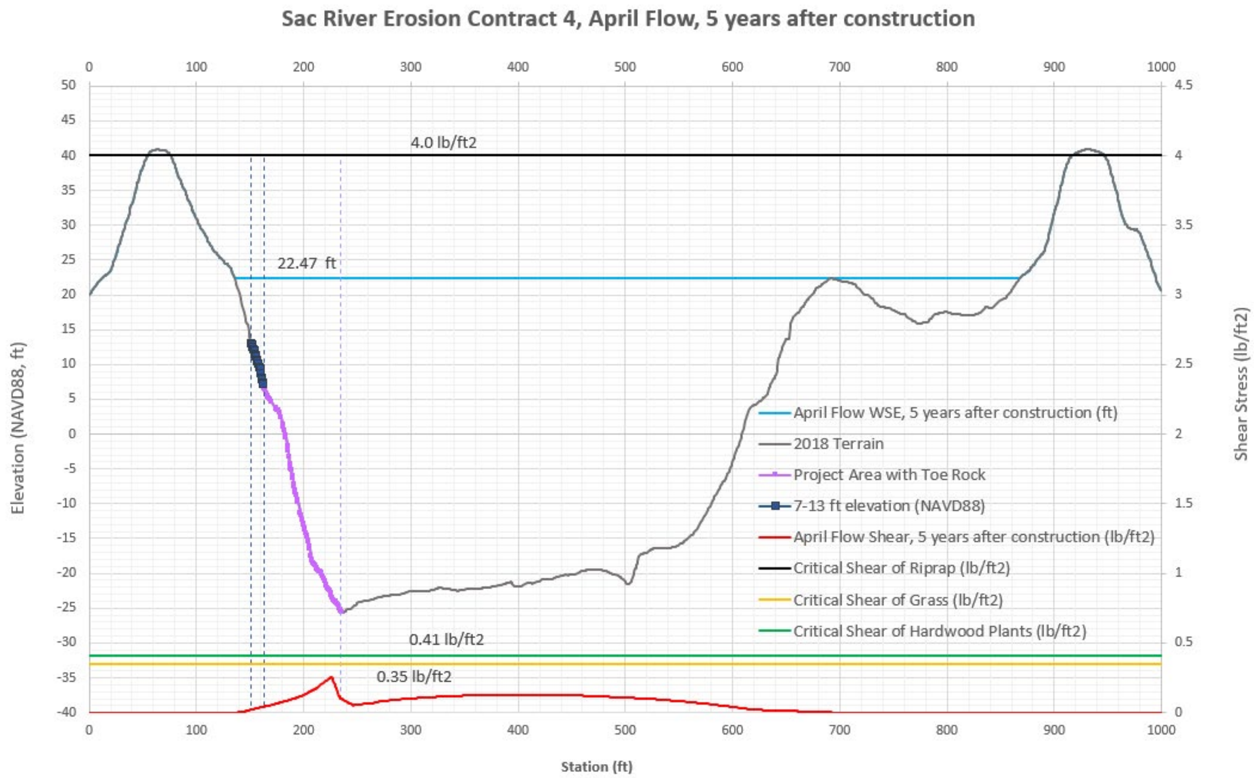

Figure 5. April runoff for five years after construction scenario showing 2D peak hydraulic results

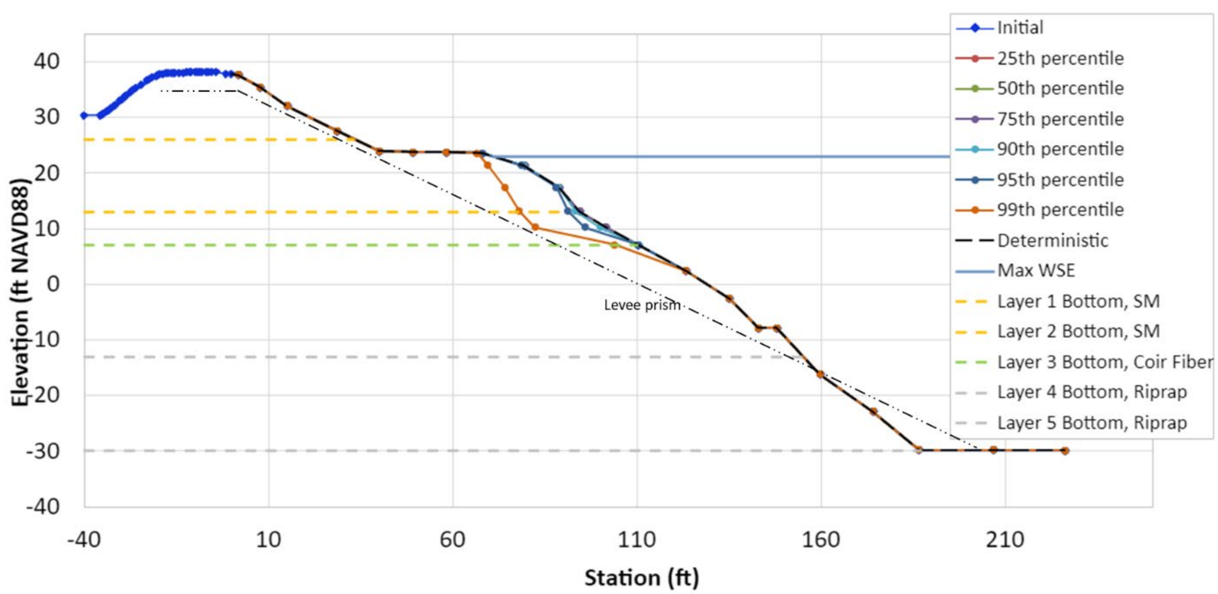

Figure 6. Soil bioengineering with toe riprap condition, unsteady seasonal flow with boat wave, stochastic results during the April runoff (peak of 78k cfs) for five years after construction scenario.

During the April runoff for the five years after construction scenario, no erosion potential was calculated based on the deterministic BSTEM results. The deterministic results matches the all the percentile lines below the 90th percentile line of the stochastic results. Based on the stochastic BSTEM results, there is some fluvial erosion for the 99th percentile line and small amount of fluvial erosion at layer 2 and layer 3 for 95th and 90th percentile lines. Given the deterministic result for this condition showing no lateral erosion and the known shear stress used in this stochastic BSTEM model representative of the channel, not the left over bank where the soil bioengineering layer is located, it would give more conservative BSTEM results. In addition, the materials between elevation 7 feet and 13 feet are grass and hardwood plants. They have much larger resisting strengths (Fischenich, 2001) compared to the driving shear from fluvial. The materials below elevation 7 ft are riprap. The fluvial shear is much less than the resisting shear of the riprap. Thus, the risk for the erosion between elevation 7 feet and 13 feet to occur is very low. That supports the recommendation to rely on the percentile lines below the 90th percentile line (e.g. the 50th and 75th percentile lines) as the likely responses of the design under a flow event close to the 1/2 AEP flow, given the distribution of the design material strengths used in the stochastic simulations.

Soil Bioengineering with Toe Riprap Condition and 15-ft Scour with Design Flow

1/325 AEP event, immediately after construction:

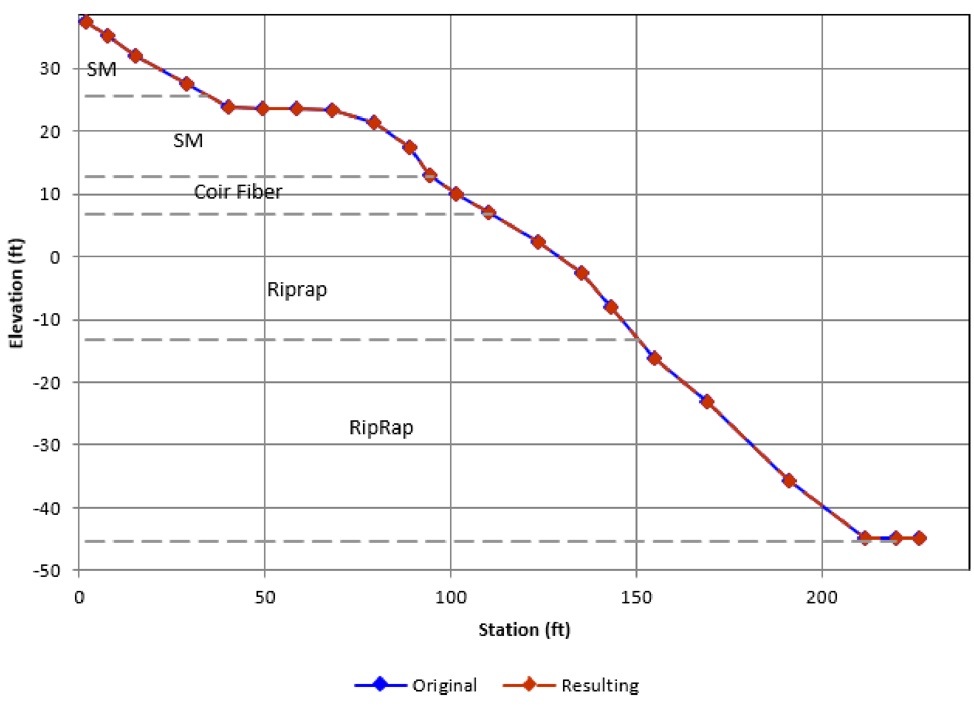

Figure 7. Soil bioengineering with bank and toe riprap and 15-ft scour condition, unsteady design flow (115k cfs), deterministic results during 1/325 AEP for just after construction scenario

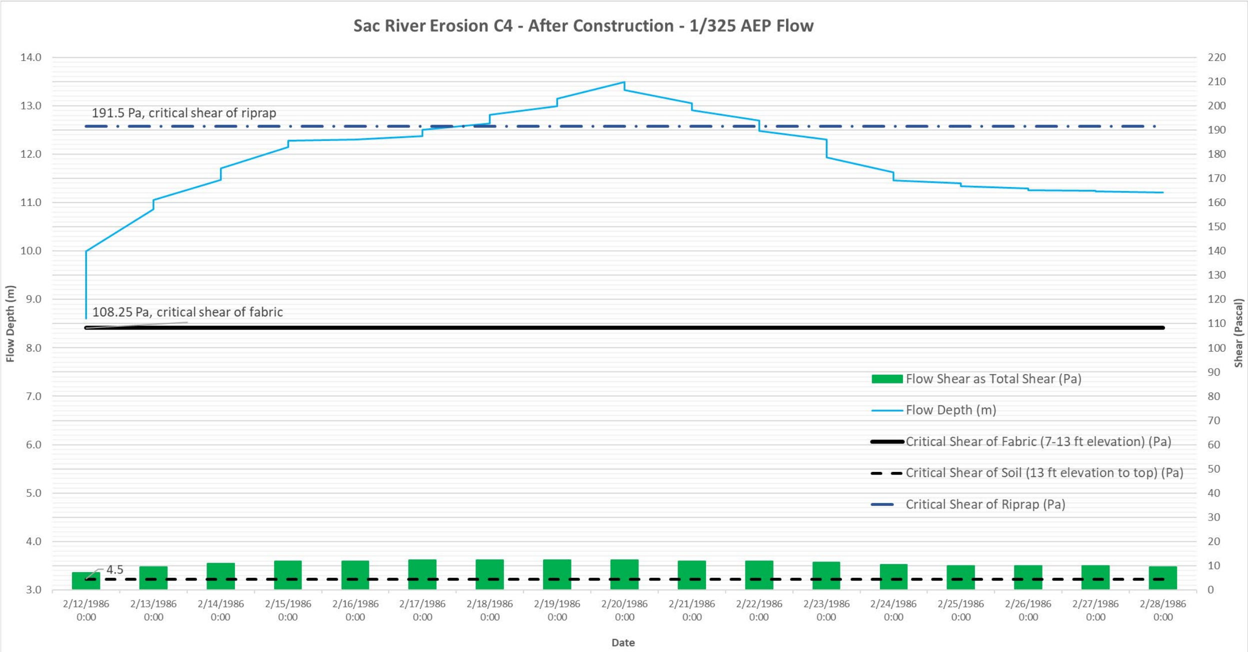

Figure 8. Components of shear stresses during simulation of BSTEM for 1/325 AEP for just after construction scenario

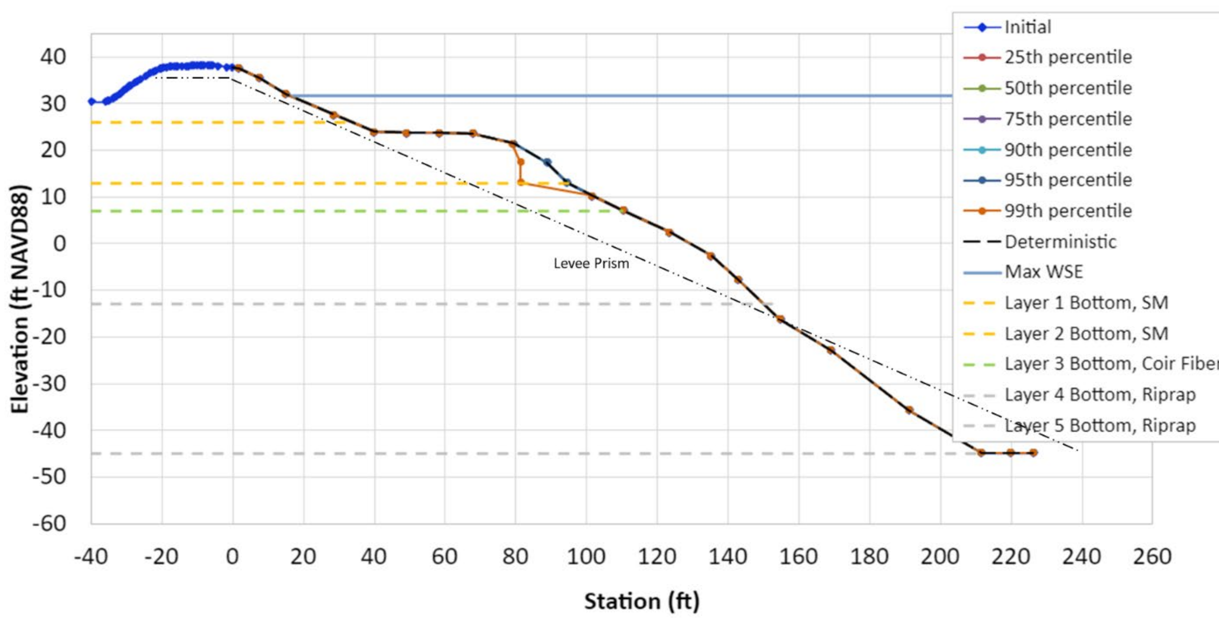

Figure 9. Soil bioengineering with toe riprap condition, unsteady design flow (115k cfs), stochastic results during 1/325 AEP for just after construction scenario

During the unsteady design flow of 115k cfs (1/325 AEP) with 15-ft scour for just after construction scenario, the deterministic results matches most of the percentile lines of the stochastic results. Based on the BSTEM results, there is some fluvial erosion at layer 2 and layer 3 for the 99th percentile line. Given the deterministic result for this condition showing no lateral erosion and the known shear stress used in this stochastic BSTEM model representative of the channel, not the left over bank where the soil bioengineering layer is located, it would give more conservative BSTEM results. Since there is no erosion potential below the 99th percentile line and the critical shear of the fabric above elevation 7 ft is much higher than the total shear from fluvial and boat wake, the risk for the erosion between elevation 7 feet and 13 feet to occur is extremely low. That supports the recommendation to rely on the percentile lines below the 90th percentile line (e.g. the 50th and 75th percentile lines) as the likely responses of the design under the design flow of 115k cfs, given the distribution of the design material strengths used in the stochastic simulations.

1/325 AEP, 5 years after construction:

During the unsteady design flow of 115k cfs (1/325 AEP) with 15-ft scour for five years after construction scenario, the deterministic result matches the majority of the percentile lines of the stochastic results. Based on the stochastic BSTEM results, there is some fluvial erosion at layer 2 and layer 3 for the 99th percentile line, and small amount of erosion for the 95th percentile line. Given the deterministic result for this condition showing no lateral erosion and the known shear stress used in this stochastic BSTEM model representative of the channel, not the left over bank where the soil bioengineering layer is located, it would give more conservative BSTEM results. In addition, the materials between elevation 7 feet and 13 feet are grass and hardwood plants. They have much larger resisting strengths (Fischenich, 2001) compared to the driving shear from fluvial. The martials below elevation 7 ft are riprap. The fluvial shear is much less than the resisting shear of the riprap. Thus, the risk for lateral erosion between elevation 7 feet and 13 feet to occur is very low. That supports the recommendation to rely on the percentile lines below the 90th percentile line (e.g. the 50th and 75th percentile lines) as the likely responses of the design under the design flow of the 1/325 AEP event, given the distribution of the design material strengths used in the stochastic simulations.

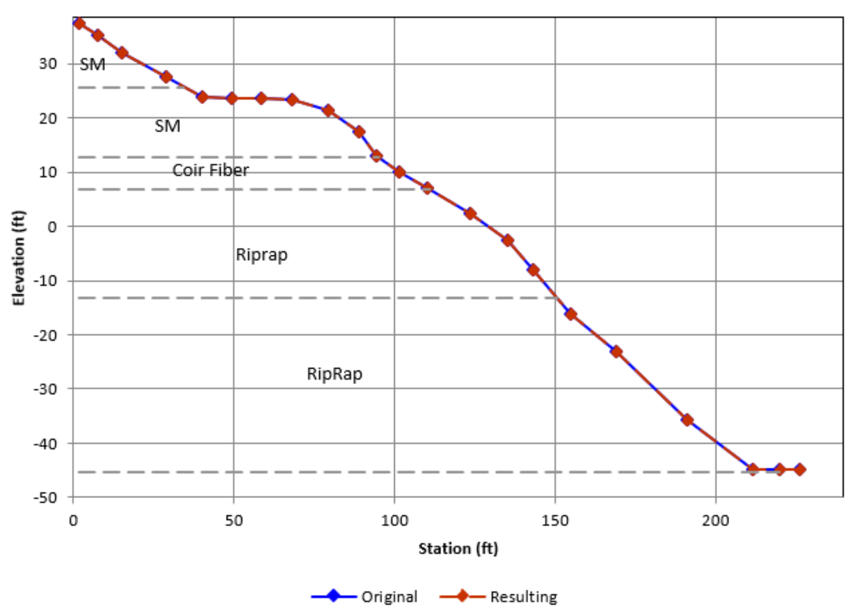

Figure 10. Soil bioengineering with toe riprap condition, unsteady design flow (115k cfs), deterministic results during 1/325 AEP for five years after construction scenario

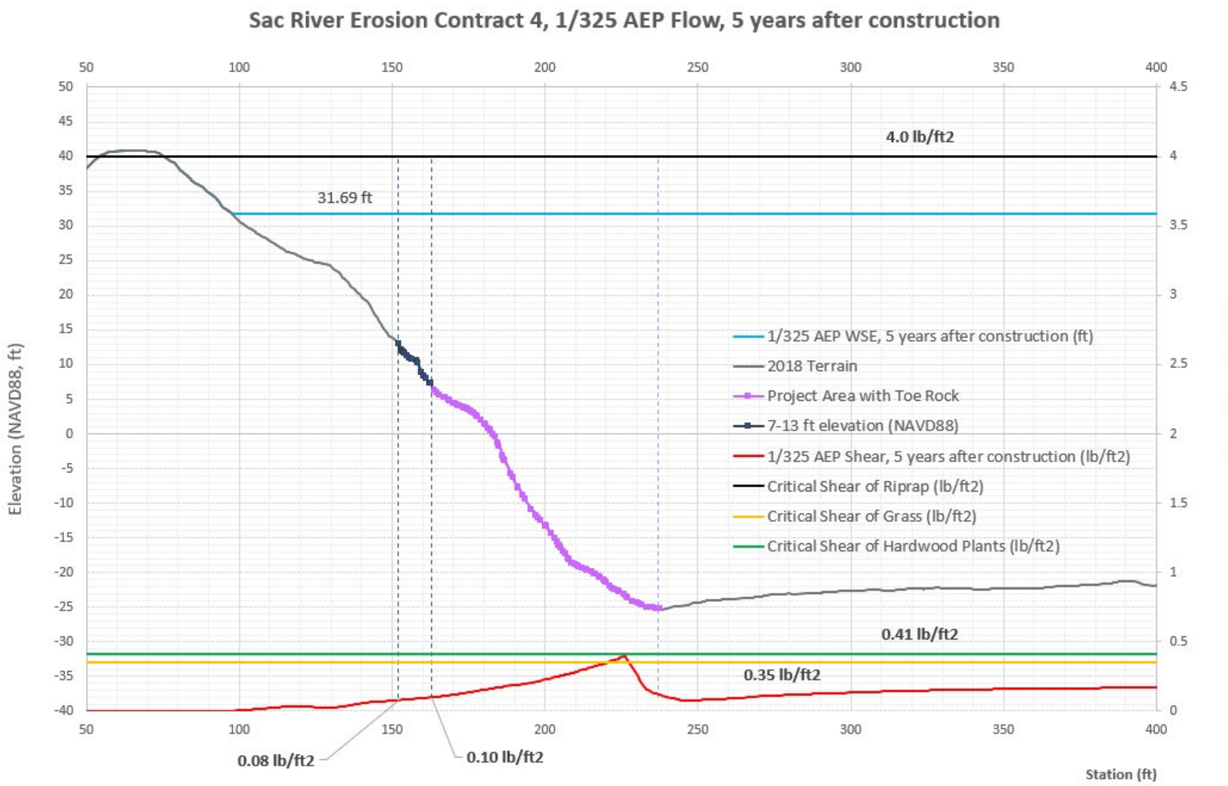

Figure 11. Design flow for five years after construction scenario showing 2D peak hydraulic results

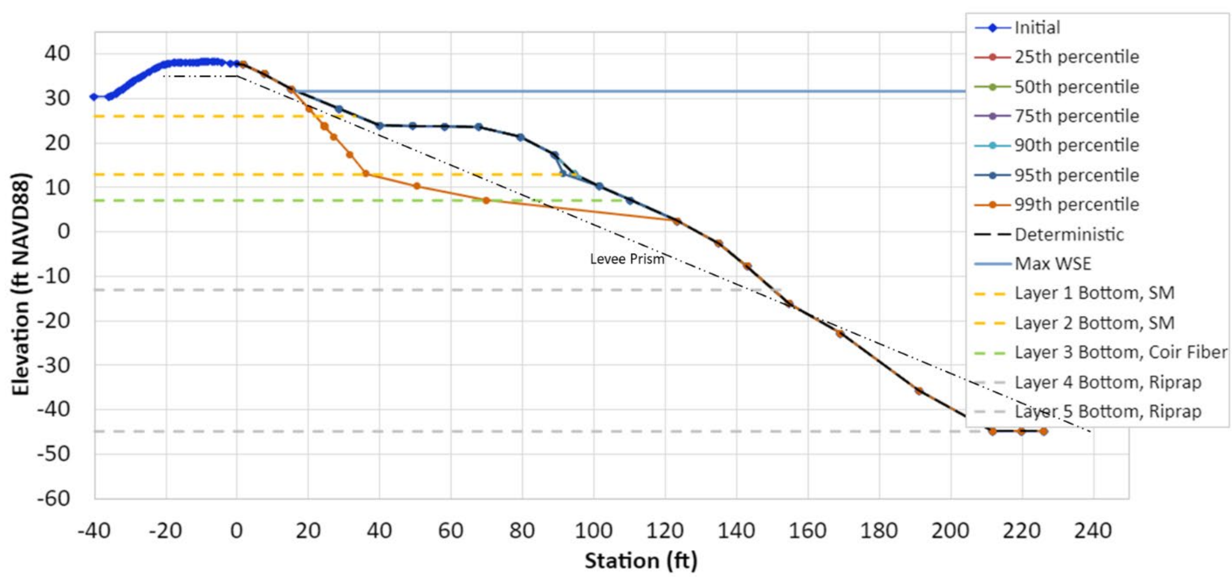

Figure 12. Soil bioengineering with toe riprap condition, unsteady design flow (115k cfs), stochastic results during 1/325 AEP for five years after construction scenario

BSTEM Analysis Summary

Table 2. Summary of BSTEM simulation results

Hydraulic Inputs	Geometry input	Deterministic Simulation	Stochastic Simulation
Historical Flow (2008-2018)	2008/2018 geometry (no erosion noted in surveys)	BSTEM with no boat wave; no lateral erosion; the design parameters are validated	Not performed
Synthetic Average Summer Flow	2018 existing geometry	BSTEM with boat wave; **no lateral erosion**	Not performed
	After construction design geometry, no toe scour	BSTEM with boat wave; **no lateral erosion**	BSTEM with boat wave; **no erosion potential for all percentile lines**
	5 years after construction, no toe scour	BSTEM with boat wave; **no lateral erosion**	BSTEM with boat wave; **no erosion potential for all the percentile lines**
Synthetic High Summer Flow	2018 existing geometry	BSTEM with boat wave; **no lateral erosion**	Not performed
	After construction design geometry, no toe scour	BSTEM with boat wave; **no lateral erosion**	BSTEM with boat wave; **no erosion potential for all percentile lines**
	5 years after construction, no toe scour	BSTEM with boat wave; **no lateral erosion**	BSTEM with boat wave; **no erosion potential for the percentile lines below the 99th**
April 2018 Flow	2018 existing geometry	BSTEM with boat wave **no lateral erosion**	Not performed
	After construction design geometry, no toe scour	BSTEM with boat wave **no lateral erosion**	BSTEM with boat wave; **no erosion potential for the percentile lines below the 99th**
	5 years after construction, no toe scour	BSTEM with boat wave; **no lateral erosion**	BSTEM with boat wave; **no erosion potential for the percentile lines below the 90th**
1/325 AEP Design Flow	2018 existing geometry	Not performed	Not performed
	After construction design geometry with 15-ft deep max toe scour	BSTEM with no boat wave; **no lateral erosion**	BSTEM with no boat wave; **no erosion potential for the percentile lines below the 99th**
	5 years after construction with 15-ft deep max toe scour	BSTEM with no boat wave; **no lateral erosion**	BSTEM with no boat wave; **no erosion potential for the percentile lines below the 95th**

Twenty simulations were performed with 1D BSTEM modeling. The descriptions of the results are bold in the summary table (Table 2). The following take-away observations from the analysis are summarized hereafter.

1. There is no lateral erosion for all BSTEM deterministic simulations. This indicates:
    a. Existing condition:

- No channel geometry changes between 2008 and 2018 were validated for the historical flow. This helped to fine tune the critical shear stresses of the design materials in the design of erosion protection and flood control for Sacramento River Contract 4
- The existing soil and vegetation conditions on the bank helped to prevent lateral erosion by both erosion driving forces (fluvial and boat wake) for the summer flows (average and high) with frequent recreational boating activities
- The increase in the river stages (increased velocity and shear stress) correspondent to higher flow regimes (up to a 1/2 AEP event) with less frequent recreational boating activities did not result in lateral erosion

b. Design condition, immediately after construction:
- The design toe rock would help to dissipate fluvial and boat wake energy to protect the site from vertical and lateral scour
- The coir fabric is a robust erosion protection material to prevent lateral erosion triggered by fluvial and boat wake from a wide spectrum of flows, low summer to the design flow (16k cfs to 115k cfs)

c. Design condition, five years after construction:
- The design toe rock would continue to provide protection against vertical and lateral erosion from both driving forces for the site after the launchable material is mobilized
- After the period of vegetation establishment through a vegetation management program, the vegetation would become robust and provide protection against lateral erosion from both erosion driving forces from a wide spectrum of flows, low summer to the design flow (16k cfs to 115k cfs). Both the toe rock and established vegetation work in conjunction as a unit similarly to an all-riprap design

2. There is no erosion potential for all BSTEM stochastic simulations below the 99th percentile line for the right after construction condition. This indicates:
   a. Proper installation of the layers of soil bioengineering would be key to the success of the design
   b. With proper installation of the design soil bioengineering layers, the risk for lateral erosion between elevation 7 feet and 13 feet to occur is very unlikely
3. There is no erosion potential for all BSTEM stochastic simulations below the 90th percentile line for the five years after construction condition. This indicates:
   a. The redundancy in the design of the toe rock and launchable rock material provides stability to the soil bioengineering layers
   b. Erosion protection for the elevation between 7 ft and 13 ft relies on proper maintenance of the planted vegetation to meet the minimum canopy coverage of 65%. Assurance of the minimum canopy coverage makes it unlikely for the risk of lateral erosion to occur

References

USACE. January 25, 2021- Updated MARCH 09, 2022. Sacramento River Contract 4 - 19-1026_Task_8_SacR_2D_RAS.

USACE. January 31, 2022 (a) - Updated April 19, 2022. Sacramento River Contract 4 - BSTEM_Historical_HECRAS.

USACE. June 1, 2022 (b) - Updated June 09, 2022. Sacramento River Contract 4 - RAS62_BSTEM19_Wave.

USACE, 2022 (c). Sacramento River Erosion Contract 4 DDR.

USACE, 2020. GeotechAppendix V4.

California Department of Boating and Waterways (DBW). 2002. California Boating Facilities Needs Assessment. Volume V. Statewide Boaters and Boating Facilities.
cbec, 2019. Draft 2008 and 2018 Surface Development and Topographic Change.
Fischenich, C. 2001. Stability Thresholds for Stream Restoration Materials. EMRRP-SR-29.