

Appendix E:

Kachess River Bull Trout Habitat Designs

Large Wood Ballasting Design and Scour Analysis Memorandum

TECHNICAL MEMORANDUM



To: Kittitas Conservation Trust
From: Dan Miller, PE
Date: June 30, 2020 **Project:** Kachess River Bull Trout Habitat
Re: 95% Designs - Large Wood Ballasting Design and Scour Analysis Memorandum

The Kachess River Bull Trout Habitat project includes a number of types of Large Wood (LW) Structures to enhance river process and provide habitats as described in the project report. Analysis of scour conditions and ballasting design were informed by the U.S. Bureau of Reclamation's (USBR) Risk Based Design Guidelines (USBR, 2014). Following is a summary of the scour analysis and ballasting design of LW structures.

LARGE WOOD BALLASTING CALCULATIONS

A project objective is to provide stable Large Wood structures without using metal fasteners and backfilling with materials salvaged on site. Stability calculations generally follow the USBR Risk Based LW guidelines.

Ballasting considers risk to the public and property in selecting appropriate design flood events and factors of safety. The site is remote with limited access. No boating is known to occur. The project reach flows into Upper Kachess Lake with no structures. The project reach and lake are located on Forest Service lands. The USBR (2014) design guidelines include matrices for Public Safety Risk and Property Damage Risk. The results of the attached matrices for the site indicates there is low risk to both public and property damage. For low public safety risk and low property damage risk the USBR (2014) design guidelines recommend a 10-year design event and factors of safety for: sliding ($FS_{\text{sliding}} > 1.25$), buoyancy ($FS_{\text{buoyancy}} > 1.5$) and rotation & overturning ($FS_{\text{r\&s}} > 1.25$).

River hydraulic flow depth and velocities were obtained from the project HEC-RAS model results for 25-year through 100-year events.

Mid Channel LW Structures

The attached spreadsheet indicates typical mid channel LW structures for high energy conditions meet desired factors of safety for buoyancy ($FS_b \sim 2.0$) and sliding ($FS_s \sim 6.1$). The structures are positioned at the upstream end of gravel bars which would prevent overturning or rotation.

Bank Buried Structures

The attached spreadsheet indicates bank buried LW structures for high energy conditions meet desired factors of safety for buoyancy ($FS_b \sim 2.1$) and sliding ($FS_s \sim 5.4$). The structures are positioned at the upstream end of gravel bars which would prevent overturning or rotation.

SCOUR

Construction of LW structures that encroach into flow create scour pools that can provide valuable habitats. Scour occurs as flow paths are diverted, creating locally higher energy capable of mobilizing substrate. The depth of scour is generally a function of depth and velocity approaching the obstruction as a measure of energy.

Guidance from USBR (USBR, 2014) recommends scour analyses for coarse bedded channels include correction factors that account for armoring of the streambed which limits the depth of scour. This recommendation is a result of the USGS (2014) study of scour in coarse-bedded rivers finding that observed scour depth is less than predicted values. This correction is included in the FHWA HEC-18 fourth edition.

Mid Channel LW Structures

Scour for a typical Mid Channel LW Structures was estimated using the HEC-18 wide pier scour methods summarized in the attached spreadsheet.

Input parameters include flow depth and velocity approaching the jam considered to be a wide pier, the width of the jam in active flow was estimated to be up to 20 feet, D50 and D90 substrate particle sizes. Flow depth and velocity for typical higher energy conditions were extracted from HEC-RAS model results to be 5 feet average depth and 10 feet per second velocities. Substrate particle sizes were estimated from the project pebble count data to be D50 ~ 0.23 feet and D95 ~ 0.43 feet.

Estimated scour depth is approximately 9.5-ft below the existing grade and accounts for armoring of the stream bed. Existing LW along Kachess River exhibit similar conditions and tend to sustain deep scour pools that provide valuable bull trout habitats. Actual scour depth configuration will change with varying flows. High flows will tend to excavate scour holes, while moderate flows will tend to deposit sediment in the scour pools.

A mid channel structure (Type C) equation from the USBR (1984) was also used as a comparison. This method indicates a similar 9.5 feet deep scour pool when the K4 armoring coefficient is applied.

To accommodate this depth of scour, the log layout in the mid channel LW structures includes a tier of logs below existing grade to provide rootwad structure within the scour pool and reduce risk of the structures being undermined, leading to failure.

Bank Buried Structures

The bank buried structures were analyzed using abutment scour methods from HEC-18. It was assumed the LW would encroach approximately 10 feet into the Kachess River flow and divert a flow average depth of 5 feet moving at 10 feet per second. Given the coarse bed of the Kachess the K4 coarse bedded armoring coefficient applied to the HEC-18 results estimates scour depth at 7.8 feet. This is similar to observed scour conditions on the Kachess River.

REFERENCES

Federal Highway Administration. May 2001. HEC18. Evaluating Scour at Bridge, Fourth Edition.

U.S. Bureau of Reclamation. Ernest Pemberton and J. Lara. January 1984. Computing Degradation and Local Scour.

U.S. Bureau of Reclamation. M. Knutson and J. Fealko. September 2014. Large Woody Material Risk Based Design Guidelines

USGS, SIR 2004-5111. Katherine J. Chase and S.R. Holnbeck. 2004. Evaluation of Pier-Scour Equations for Coarse-Bed Streams.

USBR RISK MATRICES: PUBLIC SAFETY AND PROPERTY DAMAGE

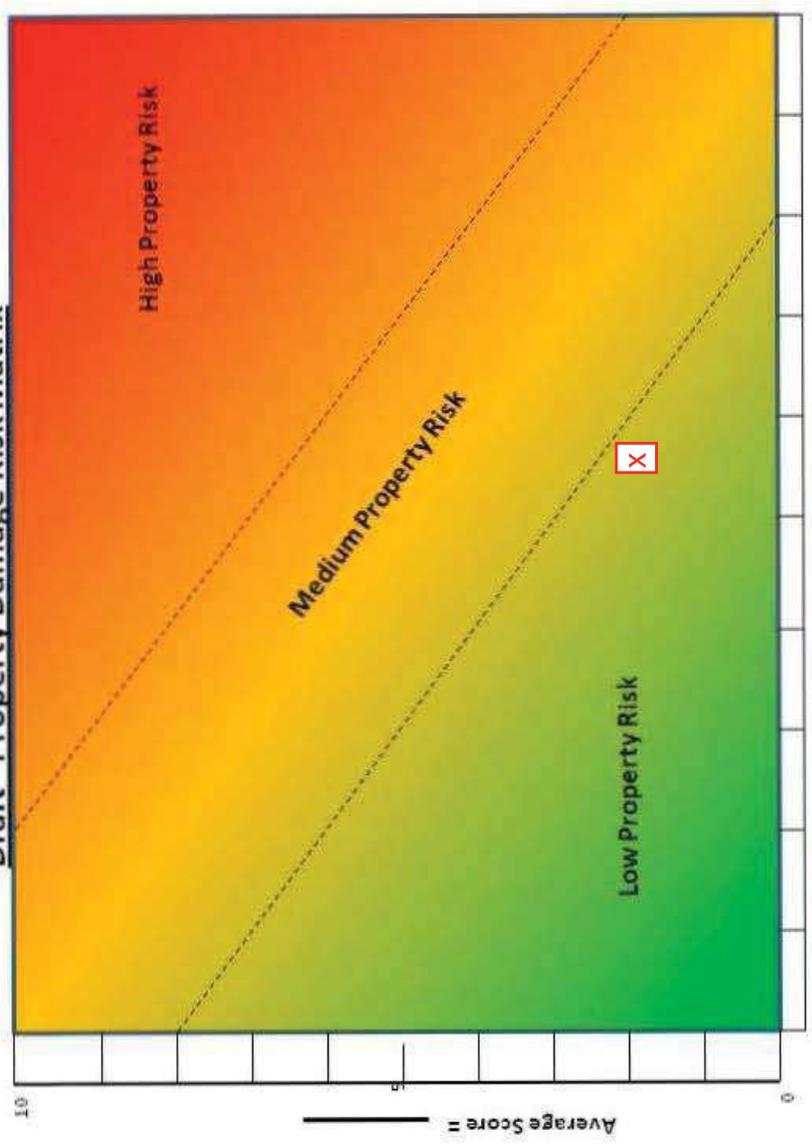
Draft - Property Damage Risk Matrix

Property/Project Characteristics

National Fore
 No Buildings
 In-channel Structures
 Floodplain structures
 Multiple
 Residential
 Land Use

Scores _____

Total Score = _____



Project: _____

Evaluator: _____

Concurrence: _____

Date: _____

Stream Response Potential

Stream Type: Bedrock (source > 10%) _____ Transport (3-10%) Response (< 3%) _____
 Riparian Corridor: Continuous/Wide _____ Discontinuous/narrow Urbanized/Levee confined _____
 Bed Scour: Boulder/Clay bed _____ Gravel/Cobble Sand/Silt _____
 Hydrologic Regime: Spring-fed _____ Rain _____ Rain-on-snow _____ Thunderstorm _____
 Bank erosion: Naturally non-erodible _____ Snowmelt _____ Erosion resistant Highly erodible _____

Score _____

Average Score = _____

Total Score = _____

BALLASTING CALCULATIONS - MID-CHANNEL LARGE WOOD STRUCTURES:

Kachess - Large Woody Structure Stability Evaluation

Structural Stability | 6.4

Structural stability of large woody material placements is evaluated herein using the procedures, formulas, and recommendations provided in the Reclamation's *Large Woody Material - Risk Based Design Guidelines* (Knutson et. al. 2014) along with insight gained from professional experience and general engineering judgment.

Factors of Safety | 6.4.1

Safety factors for structural stability were selected from *Table 4. Minimum recommended factors of safety* given the site specific public safety and property damage risk levels.

Public Safety Risk	Low	FOS_{sliding}	1.25
Property Damage Risk	Low	FOS_{buoyancy}	1.5
Stability Design Flow Criteria	10-year	FOS_{rotation}	1.25

Resistance to Flotation | 6.4.2

Flotation is typically caused by the buoyant force and the lift force acting on the wood material from water passing over its surface.

Large Wood Material Force

Accounts for the vertical buoyant force of submerged large wood and the vertical weight force of unsubmerged large wood.

$$V_{MS} = V_{LWMS} \times (\gamma_{wood} - \gamma_w)$$

V_{MS} = total volume of submerged large wood material

$$V_{LWMS} = \sum N_{LWMi} \times V_{LWMi}$$

Variable	Design Value	Units
γ_d = unit weight of wood	38	lb/ft ³
γ_w = unit weight of water	62.4	lb/ft ³
V_{MS}	2334	ft ³

F_{LWMS} (lb) 56,955	<i>Positive values are upward forces.</i>
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Lift Force

Accounts for the lift force of large wood in flowing water. Not applicable to LWS where the bed will deform around the leading edges.

$$F_L = \frac{C_L \times A_{LWM} \times \gamma_w \times U_o^2}{2 \times g}$$

	Design Value	Units / Notes
$C_L = \text{lift coefficient}$		0.2 typ. LWM value
$A_{LWM} = \text{area of large woody material perpendicular to flow}$		$A_{LWM} = \text{See Design Plan}$
$U_u = \text{upstream channel velocity at design event}$	10	ft/s
$g = \text{acceleration due to gravity}$	32.2	ft/s ²
F_L (lb)		N/A

Boulder Ballast Force

Accounts for the ballasting force of large boulders directly attached to or placed over LWM.

$$F_{bouldersub} = N_{bouldersub} \times \frac{\pi}{6} \times d_{bouldersub}^3 \times (\gamma_{boulder} - \gamma_w)$$

	Design Value	Units / Notes
$N_{bouldersub} = \text{number of submerged boulders}$	0	number
$d_{bouldersub} = \text{effective diameter of submerged boulders}$	0	ft
$\gamma_{boulder} = \text{unit weight of boulders}$	165	lb/ft ³
$F_{bouldersub}$ (lb)		N/A

Backfill Ballast Force

Accounts for the ballasting force of backfill placed directly over LWM members. Volume is based on the fill area over the log(s) and a the effective cover depth shown on the Drawings.

$$F_{backfillsub} = V_{backfillsub} \times (\gamma_s - \gamma_w)$$

	Design Value	Units / Notes
$V_{backfillsub} = \text{volume of backfill over LWM members}$	2,250	ft ³
$\gamma_s = \text{unit weight of backfill material}$	110	lb/ft ³
$F_{backfillsub}$ (lb)		-107,100

Pile Skin Friction

Accounts for the vertical resistance provided by piles within the LWM structure. USBR document equation modified by Inter-Fluve to match industry pile design standard formulations.

$$F_{piles-v} = N_{piles} \times \pi \times d_{piles} \times L_{piles} \times (k_s \times \tan \frac{2}{3}\theta \times \sigma')$$

	Design Values	Units
$N_{piles} = \text{number of piles}$	Assumes half the piles are vertically effective (i.e. angled over the logs)	1 number
$L_{piles} = \text{length of pile embedded below potential scour depth}$	10	ft
$d_{piles} = \text{nominal diameter of the piles}$	1.33	ft
$\sigma' = (L_{piles} \times (\gamma_{sat} - \gamma_w))/2$	238	lb/ft ²
$K_s = \text{coefficient of lateral earth pressure (0.5 to 1.0)}$	1.0	unit less
$\theta = \text{internal friction angle of soils}$	36	deg.
$F_{piles-v}$ (lb)		-4,439 Negative values resist upward displacement.

Piles Only Buoyancy Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{bPiles} = \frac{F_{piles-v}}{F_{LWMS} + F_L}$$

FOS_b 0.1

Note this value does not include the backfill assuming it's all lost but the piles are holding.

Backfill Only Buoyancy Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{bBackfill} = \frac{F_{backfillsub}}{F_{LWMS} + F_L}$$

FOS_b 1.9

Note this value does not include the piles.

Net Buoyancy Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{bNet} = \frac{F_{backfillsub} + F_{piles-v}}{F_{LWMS} + F_L}$$

FOS_b 2.0

Note this value includes the piles and backfill.

Resistance to Sliding | 6.4.3

LWM structures are also susceptible to failure through sliding.

Drag Force

LWM structures are pushed downstream by the fluid drag forces acting upon the wood by the flowing water.

	Design Value	Units / Notes
$F_d = \frac{C_D \times A_{LWM} \times \gamma_w \times U_c^2}{2 \times g}$		
$C_D = \text{drag coefficient}$		1 Per Equations 23 and 24
$A_{LWM} = \text{area of wetted wood normal to the flow direction}$		$A_{LWM} = \text{See Design Plan}$
		$A_{LWM} \text{ (ft}^2\text{)}$ 200
$U_c = \text{velocity adjacent to the LWM structure}$		9 ft/s <i>Velocity value is conservative for all LWS locations. Value from 100-yr event 2D model results for main channel.</i>
$g = \text{acceleration due to gravity}$		32.2 ft/s ²
$F_d \text{ (lb)}$ 15,697		

Hydrostatic Force

Hydrostatic forces act on the upstream and downstream faces of a LWM structure. They account for differences in the upstream and downstream water depths against the structure.

$F_{hu} = \frac{1}{2} \times \gamma_w \times Y_u \times A_u$	$F_{hd} = \frac{1}{2} \times \gamma_w \times Y_d \times A_d$	Variable Design Value
		$Y_u \text{ (ft)}$ 5
$F_{hu}, F_{hd} = \text{hydrostatic force on upstream and downstream side of the wood structure}$		$A_u \text{ (ft}^2\text{)}$ 200 <i>Post racking area</i>
$Y_u, Y_d = \text{water depth upstream and downstream of the structure}$		$Y_d \text{ (ft)}$ 5
$A_u, A_d = \text{area projected to flow direction on the upstream and downstream of the structure}$		$A_d \text{ (ft}^2\text{)}$ 200 <i>Plan downstream area</i>
$F_{hu} + F_{hd} = F_h \text{ (lb)}$		N/A

Impact Force

The impact force associated with debris impacting a large wood structure can be estimated by the impact force equation.

$$F_i = \frac{W_{debris}}{g} \times \frac{V_{channel}^2}{2 \times \Delta x} \times C_i \times C_o \times C_d \times C_b \times R_{max}$$

W_{debris} = weight of debris

$V_{channel}$ = channel approach velocity

Δx = deceleration distance

Coefficients (see Table 6 and Figures 11, 12 for values)

C_i = importance, C_o = orientation = 0.8, C_d = depth, C_b = blockage, R_{max} = impulse response ratio

Variable Design Value	
W_{debris} (lb)	7,354
$V_{channel}$ (ft/s)	9
Δx (ft)	5
C_i	0.5
C_o	0.8
C_d	1.0
C_b	1.0
R_{max}	0.8

F_i (lb) 592

Friction Force

Accounts for the friction force between the LWM and the channel bed. Restraint force from piles is not included as it does not exert a pressure on the LWS / bed interface.

$$= -\mu_{bed} \times (F_{LWMs} + F_L + F_{bouldersub} + F_{backfillsub})$$

	Design Value	Units / Source
μ = coefficient of bed friction = $\tan(\theta)$	0.78	unit less
θ = internal friction angle (degrees)	38	Table 5, (Knutson et. al. 2014)

F_f (lb) -39,178	Negative values resist downstream displacement.
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Lateral Resistance From Piles

Accounts for the lateral resistance provided by piles within the LWM structure. Assumes soil resistance is limiting, i.e. the pile pushes over before it breaks.

$$F_{piles-h} = N_{piles} \times \frac{L_{pile}^3 \times \frac{1}{2} \times (\gamma_s - \gamma_w) \times d_{pile} \times K_p}{h_{load} \times L_{pile}}$$

	Design Values	Units
N_{pile} = number of piles	Number of effective piles varies based on best engineering judgment.	5 number
L_{pile} = length of pile embedded below potential scour depth	15	ft
d_{pile} = diameter of the pile	1.33	ft
h_{load} = applied load height above the potential scour depth	2.5	ft
$K_p = \frac{1 + \sin \theta}{1 - \sin \theta}$	4.2	unit less

$F_{piles-h}$ (lb) -60,029	Negative values resist downstream displacement.
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Sliding Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{sliding} = \frac{F_f + F_{piles-h}}{F_d + F_{hu} + F_{hd} + F_i}$$

FOS_{sliding} 6.1

Pile Strength Factor of Safety

The factor of safety for the timber bending stress capacity of the pile. This evaluates the potential for the pile(s) to break under load prior to the pile pushing over in the ground.

		Design Values	Units
$F_b = \text{Timber Bending Stress Capacity}$ per Timber Pile Manual Table 3-1 or AWC NDS Supplement Table 4D		1,200	psi
		172,800	psf
$d_{pile} = \text{diameter of the pile}$			1.33 ft
$I = \text{circular cross – sectional moment of inertia}$	$I = \frac{\pi B^4}{4}$		2.48 ft ⁴
$S = \text{circular section modulus}$	$S = \frac{\pi B^3}{32}$		0.233 ft ³
$C_F = \text{strength reduction size factor}$ for diameters greater than 12"	$C_F = \frac{1}{B}^{(1/9)}$		0.969 --
$M_p = \text{applied moment per pile}$	$M_p = \frac{(F_d + F_i + F_h) \times h_{load}}{N_{piles}}$		8,144 ft-lb
$f_b = \text{applied pile bending stress}$	$f_b = \frac{M_p}{S}$		34,998 psf
$F_{bx} = \text{Pile bending stress capacity}$	$F_{bx} = F_b \times C_F$		1,162 psi 167,364 psf
$FOS_{pile\ strength} = \frac{F_{bx}}{f_b}$			
		FOS_{pile strength} 4.8	

References

Large Woody Material - Risk Based Design Guidelines

M. Knutson, J. Fealko. 2014. *Large Woody Material - Risk Based Design Guidelines*. U.S. Department of the Interior Bureau of Reclamation Pacific Northwest Region & Technical Services. Boise, Idaho. September 2014. Online at: <http://www.usbr.gov/pn//fcrps/documents/lwm.pdf>

ASTM D25. Allowable Stress Values for Treated Round Timber Piles.

Timber Pile Design and Construction Manual, Timber Piling Council, 2015.

American Wood Council (2018) National Design Specifications for Wood Construction, Design Supplement.

BALLASTING CALCULATIONS – BANK BURIED LARGE WOOD STRUCTURES:

Kachess - Large Woody Structure Stability Evaluation: Bank Buried Jam

Structural Stability | 6.4

Structural stability of large woody material placements is evaluated herein using the procedures, formulas, and recommendations provided in the Reclamation's *Large Woody Material - Risk Based Design Guidelines* (Knutson et. al. 2014) along with insight gained from professional experience and general engineering judgment.

Factors of Safety | 6.4.1

Safety factors for structural stability were selected from *Table 4. Minimum recommended factors of safety* given the site specific public safety and property damage risk levels.

Public Safety Risk	Low	FOS_{sliding}	1.25
Property Damage Risk	Low	FOS_{buoyancy}	1.5
Stability Design Flow Criteria	10-year	FOS_{rotation}	1.25

Resistance to Flotation | 6.4.2

Flotation is typically caused by the buoyant force and the lift force acting on the wood material from water passing over its surface.

Large Wood Material Force

Accounts for the vertical buoyant force of submerged large wood and the vertical weight force of unsubmerged large wood.

$$V_{MS} = V_{LWMS} \times (\gamma_{wood} - \gamma_w)$$

V_{MS} = total volume of submerged large wood material

$$V_{LWMS} = \sum N_{LWMi} \times V_{LWMi}$$

Variable	Design Value	Units
γ_d = unit weight of wood	38	lb/ft ³
γ_w = unit weight of water	62.4	lb/ft ³
V_{MS}	1690	ft ³

F_{LWMS} (lb) 41,234 Positive values are upward forces.

Lift Force

Accounts for the lift force of large wood in flowing water. Not applicable to LWS where the bed will deform around the leading edges.

$$F_L = \frac{C_L \times A_{LWM} \times \gamma_w \times U_o^2}{2 \times g}$$

	Design Value	Units / Notes
$C_L = \text{lift coefficient}$		0.2 typ. LWM value
$A_{LWM} = \text{area of large woody material perpendicular to flow}$		$A_{LWM} = \text{See Design Plan}$
$U_u = \text{upstream channel velocity at design event}$	10	ft/s
$g = \text{acceleration due to gravity}$	32.2	ft/s ²
F_L (lb)		N/A

Boulder Ballast Force

Accounts for the ballasting force of large boulders directly attached to or placed over LWM.

$$F_{bouldersub} = N_{bouldersub} \times \frac{\pi}{6} \times d_{bouldersub}^3 \times (\gamma_{boulder} - \gamma_w)$$

	Design Value	Units / Notes
$N_{bouldersub} = \text{number of submerged boulders}$	0	number
$d_{bouldersub} = \text{effective diameter of submerged boulders}$	0	ft
$\gamma_{boulder} = \text{unit weight of boulders}$	165	lb/ft ³
$F_{bouldersub}$ (lb)		N/A

Backfill Ballast Force

Accounts for the ballasting force of backfill placed directly over LWM members. Volume is based on the fill area over the log(s) and a the effective cover depth shown on the Drawings.

$$F_{backfillsub} = V_{backfillsub} \times (\gamma_s - \gamma_w)$$

	Design Value	Units / Notes
$V_{backfillsub} = \text{volume of backfill over LWM members}$	1,800	ft ³
$\gamma_s = \text{unit weight of backfill material}$	110	lb/ft ³
$F_{backfillsub}$ (lb)		-85,680

Pile Skin Friction

Accounts for the vertical resistance provided by piles within the LWM structure. USBR document equation modified by Inter-Fluve to match industry pile design standard formulations.

$$F_{piles-v} = N_{piles} \times \pi \times d_{piles} \times L_{piles} \times (k_s \times \tan \frac{2}{3}\theta \times \sigma')$$

	Design Values	Units
$N_{piles} = \text{number of piles}$	Assumes half the piles are vertically effective (i.e. angled over the logs)	0 number
$L_{piles} = \text{length of pile embedded below potential scour depth}$		10 ft
$d_{piles} = \text{nominal diameter of the piles}$		1.33 ft
$\sigma' = (L_{piles} \times (\gamma_{sat} - \gamma_w))/2$		238 lb/ft ²
$K_s = \text{coefficient of lateral earth pressure (0.5 to 1.0)}$		1.0 unit less
$\theta = \text{internal friction angle of soils}$		36 deg.
$F_{piles-v}$ (lb)		0 Negative values resist upward displacement.

Piles Only Buoyancy Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{bPiles} = \frac{F_{piles-v}}{F_{LWMS} + F_L}$$

FOS_b 0.0

Note this value does not include the backfill assuming it's all lost but the piles are holding.

Backfill Only Buoyancy Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{bBackfill} = \frac{F_{backfillsub}}{F_{LWMS} + F_L}$$

FOS_b 2.1

Note this value does not include the piles.

Net Buoyancy Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{bNet} = \frac{F_{backfillsub} + F_{piles-v}}{F_{LWMS} + F_L}$$

FOS_b 2.1

Note this value includes the piles and backfill.

Resistance to Sliding | 6.4.3

LWM structures are also susceptible to failure through sliding.

Drag Force

LWM structures are pushed downstream by the fluid drag forces acting upon the wood by the flowing water.

	Design Value	Units / Notes
$F_d = \frac{C_D \times A_{LWM} \times \gamma_w \times U_c^2}{2 \times g}$		
$C_D =$ drag coefficient		1 Per Equations 23 and 24
$A_{LWM} =$ area of wetted wood normal to the flow direction		$A_{LWM} =$ See Design Plan A_{LWM} (ft²) 75
$U_c =$ velocity adjacent to the LWM structure		9 ft/s Velocity value is conservative for all LWS locations. Value from 100-yr event 2D model results for main channel.
$g =$ acceleration due to gravity		32.2 ft/s ²
F_d (lb) 5,886		

Hydrostatic Force

Hydrostatic forces act on the upstream and downstream faces of a LWM structure. They account for differences in the upstream and downstream water depths against the structure.

$F_{hu} = \frac{1}{2} \times \gamma_w \times Y_u \times A_u$	$F_{hd} = \frac{1}{2} \times \gamma_w \times Y_d \times A_d$	Variable Design Value
		Y_u (ft) 5
F_{hu} , $F_{hd} =$ hydrostatic force on upstream and downstream side of the wood structure		A_u (ft ²) 75 Post racking area
Y_u , $Y_d =$ water depth upstream and downstream of the structure		Y_d (ft) 5
A_u , $A_d =$ area projected to flow direction on the upstream and downstream of the structure		A_d (ft ²) 75 Plan downstream area
$F_{hu} + F_{hd} = F_h$ (lb)		N/A

Impact Force

The impact force associated with debris impacting a large wood structure can be estimated by the impact force equation.

$$F_i = \frac{W_{debris}}{g} \times \frac{V_{channel}^2}{2 \times \Delta x} \times C_i \times C_o \times C_d \times C_b \times R_{max}$$

W_{debris} = weight of debris

$V_{channel}$ = channel approach velocity

Δx = deceleration distance

Coefficients (see Table 6 and Figures 11, 12 for values)

C_i = importance, C_o = orientation = 0.8, C_d = depth, C_b = blockage, R_{max} = impluse response ratio

Variable Design Value	
W_{debris} (lb)	7,354
$V_{channel}$ (ft/s)	9
Δx (ft)	5
C_i	0.5
C_o	0.8
C_d	1.0
C_b	1.0
R_{max}	0.8

F_i (lb) 592

Friction Force

Accounts for the friction force between the LWM and the channel bed. Restraint force from piles is not included as it does not exert a pressure on the LWS / bed interface.

$$= -\mu_{bed} \times (F_{LWMs} + F_L + F_{bouldersub} + F_{backfillsub})$$

	Design Value	Units / Source
a = coefficient of bed friction = $\tan(\theta)$	0.78	unit less
θ = internal friction angle (degrees)	38	Table 5, (Knutson et. al. 2014)

F_f (lb) -34,725	Negative values resist downstream displacement.
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Lateral Resistance From Piles

Accounts for the lateral resistance provided by piles within the LWM structure. Assumes soil resistance is limiting, i.e. the pile pushes over before it breaks.

$$F_{piles-h} = N_{piles} \times \frac{L_{pile}^3 \times \frac{1}{2} \times (\gamma_s - \gamma_w) \times d_{pile} \times K_p}{h_{load} \times L_{pile}}$$

	Design Values	Units
N_{pile} = number of piles	Number of effective piles varies based on best engineering judgment.	0 number
L_{pile} = length of pile embedded below potential scour depth	15	ft
d_{pile} = diameter of the pile	1.33	ft
h_{load} = applied load height above the potential scour depth	2.5	ft
$K_p = \frac{1 + \sin \theta}{1 - \sin \theta}$	4.2	unit less

$F_{piles-h}$ (lb) 0	Negative values resist downstream displacement.
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Sliding Factor of Safety

The factor of safety is the absolute value of the sum of resisting forces divided by the sum of driving forces.

$$FOS_{sliding} = \frac{F_f + F_{piles-h}}{F_d + F_{hu} + F_{hd} + F_i}$$

FOS_{sliding} 5.4

Pile Strength Factor of Safety

The factor of safety for the timber bending stress capacity of the pile. This evaluates the potential for the pile(s) to break under load prior to the pile pushing over in the ground.

		Design Values	Units
$F_b = \text{Timber Bending Stress Capacity}$ per Timber Pile Manual Table 3-1 or AWC NDS Supplement Table 4D		1,200	psi
		172,800	psf
$d_{pile} = \text{diameter of the pile}$		1.33	ft
$I = \text{circular cross – sectional moment of inertia}$	$I = \frac{\pi B^4}{4}$	2.48	ft ⁴
$S = \text{circular section modulus}$	$S = \frac{\pi B^3}{32}$	0.233	ft ³
$C_F = \text{strength reduction size factor}$ for diameters greater than 12"	$C_F = \frac{1}{B}^{(1/9)}$	0.969	--
$M_p = \text{applied moment per pile}$	$M_p = \frac{(F_d + F_i + F_h) \times h_{load}}{N_{piles}}$	#DIV/0!	ft-lb
$f_b = \text{applied pile bending stress}$	$f_b = \frac{M_p}{S}$	#DIV/0!	psf
$F_{bx} = \text{Pile bending stress capacity}$	$F_{bx} = F_b \times C_F$	1,162	psi
		167,364	psf
$FOS_{pile\ strength} = \frac{F_{bx}}{f_b}$		FOS_{pile strength} #DIV/0!	

References

Large Woody Material - Risk Based Design Guidelines

M. Knutson, J. Fealko. 2014. *Large Woody Material - Risk Based Design Guidelines*. U.S. Department of the Interior Bureau of Reclamation Pacific Northwest Region & Technical Services. Boise, Idaho. September 2014. Online at: <http://www.usbr.gov/pn//fcrps/documents/lwm.pdf>

ASTM D25. Allowable Stress Values for Treated Round Timber Piles.

Timber Pile Design and Construction Manual, Timber Piling Council, 2015.

American Wood Council (2018) National Design Specifications for Wood Construction, Design Supplement.

DEPTH OF SCOUR ESTIMATES - MID-CHANNEL LARGE WOOD STRUCTURES:

HEC-18 Mueller Equation

$$K4 = 0.4 * \frac{V_o - V_{i50}}{V_{c50} - V_{i95}}^{0.15} \quad \text{eqn 7}$$

$K4 = 0.43$
 0.4 minimum value

Where:

b =	10	Width of mid channel obstruction, ft		
yo =	5	Depth of flow directly upstream, ft		
Vo =	10	Approach velocity immediately upstream, fps		
Vi50 =	5.2	Approach V req'd to initiate scour for D50, fps	= 0.645 * (D50/b)^0.053 * Vc50, fps	eqn 6b
Vc50 =	9.8	Critical V for incipient motion of D50, fps	= 12.21 (yo^1/6) (D50^1/3), fps	eqn 7a
Vi95 =	6.6	Approach V req'd to initiate scour for D95, fps	= 0.645 * (D95/b)^0.053 * Vc95, fps	eqn 7b
Vc95 =	12.1	Critical V for incipient motion of D95, fps	= 12.21 (yo^1/6) (D95^1/3), fps	eqn 7c
D50 =	0.23	ft		
D95 =	0.43	ft		

Ref: FHWA HEC-18, 4th edition

Pier Scour

$$\frac{Y_s}{Y_1} = 2.0 * K1 * K2 * K3 * K4 * (a/Y_1)^{0.65} * Fr^{0.43} \quad \text{eqn 6.1}$$

Ys =	9.5	scour depth, ft	
Y1 =	5	flow depth directly upstream, ft (Yo from USGS mid channel)	
K1 =	1.0	Correction for nose shape	
K2 =	1.0	Correction for angle of attack	
K3 =	1.0	Correction for bed condition	
K4 =	0.43	Correction for armoring of bed (from USGS mid channel)	
a =	20.0	Pier width, ft	
L =	20.0	length of pier, ft	
Fr =	0.79	Froude upstream of pier, ft.	= V1/(g*y1)^0.5
V1 =	10	velocity upstream of pier, fps	
g =	32.2	f/s^2	

U.S. Bureau of Reclamation. January 1984.
Computing Degradation and Local Scour
Ernest Pemberton and J. Lara.

Mid channel structure scour estimate (Type C, pg 40)

$$\frac{ds}{b} = 1.84 * (d/b)^{0.3} * (Fc)^{0.25} \quad \text{eqn: 33}$$

where:

ds = 22.3 depth of scour, ft
b = 20 pier size, ft
d = 5 flow depth, ft
Fc = $0.71 Vc / (g*d)^{0.5}$ = threshold froude number
Vc = 9 threshold velocity, fps (Figure 12)
g = 32.2 ft/s/s

Apply USGS/HEC18 armoring correction: K4

$$ds * K4 = 9.5 \text{ ft}$$

DEPTH OF SCOUR ESTIMATES – BANK BURIED LARGE WOOD STRUCTURES:

Kachess Scour Analysis - Bank Buried Jam

Ref: FHWA HEC-18, 5th edition 2012

Abutment Scour

Froehlich live bed abutment scour eqn

Table 8.1 - Abutment shape coefficients

Description	K1
vertical-wall	1
vertical-wall w/ wingwalls	0.82
spillthrough	0.55

eqn: 8.1 $Y_s / Y_a = 2.27 * K1 * K2 * ((L/Y_a)^{0.43}) * (Fr^{0.61}) + 1$

- K1 = 1 coefficient for abutment shape (T8.1)
- K2 = 1 coefficient for angle of embankment of flow (F8.5)
- L = 10 length of active flow obstructed by the embankment, ft
- Ae = 50 flow area of the approach cross section obstructed by the embankment, sq ft
- Fr = 0.79 Froude
- Ve = 10 Q_e/A_e , fps
- Qe = 500 flow obstructed by abutment and approach embankment $\sim Q * A$, cfs
- Ya = 5 average depth of flow on the floodplain ($A3/L$), ft
- L = 10 length of embankment projected normal to flow, ft
- Ys = 18.2 scour depth, ft

Apply USGS/HEC18 armoring correction: K4

$Y_s * K4 = 7.8$ ft

scour * factor