Buoyancy Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/27/2023

Spreadsheet Description

- The spreadsheet below is used to calculate the Factor of Safety against Buoyant uplift of the LWM

Assumptions:

1) The LWM structure behaves as a single structure under the design load and will not experience any shearing at joints
2) The LWM structure will be submerged during the design event.
3) Negative buoyancy is uplift, positive numbers equals downward.
4) Ballast material remains intact and is not scoured out.
5) The uplift due to racking material is evenly dividing among all layers.

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells automatically populated from Input to Interface Tab)
Input (Cells requiring input from a dropdown list)
Output (Cells automatically updated are this color)
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FBD and Equations:

$$FOS_b = \frac{F_{LWMd} + F_{boulders} + F_{soil} + F_{piles-e}}{|F_{LWMs} + F_L|}$$ **Equation 18**

FOS_b = *buoyancy factor of safety*

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design buoyancy factor of safety (FOS_b) for this structure is #.# per Table 4 "*Minimum Recommended Factors of Safety".***

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{buoyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Large Wood Material Force - Dry (F_{LWMd})

$$F_{LWMd} = V_{LWMd} * \gamma_{wood}$$ **Equation 3**

V_{LWMd} = *volume of dry large wood material*

Comment: Assumed to be zero because structure assumed to be submerged during design event.

2. Boulder Ballast Force ($F_{boulder}$)

$N_{bouldersub}$			Number of submerged boulders (from design)
$d_{bouldersub}$	2.5	ft	Effective diameter of submerged boulder (ft, from spec)
$\gamma_{boulder}$	146	lb/ft^3	unit weight of boulders (Table 5)
γ_{water}	62.4	lb/ft^3	unit weight of water
$F_{bouldersub}$		lb	Eqn. 6
$N_{boulderdry}$			Number of dry boulders (from detail)
$d_{boulderdry}$	2.5	ft	Effective diameter of dry boulder (ft, from spec)
$F_{boulderdry}$		lb	Eqn. 7
$F_{boulder}$		**lb**	**Eqn. 5**

Comment: The intent is design without the use of boulders so it is assumed no boulders are used.

$$F_{boulder} = F_{bouldersub} + F_{boulderdry}$$ **Equation 5**

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

$N_{bouldersub}$ = *number of submerged boulders*
$d_{bouldersub}$ = *effective diameter of submerged boulders*
$\gamma_{boulder}$ = *unit weight of boulders*

$$F_{boulderdry} = N_{boulderdry} * \frac{\pi}{6} * d_{boulderdry}^3 * \gamma_{boulder}$$ **Equation 7**

$N_{boulderdry}$ = *number of unsubmerged boulders*
$d_{boulderdry}$ = *effective diameter of unsubmerged boulders*

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3. Soil Backfill Force (F_{soil})

$N_{logssub1}$	2		Number of Type 1 buried logs (from detail)
L_{eb1}	26.5	ft	Average embedded length of Type 1 logs (from detail)
d_{bole1}	1.5	ft	Average diameter of Type 1 logs (from detail)
$h_{soilsub1}$	3	ft	Average height of submerged soil above Type 1 log (from detail)
$V_{soilsub1}$	239	ft^3	Volume of submerged soil above Type 1 log (from detail)
$h_{soildry1}$		ft	Average height of dry soil above Type 1 log (from detail)
$V_{soildry1}$		ft^3	Volume of dry soil above Type 1 log (from detail)
$N_{logssub2}$	1		Number of Type 2 buried logs (from detail)
L_{eb2}		ft	Average embedded length of Type 2 logs (from detail)
d_{bole2}	2	ft	Average diameter of Type 2 logs (from detail)
$h_{soilsub2}$		ft	Average height of submerged soil above Type 2 log (from detail)
$V_{soilsub2}$		ft^3	Volume of submerged soil above Type 2 log (from detail)
$h_{soildry2}$		ft	Average height of dry soil above Type 2 log (from detail)
$V_{soildry2}$		ft^3	Volume of dry soil above Type 2 log (from detail)
$N_{logssub3}$	3		Number of Type 3 buried logs (from detail)
L_{eb3}		ft	Average embedded length of Type 3 logs (from detail)
d_{bole3}	1	ft	Average diameter of Type 3 logs (from detail)
$h_{soilsub3}$		ft	Average height of submerged soil above Type 3 log (from detail)
$V_{soilsub3}$		ft^3	Volume of submerged soil above Type 3 log (from detail)
$h_{soildry3}$		ft	Average height of dry soil above Type 3 log (from detail)
$V_{soildry3}$		ft^3	Volume of dry soil above Type 3 log (from detail)
γ_{soil}	126	lb/ft^3	Specific Gravity of bank/backfill material (Table 5)
γ_{water}	62.4	lb/ft^3	Unit weight of water
SG_{rock}	2.64		Specific Gravity of Rock (Using unit weight of bedrock from Table 5)
e	0.31		Eqn. 14
γ_{sat}	141	lb/ft^3	Eqn. 13
γ'_{soil}	78.3	lb/ft^3	Eqn. 12
F_{soil}	**18,668**	**lb**	**Eqn. 8**

$$F_{soil} = \sum_i^n V_{soilsub_i} * \gamma'_{soil} + V_{soildry_i} * \gamma_{soil}$$ **Equation 8**

$$V_{soilsub_i} = L_{eb_i} d_{bole_i} h_{soilsub_i}$$ **Equation 9**

$V_{soilsubi}$ = volume of submerged soil above log i
L_{ebi} = embedded length of log i
d_{bolei} = bole diameter of log i
$h_{soilsubi}$ = height of submerged soil above log i

$$V_{soildry_i} = L_{eb_i} d_{bole_i} h_{soildry_i}$$ ***Equation 10***

$V_{soildryi}$ = volume of dry soil above log i
$h_{soildryi}$ = height of dry soil above log i

$$\gamma_{soil} = (99.2 + 18.6 * \log(d_{50}))$$ **Equation 11**

d_{50} = median grain size in millimeters

$$\gamma'_{soil} = \gamma_{sat} - \gamma_w$$ **Equation 12**

$$\gamma_{sat} = \frac{(SG_{rock} + e) * \gamma_w}{1 + e}$$ **Equation 13**

$$e = \frac{SG_{rock} * \gamma_w}{\gamma_{soil}} - 1$$ **Equation 14**

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4. Pile Skin Friction

N_{piles}			Number of piles (Design)
d_{piles}	0.5	ft	Diameter of piles (Design)
L_{piles}	7.5	ft	Embedded length of piles (Design)
k_s	1		Coefficient of lateral earth pressure (0.5 to 1.5 depending on soil and density)
Placement Method	Driven or Vibrated		Method of pile placement
Placement Multiplier	1		See RBDG (P. 52)
Pile Placement Location	Bed		Bed or Bank
ϕ_{soil}	0.72	rad	Internal angle of friction of soils (Table 5)
γ_{soil}	137	lb/ft^3	Specific Weight of Soil
e	0.20		Eqn. 14
γ_{sat}	148	lb/ft^3	Eqn. 13
γ_{water}	62.4	lb/ft^3	Unit weight of water
σ'	638	lb/ft^2	Eqn 16
γ_{wood}	33	lb/ft^3	Unit weight of wood
$F_{piles-v}$		**lb**	**Eqn 15**

$$F_{piles-v} = N_{piles} * \pi * d_{piles} * L_{piles}(k_s * \tan\frac{2}{3}\emptyset * \sigma' + \frac{d_{piles}}{4} * (\gamma_{wood} - \gamma_w))$$

Equation 15

N_{piles} = number of piles
d_{piles} = diameter of piles
L_{piles} = embedded length of piles
k_s = coefficient of lateral earth pressure (0.5 to 1.5 depending on soil and density)
ϕ = internal angle of friction of soils

$$\sigma' = L_{piles} * (\gamma_{sat} - \gamma_w)$$

Equation 16

$$\gamma_{sat} = \frac{(SG_{rock} + e) * \gamma_w}{1 + e}$$

Equation 13

$$e = \frac{SG_{rock} * \gamma_w}{\gamma_{soil}} - 1$$

Equation 14

Assumptions:
*** k_s = 1**
**** This calculation is based on the assumption that piles are driven or vibrated into place. If piles are drilled or excavated, the associated coefficicient of lateral earth pressures shall be approx. 50% and 25% of the driven value, respectively.**
***** For use in buoyancy calculations, piles must be mechanically fastened.**
****** Top 2' of pile embedment disregarded for calculation to account for vortex shedding.**

5. Large Wood Material Force - Submerged (F_{LWMs})

$$F_{LWMs} = V_{LWMs} * (\gamma_{wood} - \gamma_w)$$

Equation 2

V_{LWMs} = volume of submerged large wood material
γ_{wood} = unit weight of wood
γ_w = unit weight of water

$N_{logssub1}$	2		Number of log type 1 (from detail)
L_{log1}	40	ft	Length of log type 1 (from detail)
d_{bole1}	1.5	ft	Diameter of log type 1 (from detail)
d_{rw1}	3.00	ft	Diameter of rootwad of log type 1 (from detail)
V_{LWMs1}	156	ft^3	Volume of LWM1
$N_{logssub2}$	2		Number of log type 2 (from detail)
L_{eb2}	25	ft	Length of log type 2 (from detail)
d_{bole2}	1.75	ft	Diameter of log type 2 (from detail)
d_{rw2}	4	ft	Diameter of rootwad of log type 2 (from detail)
V_{LWMs2}	150	ft^3	Volume of LWM2
$N_{logssub3}$	1		Number of log type 3 (from detail)
L_{eb3}	15	ft	Length of log type 3 (from detail)
d_{bole3}	0.75	ft	Diameter of log type 3 (from detail)

Volume of Rootwad

National Large Wood Manual. 2016

Equation 6-4 (p. 6-38)

$V_{rw} = \pi * t_k * w_k^2 / 3$

$\pi * (2d_{bole}) * (1/2d_{rw})^2 / 3$

t_k = Thickness of rootwad measured in direction parallel to trunk

= 4 times the radius of the log ($4r_k$ or

w_k =

Radius of rootwad

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d_{rw3}		ft	Diameter of rootwad of log type 3 (from detail)
V_{LWMs3}	7	ft^3	Volume of LWM3
V_{LWMs}	312	ft^3	Volume of LWM
γ_{wood}	33.0	lb/ft^3	Unit weight of logs
γ_w	62.4	lb/ft^3	Unit weight of water
F_{LWMs}	**-9,165**	**lb**	**Eqn. 3**

= 2.5 times the radius of the log ($2.5r_k$ or $1.25d_{bole}$) or 1/2 d_{rw} specified

6. Lift Forces (F_L)

$$F_L = -\frac{C_L \cdot A_{LWM} \cdot \gamma_w \cdot U_o^2}{2 \cdot g} \qquad \text{Equation 4}$$

C_L = lift coefficient
A_{LWM} = area of large woody material perpendicular to flow
u_u = upstream channel velocity at design event
g = acceleration due to gravity

C_L	0.45		Lift Coefficient
A_{LWM}	120	ft^2	Calc'd in Drag Forces
γ_w	62.4	lb/ft^3	Unit weight of water
U_o	6.5	ft/s	upstream velocity (from model)
g	32.2	ft/s^2	Unit weight of water
F_L	**-2,211**	**lb**	**Eqn. 4**

Comment: Lift forces neglected per Section 6.4.2 of BOR Risk Based Design Guidelines

Factor of Safety

FOS_b =	$(F_{LMDd} + F_{boulders} + F_{soil} + F_{piles\text{-}v}) / (F_{LWMs} + F_L)$		
F_{LWMd}		lb	Assumed Zero
$F_{boulder}$		lb	
F_{soil}	18,668	lb	
$F_{piles\text{-}v}$		lb	
F_{LWMs}	-9,165	lb	
F_L	-2,211	lb	
FOS_b	**1.64**		**STABLE FOR BUOYANCY**

Summary Comments:

Sliding Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

Spreadsheet Description

Purpose: The spreadsheet below is used to calculate the Factor of Safety against LWM sliding.

Assumptions:
1) The LWM structure behaves as a single structure under the design load and will not experience any shearing at joints.
2) The effect of soil in back of the structure is negligible.
3) The structure will be submerged during the design event.
4) Channel velocity (V_c) taken from hydraulic model.
5) This LWM structure experiences the largest loads. All LWM structures on site will be designed based on this LWM structure's loadings.

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FBD and Equations:

$$FOS_{sliding} = \frac{|F_{hd}+F_f+F_{piles-h}+F_{passive}|}{F_d+F_{hu}+F_t}$$ Equation 41

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design Sliding Factor of Safety ($FOS_{sliding}$) for this structure is #.# per Table 4 "Minimum Recommended Factors of Safety".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{bouyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Drag Force (F_d)

Y_u	4.50	ft	Upstream water depth
hdebris	6	ft	Debris height (incl. accumulation)
wdebris	20	ft	Debris width (incl. accumulation)
Debris Shape	Rectangle		
A_{LWM}	120	ft^2	Wetted area of LWM
γ_{water}	62.40	lb/ft^3	Unit weight of water
v_c	6.50	ft/s	Velocity from Model
g	32.20	ft/s^2	Acceleration due to gravity
A_b	120.00	ft^2	Debris area
$w_{channel}$	60	ft	Channel width
c_d	1.50		NLWM Worst Case
F_d	7369	lb	Eqn 19

$$F_d = \frac{C_D * A_{LWM} * \gamma_w * U_c^2}{2 * g}$$ **Equation 19**

F_d = *drag force*
C_d = *drag coefficient*
A_{LWM} = *area of wetted debris based on the upstream water surface elevation projected normal to flow direction and the potential drift accumulation*
γ_w = *unit weight of water*
U_c = *velocity in contracted section*
g = *acceleration due to gravity*

Cd can be assumed 0.9 when fully submerged, 1.5 when WSEL withi

$$C_{d-applied} = \frac{C_d}{(1-B)^2}$$ C_d is typically estimated as 1.0 Equation 27

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3. Impact Force (F_i)

L_{debris}	40	ft	Length of debris member (Design)
$d_{boledebris}$	1.5	ft	Bole diameter of debris member (Design)
$d_{rwdebris}$	4	ft	Rootwad diameter of debris member (Design)
V_{debris}	83	ft^3	Volume of debris
γ_{wood}	33	lb/ft^3	Unit weight of wood
w_{debris}	2,747	lb	weight of debris
g	32.2	ft/s^2	Acceleration due to gravity
$V_{channel}$	6.5	ft/s	Velocity from Model
Δt	0.03	sec	Impact Interval (0.03 sec recommended)
C_i	0.8		Coefficient of importance (from Table 6)
C_o	0.8		Coefficient of orientation
C_d	0.875		Figure 11 (need water depth from model)
Degree of Screening or Sheltering Upstream	Limited upstream screening, flow path 20' wide		ASCE 7-05
C_b	0.6		ASCE 7-05
R_{max}	0.8		Response ratio for impulsive loads
F_i	**7,805**	**lb**	**Eqn 30**

$$F_i = \frac{\pi w_{debris} * V_{channel} * C_i * C_o * C_d * C_b * R_{max}}{2 * g * \Delta t}$$ **Equation 30**

F_i = impact force

w_{debris} = weight of debris

g = acceleration constant due to gravity

$V_{channel}$ = water velocity in channel

Δt = time from initial velocity to zero velocity

C_i = coefficient of importance

C_o = coefficient of orientation = 0.8

C_d = coefficient of depth

C_b = coefficient of blockage

R_{max} = response ratio for impulsive loads = 0.8

Assumption:

***Largest impact force would be generated by structure being struck by floating large key member. For impact calculation, assuming 18" diameter, 30' long member with rootwad impacts structure.**
****See Section 6.3.3 of LWM RBDG (P. 44) for debris loading sizing.**

4. Friction Force (F_f)

ϕ_{bed}	0.72	radians	Calculated for streambed material (small cobble)
μ_{bed}	0.87		Eqn 32
F_{LWMd}		lb	Buoyancy Calcs
$F_{boulder}$		lb	Buoyancy Calcs
F_{soil}	18668	lb	Buoyancy Calcs
$F_{piles-v}$		lb	Buoyancy Calcs
F_{LWMs}	-9165	lb	Buoyancy Calcs
F_L	-2211	lb	Buoyancy Calcs
F_b	7,293	lb	Eqn 17
F_f	**-6,340**	**lb**	**Eqn 31**

$$F_f = -\mu_{bed} * (F_b - F_{piles-v})$$ Equation 31

F_f = force due to frictional resistance

F_b-$F_{piles-v}$ >0

$$\mu_{bed} = \tan \emptyset$$ Equation 32

$$F_b = F_{LWMs} + F_{LWMd} + F_L + F_{boulder} + F_{soil} + F_{piles-v}$$ ***Equation 17***

Note:
***If buoyancy forces are less than vertical pile forces (Fb-Fpiles-v<0), then friction force = 0.**

Sliding Calculations

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Latest Revision: #########

5. Passive Forces ($F_{passive}$)

ϕ_{bank}	0.66	radians	Calculated for bank material (very course gravel)
K_p	4.20		Eqn 34
γ_{water}	62.4	lb/ft^3	Unit weight of water
γ_{soil}	126	lb/ft^3	Unit weight of soil
γ_{sat}	141	lb/ft^3	Previously calculated for buoyancy calcs
$N_{logssub1}$	2		Number of log type 1 (from detail)
Orientation$_1$**	Perpendicular		Perpendicular or Parallel to flow
L_{eb1}	26.5	ft	Length of log type 1 (from detail)
d_{bole1}	1.5	ft	Diameter of log type 1 (from detail)
D_{sub1}	3	ft	Depth of submerged soil above log 1
D_{dry1}		ft	Depth of dry soil above log 1
σ_{v1}	235	lb/ft^2	
$\sigma_{v1}*L_{eb1}*\gamma_{soil}$	18,668	lb	
$N_{logssub2}$	1		Number of log type 2 (from detail)
Orientation$_2$**	Parallel		Perpendicular or Parallel to flow
L_{eb2}		ft	Length of log type 2 (from detail)
d_{bole2}	2	ft	Diameter of log type 2 (from detail)
D_{sub2}		ft	Depth of submerged soil above log 2
D_{dry2}		ft	Depth of dry soil above log 2
σ_{v2}		lb/ft^2	
$\sigma_{v2}*L_{eb2}*\gamma_{soil}$		lb	
$N_{logssub3}$	3		Number of log type 3(from detail)
Orientation$_3$**	Perpendicular		Perpendicular or Parallel to flow
L_{eb3}		ft	Length of log type 3 (from detail)
d_{bole3}	1	ft	Diameter of log type 3 (from detail)
D_{sub3}		ft	Depth of submerged soil above log 3
D_{dry3}		ft	Depth of dry soil above log 3
σ_{v3}		lb/ft^2	
$\sigma_{v3}*L_{eb3}*\gamma_{soil}$		lb	
$F_{passive}$	**-39,238**	**lb**	**Eqn 31**

4.20374584

**** Eqns 33 through 35 represent the case where passive forces act**

$$F_{passive} = -0.5 * K_p * \sum_i^n \sigma_{v_i} * L_{em_i} * d_{log_i}$$ Equ

$$K_p = \frac{1+\sin\phi}{1-\sin\phi}$$ Equ

$$\sigma_{v_i} = D_{sub_i} * (\gamma_{sat} - \gamma_{water}) + D_{dry_i} * \gamma_{soil}$$ Equ

D_{subi} = depth of submerged soil above log i
D_{dryi} = depth of dry soil above log i
L_{emi} = embedded length of log i
d_{logi} = diameter of log i

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6. Lateral Resistance from Piles ($F_{piles\text{-}h}$)

N_{piles}	4		Number of piles (Design)
d_{piles}	1	ft	Diameter of piles (Design)
L_{piles}	8	ft	Embedded length of piles below scour (Design)
Placement Method	Drilled		Method of pile placement
Placement Multiplier	0.25		See RBDG (P. 52)
Pile Placement Location	Bed		Bed or Bank
γ_{water}	62.4	lb/ft^3	Unit weight of water
γ_{soil}	137	lb/ft^3	Unit weight of soil
γ_e	74.6	lb/ft^3	Eqn 37
ϕ_{soil}	0.72	radians	Calculated for material pile is located
K_p	4.81		Eqn 38
h_{load}**	3	ft	Height above scour depth load is applied
$F_{piles\text{-}h}$	**-8,359**	**lb**	**Eqn 15**

*** Top 2' of pile embedment disregarded for calculation to account for vortex shedding.**

**** Analysis also assumes that the resultant force is located at half of the flow depth on the upstream side of the LWM structure to produce a conservative moment on the pile.**

$$F_{piles-h} = -N_{piles} * \frac{L_{pile}^3 * \frac{1}{2} * \gamma_e * d_{pile} * K_p}{h_{load} + L_{pile}} \quad \text{Equation 36}$$

N_{piles} = number of piles
L_{pile} = length of pile embedded below potential scour depth

$$\gamma_e = \gamma_s - \gamma_w \quad \text{effective unit weight of soil} \quad \text{Equation 37}$$

γ_s = dry unit weight of the soil

γ_w = unit weight of the soil
d_{pile} = diameter of the pile
h_{load} = height above the potential scour depth the load is applied

$$K_p = \frac{1+\sin\phi}{1-\sin\phi} \quad \text{Equation 38}$$

Factor of Safety

$FOS_{sliding}$ =	$(F_{hd} + F_f + F_{piles\text{-}h} + F_{passive}) / (F_d + F_{hu} + F_i)$		
F_d	7,369	lb	
F_{hu}		lb	
F_{hd}		lb	
F_i	7,805	lb	
F_f	-6,340	lb	
$F_{passive}$	-39,238	lb	
$F_{piles\text{-}h}$	-8,359	lb	
$FOS_{sliding}$	**3.55**		**STABLE FOR SLIDING**

Summary Comments:

Rotation Calculations

Project: Tucannon
Project Number: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

Spreadsheet Description

Purpose: The spreadsheet below is used to calculate the Factor of Safety against LWM structure horizontal rotation.

Assumptions:
1) The LWM structue behaves as a single structure under the design load.
2) The effect of soil in back of the structure is negligible.
3) The structure will be submerged during the design event
4) This LWM structure experiences the largest loads. All LWM structures on site will be designed based on this LWM structure's loadings

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells requiring input from a dropdown list)
Input (Cells automatically populated from Input to Interface Tab)
Output (Cells that are automatically updated are this color)
Output (Cells that are automatically updated with previously calculated values are this color)

FBD and Equations:

$$FOS_{rotation} = \frac{MR_{rotation}}{MD_{rotation}}$$ **Equation 45**

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design Rotation Factor of Safety ($FOS_{rotation}$) for this structure is #.# per Table 4 "Minimum Recommended Factors of Safety".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{bouyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Resistance to Rotation ($MR_{rotation}$ and $MD_{rotation}$)

$$MD_{rotation} = (F_i + F_d + F_{hu}) * \left(\frac{L_{sp}+L_{ebp}}{2}\right)$$ **Equation 42**

L_{sp} = length of wood structure from tip to point of rotation measured perpendicular to flow

L_{ebp} = embedded length of wood structure measured perpendicular to flow

$$MR_{rotation} = \left| F_{hd} * \left(\frac{L_{sp}+L_{ebp}}{2}\right) + F_{passive} * \frac{L_{ebp}}{2} + F_f * \frac{L_{sp}}{2} + \sum_i^n F_{pile-h_i} * L_{ph_i} \right|$$ **Equation 43**

$$F_{pile-h_i} = \frac{F_{piles-h}}{N_{piles}}$$ **Equation 44**

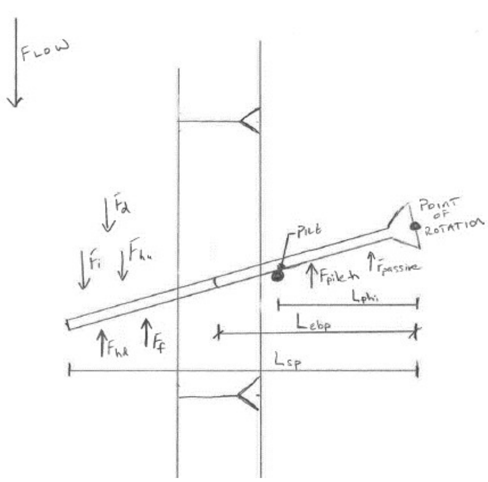
L_{phi} = distance from pile 'i' to the point of rotation measured perpendicular to flow

Driving:

L_{sp}	20	ft	Length of wood structure from tip to point of rotation measured perpendicular to flow
L_{ebp}	10	ft	Embedded length of wood structure measured perp. to flow
F_i	7,805	lb	Impact Forces (Calc'd in Sliding)
F_d	7,369	lb	Drag Forces (Calc'd in Sliding)
F_{hu}		lb	Upstream Hydrostatic Forces (Calc'd in Sliding)
$MD_{rotation}$	**227,613**	**lb*ft**	**Eqn 42**

Resisting:

F_{hd}		lb	Downstream Hydrostatic Forces (Calc'd in Sliding)
$F_{passive}$	-39,238	lb	Passive Forces (Calc'd in Sliding)
F_f	-6,340	lb	Friction Forces (Calc'd in Sliding)
F_{pile-h}	-8,359	lb	Lateral Resistance from Piles (Calc'd in Sliding)
$F_{pile-hi}$	-2,090	lb	Lateral Resistance from Piles (Calc'd in Sliding)
N_{piles}	4		Number of Piles (Design)
L_{phi}	35	ft	Distance from pile to the point of rotation measured perp. to flow.
$MR_{rotation}$	**552,166**	**lb*ft**	**Eqn 43**



Factor of Safety

$FOS_{rotation}$ =	*$MR_{rotation}$ / $MD_{rotation}$*		
$MD_{rotation}$	227,613	lb	
$MR_{rotation}$	552,166	lb	
$FOS_{rotation}$	**2.43**		**STABLE FOR ROTATION**

Summary Comments:

Rotation Calculations

Project:	Tucannon	**Analyst:**	ASD
Project Number:	Project Number	**Calculations Checked By:**	ALJ
		Latest Revision:	#########

Overturning Calculations

Project: Tucannon
Project Number: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/27/2023

Spreadsheet Description

Purpose: The spreadsheet below is used to calculate the Factor of Safety against vertical overturning.

Assumptions:
1) The LWM structure behaves as a single structure under the design load.
2) The effect of soil in back of the structure is negligible.
3) The structure will be submerged during the design event
4) This LWM structure experiences the largest loads. All LWM structures on site will be designed based on this LWM structure's loadings

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells requiring input from a dropdown list)
Input (Cells automatically populated from Input to Interface Tab)
Output (Cells automatically updated are this color)
Output (Cells automatically updated with previously calculated values are this color)

FBD and Equations:

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$ **Equation 49**

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design Overturn Factor of Safety ($FOS_{overturn}$) for this structure is #.# per Table 4 "Minimum Recommended Factors of Safety".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{buoyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Resistance to Overturn ($MR_{rotation}$ and $MD_{rotation}$)

Driving:

F_i	7,805	lb	Impact Forces (Calc'd in Sliding)
F_d	7,369	lb	Drag Forces (Calc'd in Sliding)
F_{hu}		lb	Upstream Hydrostatic Forces (Calc'd in Sliding)
F_L	-2,211	lb	Lift Forces (Assumed Zero in Buoyancy Calcs)
Y_u	4.5	ft	Upstream water elevation from model
d_{ubury}		ft	Depth at upstream side of structure from channel bottom to point of rotation measured perp to flow
L_s		ft	Length of structure parallel to flow
$MD_{overturn}$	**51,704**	**lb*ft**	**Eqn 46**

$$MD_{overturn} = F_i * (Y_u + d_{bury}) + F_d * \left(\frac{Y_u}{2} + d_{bury}\right) + F_{hu} * \left(\frac{Y_u}{3} + du_{bury}\right) + |F_L| * L_s$$

Equation 46

du_{bury} = depth at the upstream side of the structure from channel bottom to point of rotation measured perpendicular to flow
Ls = length of structure measured parallel to flow

$$MR_{overturn} = |F_{hd}| * \left(\frac{Y_d}{2} + dd_{bury}\right) + |F_{passive}| * (dd_{bury}) + (F_b - F_L - F_{piles-v}) * \frac{L_s}{2} + \sum_i^n F_{pile-v_i} * Lpv_i$$ **Equation 47**

$$F_{pile-v_i} = \frac{F_{piles-v}}{N_{piles}}$$ **Equation 48**

L_{pvi} = distance from pile 'i' to the point of rotation measured parallel to flow

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$ **Equation 49**

Resisting:

F_{hd}		lb	Downstream Hydrostatic Forces (Calc'd in Sliding)
$F_{passive}$	-39,238	lb	Passive Forces (Calc'd in Sliding)
F_b	7,293	lb	Buoyancy Forces (Calc'd in Sliding)
F_{pile-v}	-8,359	lb	Lateral Resistance from Piles (Calc'd in Sliding)
Y_d	4.5	ft	Downstream water elevation
d_{dbury}	4.5	ft	Depth at downstream side of structure from channel bottom to point of rotation measured perp to flow
N_{piles}	2		Number of Piles (Design)
L_{pvi}	35	ft	Distance from pile to the point of rotation measured parallel to flow.
$F_{pile-vi}$		lb	Eqn 48
$MR_{overturn}$	**176,570**	**lb*ft**	**Eqn 47**

Factor of Safety

$FOS_{overturnon}$ = $MR_{overturn}$ / $MD_{overturn}$			
$MD_{overturn}$	51,704	lb	
$MR_{overturn}$	176,570	lb	
$FOS_{overturn}$	**3.42**		**STABLE FOR OVERTURN**

Overturning Calculations

Project:	Tucannon	**Analyst:**	ASD
Project Number:	Project Number	**Calculations Checked By:**	ALJ
		Latest Revision:	2/27/2023

Summary Comments:

Factor of Safety Summary

Project: Tucannon
Project Number: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/27/2023

Spreadsheet Description

Purpose: The spreadsheet below summarizes the factors of safety for the LWD structure.

Assumptions:

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells automatically populated from Input to Interface Tab)
Output (Cells automatically updated are this color)
Output (Cells automatically updated with previously calculated values are this

Tables and Equations:

$$FOS_b = \frac{F_{LWMd} + F_{boulders} + F_{soil} + F_{piles-v}}{|F_{LWMs} + F_L|}$$ Equation 18

FOS_b = buoyancy factor of safety

$$FOS_{sliding} = \frac{|F_{hd} + F_f + F_{piles-h} + F_{passive}|}{F_d + F_{hu} + F_l}$$ Equation 41

$$FOS_{rotation} = \frac{MR_{rotation}}{MD_{rotation}}$$ Equation 45

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$ Equation 49

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{buoyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Factors of Safety Summary

Project Public Safety Risk	*High*
Project Property Damage Risk	*Low*

Safety Factors		Minimum Recommended Safety Factor	Calculated Safety Factor	Result
Buoyancy	FOS_b	1.50	1.64	**OK!**
Sliding	$FOS_{sliding}$	1.25	3.55	**OK!**
Rotation	$FOS_{rotation}$	1.25	2.43	**OK!**
Overturn	$FOS_{overturn}$	1.25	3.42	**OK!**

Summary Comments:

Buoyancy Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/28/2023

Spreadsheet Description

- The spreadsheet below is used to calculate the Factor of Safety against Buoyant uplift of the LWM

Assumptions:

1) The LWM structure behaves as a single structure under the design load and will not experience any shearing at joints
2) The LWM structure will be submerged during the design event.
3) Negative buoyancy is uplift, positive numbers equals downward.
4) Ballast material remains intact and is not scoured out.
5) The uplift due to racking material is evenly dividing among all layers.

Input (Cells Requiring Input from Structure Detail)
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Output (Cells automatically updated are this color)
Output (Cells automatically updated with previously calculated values are this color)

FBD and Equations:

$$FOS_b = \frac{F_{LWMd} + F_{boulders} + F_{soil} + F_{piles-e}}{|F_{LWMs} + F_L|} \quad \text{Equation 18}$$

FOS_b = buoyancy factor of safety

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design buoyancy factor of safety (FOS_b) for this structure is #.# per Table 4 "*Minimum Recommended Factors of Safety*".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{buoyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Large Wood Material Force - Dry (F_{LWMd})

$$F_{LWMd} = V_{LWMd} * \gamma_{wood} \quad \text{Equation 3}$$

V_{LWMd} = volume of dry large wood material

Comment: Assumed to be zero because structure assumed to be submerged during design event.

2. Boulder Ballast Force ($F_{boulder}$)

$N_{bouldersub}$			Number of submerged boulders (from design)
$d_{bouldersub}$	2.5	ft	Effective diameter of submerged boulder (ft, from spec)
$\gamma_{boulder}$	146	lb/ft^3	unit weight of boulders (Table 5)
γ_{water}	62.4	lb/ft^3	unit weight of water
$F_{bouldersub}$		lb	Eqn. 6
$N_{boulderdry}$			Number of dry boulders (from detail)
$d_{boulderdry}$	2.5	ft	Effective diameter of dry boulder (ft, from spec)
$F_{boulderdry}$		lb	Eqn. 7
$F_{boulder}$		**lb**	**Eqn. 5**

$$F_{boulder} = F_{bouldersub} + F_{boulderdry} \quad \text{Equation 5}$$

$$F_{bouldersub} = N_{bouldersub} * \frac{\pi}{6} * d^3_{bouldersub} * (\gamma_{boulder} - \gamma_w) \quad \text{Equation 6}$$

$N_{bouldersub}$ = number of submerged boulders
$d_{bouldersub}$ = effective diameter of submerged boulders
$\gamma_{boulder}$ = unit weight of boulders

$$F_{boulderdry} = N_{boulderdry} * \frac{\pi}{6} * d^3_{boulderdry} * \gamma_{boulder} \quad \text{Equation 7}$$

$N_{boulderdry}$ = number of unsubmerged boulders
$d_{boulderdry}$ = effective diameter of unsubmerged boulders

Comment: The intent is design without the use of boulders so it is assumed no boulders are used.

Buoyancy Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/28/2023

3. Soil Backfill Force (F_{soil})

$N_{logssub1}$	1		Number of Type 1 buried logs (from detail)
L_{eb1}	20	ft	Average embedded length of Type 1 logs (from detail)
d_{bole1}	1.25	ft	Average diameter of Type 1 logs (from detail)
$h_{soilsub1}$		ft	Average height of submerged soil above Type 1 log (from detail)
$V_{soilsub1}$		ft^3	Volume of submerged soil above Type 1 log (from detail)
$h_{soildry1}$		ft	Average height of dry soil above Type 1 log (from detail)
$V_{soildry1}$		ft^3	Volume of dry soil above Type 1 log (from detail)
$N_{logssub2}$	2		Number of Type 2 buried logs (from detail)
L_{eb2}	27	ft	Average embedded length of Type 2 logs (from detail)
d_{bole2}	1.75	ft	Average diameter of Type 2 logs (from detail)
$h_{soilsub2}$	3	ft	Average height of submerged soil above Type 2 log (from detail)
$V_{soilsub2}$	284	ft^3	Volume of submerged soil above Type 2 log (from detail)
$h_{soildry2}$		ft	Average height of dry soil above Type 2 log (from detail)
$V_{soildry2}$		ft^3	Volume of dry soil above Type 2 log (from detail)
$N_{logssub3}$			Number of Type 3 buried logs (from detail)
L_{eb3}	25	ft	Average embedded length of Type 3 logs (from detail)
d_{bole3}	1.75	ft	Average diameter of Type 3 logs (from detail)
$h_{soilsub3}$		ft	Average height of submerged soil above Type 3 log (from detail)
$V_{soilsub3}$		ft^3	Volume of submerged soil above Type 3 log (from detail)
$h_{soildry3}$		ft	Average height of dry soil above Type 3 log (from detail)
$V_{soildry3}$		ft^3	Volume of dry soil above Type 3 log (from detail)
γ_{soil}	131	lb/ft^3	Specific Gravity of bank/backfill material (Table 5)
γ_{water}	62.4	lb/ft^3	Unit weight of water
SG_{rock}	2.64		Specific Gravity of Rock (Using unit weight of bedrock from Table 5)
e	0.26		Eqn. 14
γ_{sat}	144	lb/ft^3	Eqn. 13
γ'_{soil}	81.4	lb/ft^3	Eqn. 12
F_{soil}	**23,071**	**lb**	**Eqn. 8**

$$F_{soil} = \sum_i^n V_{soilsub_i} * \gamma'_{soil} + V_{soildry_i} * \gamma_{soil}$$ **Equation 8**

$$V_{soilsub_i} = L_{eb_i} d_{bole_i} h_{soilsub_i}$$ **Equation 9**

$V_{soilsubi}$ = volume of submerged soil above log i
L_{ebi} = embedded length of log i
d_{bolei} = bole diameter of log i
$h_{soilsubi}$ = height of submerged soil above log i

$$V_{soildry_i} = L_{eb_i} d_{bole_i} h_{soildry_i}$$ ***Equation 10***

$V_{soildryi}$ = volume of dry soil above log i
$h_{soildryi}$ = height of dry soil above log i

$$\gamma_{soil} = (99.2 + 18.6 * \log(d_{50}))$$ **Equation 11**

d_{50} = median grain size in millimeters

$$\gamma'_{soil} = \gamma_{sat} - \gamma_w$$ **Equation 12**

$$\gamma_{sat} = \frac{(SG_{rock} + e) * \gamma_w}{1 + e}$$ **Equation 13**

$$e = \frac{SG_{rock} * \gamma_w}{\gamma_{soil}} - 1$$ **Equation 14**

Buoyancy Calculations

Project:	Tucannon	**Analyst:**	ASD
Project No.:	Project Number	**Calculations Checked By:**	ALJ
		Latest Revision:	2/28/2023

4. Pile Skin Friction

N_{piles}			Number of piles (Design)
d_{piles}	0.83	ft	Diameter of piles (Design)
L_{piles}	8	ft	Embedded length of piles (Design)
k_s	1		Coefficient of lateral earth pressure (0.5 to 1.5 depending on soil and density)
Placement Method	Excavated		Method of pile placement
Placement Multiplier	0.25		See RBDG (P. 52)
Pile Placement Location	Bed		Bed or Bank
ϕ_{soil}	0.72	rad	Internal angle of friction of soils (Table 5)
γ_{soil}	137	lb/ft^3	Specific Weight of Soil
e	0.20		Eqn. 14
γ_{sat}	148	lb/ft^3	Eqn. 13
γ_{water}	62.4	lb/ft^3	Unit weight of water
σ'	681	lb/ft^2	Eqn 16
γ_{wood}	33	lb/ft^3	Unit weight of wood
$F_{piles-v}$		**lb**	**Eqn 15**

$$F_{piles-v} = N_{piles} * \pi * d_{piles} * L_{piles}(k_s * \tan\frac{2}{3}\phi * \sigma' + \frac{d_{piles}}{4} * (\gamma_{wood} - \gamma_w))$$

Equation 15

N_{piles} = number of piles
d_{piles} = diameter of piles
L_{piles} = embedded length of piles
k_s = coefficient of lateral earth pressure (0.5 to 1.5 depending on soil and density)
ϕ = internal angle of friction of soils

$$\sigma' = L_{piles} * (\gamma_{sat} - \gamma_w)$$

Equation 16

$$\gamma_{sat} = \frac{(SG_{rock}+e)*\gamma_w}{1+e}$$

Equation 13

$$e = \frac{SG_{rock}*\gamma_w}{\gamma_{soil}} - 1$$

Equation 14

Assumptions:
*** k_s = 1**
**** This calculation is based on the assumption that piles are driven or vibrated into place. If piles are drilled or excavated, the associated coefficicient of lateral earth pressures shall be approx. 50% and 25% of the driven value, respectively.**
***** For use in buoyancy calculations, piles must be mechanically fastened.**
****** Top 2' of pile embedment disregarded for calculation to account for vortex shedding.**

5. Large Wood Material Force - Submerged (F_{LWMs})

$$F_{LWMs} = V_{LWMs} * (\gamma_{wood} - \gamma_w)$$

Equation 2

V_{LWMs} = volume of submerged large wood material
γ_{wood} = unit weight of wood
γ_w = unit weight of water

$N_{logssub1}$	1		Number of log type 1 (from detail)
L_{log1}	20	ft	Length of log type 1 (from detail)
d_{bole1}	1.25	ft	Diameter of log type 1 (from detail)
d_{rw1}		ft	Diameter of rootwad of log type 1 (from detail)
V_{LWMs1}	25	ft^3	Volume of LWM1
$N_{logssub2}$	2		Number of log type 2 (from detail)
L_{eb2}	40	ft	Length of log type 2 (from detail)
d_{bole2}	1.75	ft	Diameter of log type 2 (from detail)
d_{rw2}	4.38	ft	Diameter of rootwad of log type 2 (from detail)
V_{LWMs2}	227	ft^3	Volume of LWM2
$N_{logssub3}$			Number of log type 3 (from detail)
L_{eb3}	40	ft	Length of log type 3 (from detail)
d_{bole3}	1.75	ft	Diameter of log type 3 (from detail)

Volume of Rootwad

National Large Wood Manual. 2016

Equation 6-4 (p. 6-38)

$V_{rw} = \pi * t_k * w_k^2 / 3$
$\pi * (2d_{bole}) * (1/2 d_{rw})^2 / 3$

t_k = Thickness of rootwad measured in direction parallel to trunk
= 4 times the radius of the log ($4r_k$ or

w_k =
Radius of rootwad

Buoyancy Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/28/2023

d_{rw3}		ft	Diameter of rootwad of log type 3 (from detail)
V_{LWMs3}		ft^3	Volume of LWM3
V_{LWMs}	252	ft^3	Volume of LWM
γ_{wood}	33.0	lb/ft^3	Unit weight of logs
γ_w	62.4	lb/ft^3	Unit weight of water
F_{LWMs}	**-7,410**	**lb**	**Eqn. 3**

= 2.5 times the radius of the log ($2.5r_k$ or $1.25d_{bole}$) or 1/2 d_{rw} specified

6. Lift Forces (F_L)

$$F_L = -\frac{C_L * A_{LWM} * \gamma_w * U_o^2}{2 * g} \quad \textbf{Equation 4}$$

C_L = lift coefficient
A_{LWM} = area of large woody material perpendicular to flow
u_u = upstream channel velocity at design event
g = acceleration due to gravity

C_L	0.45		Lift Coefficient
A_{LWM}	75	ft^2	Calc'd in Drag Forces
γ_w	62.4	lb/ft^3	Unit weight of water
U_o	6.5	ft/s	upstream velocity (from model)
g	32.2	ft/s^2	Unit weight of water
F_L	**-1,382**	**lb**	**Eqn. 4**

Comment: Lift forces neglected per Section 6.4.2 of BOR Risk Based Design Guidelines

Factor of Safety

FOS_b =	$(F_{LMDd} + F_{boulders} + F_{soil} + F_{piles-v}) / (F_{LWMs} + F_L)$		
F_{LWMd}		lb	Assumed Zero
$F_{boulder}$		lb	
F_{soil}	23,071	lb	
$F_{piles-v}$		lb	
F_{LWMs}	-7,410	lb	
F_L	-1,382	lb	
FOS_b	**2.62**		**STABLE FOR BUOYANCY**

Summary Comments:

Sliding Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

Spreadsheet Description

Purpose: The spreadsheet below is used to calculate the Factor of Safety against LWM sliding.

Assumptions:
1) The LWM structure behaves as a single structure under the design load and will not experience any shearing at joints.
2) The effect of soil in back of the structure is negligible.
3) The structure will be submerged during the design event.
4) Channel velocity (V_c) taken from hydraulic model.
5) This LWM structure experiences the largest loads. All LWM structures on site will be designed based on this LWM structure's loadings.

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
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Output (Cells automatically updated with previously calculated values are this color)

FBD and Equations:

$$FOS_{sliding} = \frac{|F_{hd}+F_f+F_{piles-h}+F_{passive}|}{F_d+F_{hu}+F_l}$$ Equation 41

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design Sliding Factor of Safety ($FOS_{sliding}$) for this structure is #.# per Table 4 "Minimum Recommended Factors of Safety".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{bouyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Drag Force (F_d)

Y_u	3.50	ft	Upstream water depth
hdebris	5	ft	Debris height (incl. accumulation)
wdebris	15	ft	Debris width (incl. accumulation)
Debris Shape	Rectangle		
A_{LWM}	75	ft^2	Wetted area of LWM
γ_{water}	62.40	lb/ft^3	Unit weight of water
v_c	6.50	ft/s	Velocity from Model
g	32.20	ft/s^2	Acceleration due to gravity
A_b	75.00	ft^2	Debris area
$w_{channel}$	60	ft	Channel width
c_d	1.50		NLWM Worst Case
F_d	4606	lb	Eqn 19

$$F_d = \frac{C_D * A_{LWM} * \gamma_w * U_c^2}{2 * g}$$ Equation 19

F_d = drag force
C_d = drag coefficient
A_{LWM} = area of wetted debris based on the upstream water surface elevation projected normal to flow direction and the potential drift accumulation
γ_w = unit weight of water
U_c = velocity in contracted section
g = acceleration due to gravity

Cd can be assumed 0.9 when fully submerged, 1.5 when WSEL withi

$$C_{d-applied} = \frac{C_d}{(1-B)^2}$$ C_d is typically estimated as 1.0 Equation 27

Sliding Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

3. Impact Force (F_i)

L_{debris}	40	ft	Length of debris member (Design)
$d_{boledebris}$	1.5	ft	Bole diameter of debris member (Design)
$d_{rwdebris}$	3	ft	Rootwad diameter of debris member (Design)
V_{debris}	78	ft^3	Volume of debris
γ_{wood}	33	lb/ft^3	Unit weight of wood
w_{debris}	2,566	lb	weight of debris
g	32.2	ft/s^2	Acceleration due to gravity
$V_{channel}$	6.5	ft/s	Velocity from Model
Δt	0.03	sec	Impact Interval (0.03 sec recommended)
C_i	0.8		Coefficient of importance (from Table 6)
C_o	0.8		Coefficient of orientation
C_d	0.625		Figure 11 (need water depth from model)
Degree of Screening or Sheltering Upstream	Limited upstream screening, flow path 20' wide		ASCE 7-05
C_b	0.6		ASCE 7-05
R_{max}	0.8		Response ratio for impulsive loads
F_i	**5,207**	**lb**	**Eqn 30**

$$F_i = \frac{\pi w_{debris} * V_{channel} * C_i * C_o * C_d * C_b * R_{max}}{2 * g * \Delta t}$$ **Equation 30**

$F_i = impact\ force$

$w_{debris} = weight\ of\ debris$

$g = acceleration\ constant\ due\ to\ gravity$

$V_{channel} = water\ velocity\ in\ channel$

$\Delta t = time\ from\ initial\ velocity\ to\ zero\ velocity$

$C_i = coefficient\ of\ importance$

$C_o = coefficient\ of\ orientation = 0.8$

$C_d = coefficient\ of\ depth$

$C_b = coefficient\ of\ blockage$

$R_{max} = response\ ratio\ for\ impulsive\ loads = 0.8$

Assumption:

***Largest impact force would be generated by structure being struck by floating large key member. For impact calculation, assuming 18" diameter, 30' long member with rootwad impacts structure.**
****See Section 6.3.3 of LWM RBDG (P. 44) for debris loading sizing.**

4. Friction Force (F_f)

ϕ_{bed}	0.72	radians	Calculated for streambed material (small cobble)
μ_{bed}	0.87		Eqn 32
F_{LWMd}		lb	Buoyancy Calcs
$F_{boulder}$		lb	Buoyancy Calcs
F_{soil}	23071	lb	Buoyancy Calcs
$F_{piles-v}$		lb	Buoyancy Calcs
F_{LWMs}	-7410	lb	Buoyancy Calcs
F_L	-1382	lb	Buoyancy Calcs
F_b	14,279	lb	Eqn 17
F_f	**-12,413**	**lb**	**Eqn 31**

$$F_f = -\mu_{bed} * (F_b - F_{piles-v})$$ Equation 31

F_f = force due to frictional resistance

$F_b - F_{piles-v} > 0$

$$\mu_{bed} = \tan \emptyset$$ Equation 32

$$F_b = F_{LWMs} + F_{LWMd} + F_L + F_{boulder} + F_{soil} + F_{piles-v}$$ ***Equation 17***

Note:
***If buoyancy forces are less than vertical pile forces (Fb-Fpiles-v<0), then friction force = 0.**

Sliding Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

5. Passive Forces ($F_{passive}$)

Φ_{bank}	0.70	radians	Calculated for bank material (very course gravel)	
K_p	4.60		Eqn 34	4.59890993
γ_{water}	62.4	lb/ft^3	Unit weight of water	
γ_{soil}	131	lb/ft^3	Unit weight of soil	
γ_{sat}	144	lb/ft^3	Previously calculated for buoyancy calcs	
$N_{logssub1}$	1		Number of log type 1 (from detail)	
Orientation$_1$**	Perpendicular		Perpendicular or Parallel to flow	
L_{eb1}	20	ft	Length of log type 1 (from detail)	
d_{bole1}	1.25	ft	Diameter of log type 1 (from detail)	
D_{sub1}		ft	Depth of submerged soil above log 1	
D_{dry1}		ft	Depth of dry soil above log 1	
σ_{v1}		lb/ft^2		
$\sigma_{v1} * L_{eb1} * \gamma_{soil}$		lb		
$N_{logssub2}$	2		Number of log type 2 (from detail)	
Orientation$_2$**	Perpendicular		Perpendicular or Parallel to flow	
L_{eb2}	27	ft	Length of log type 2 (from detail)	
d_{bole2}	1.75	ft	Diameter of log type 2 (from detail)	
D_{sub2}	3	ft	Depth of submerged soil above log 2	
D_{dry2}		ft	Depth of dry soil above log 2	
σ_{v2}	244	lb/ft^2		
$\sigma_{v2} * L_{eb2} * \gamma_{soil}$	23,071	lb		
$N_{logssub3}$			Number of log type 3(from detail)	
Orientation$_3$**	Parallel		Perpendicular or Parallel to flow	
L_{eb3}	40	ft	Length of log type 3 (from detail)	
d_{bole3}	1.75	ft	Diameter of log type 3 (from detail)	
D_{sub3}		ft	Depth of submerged soil above log 3	
D_{dry3}		ft	Depth of dry soil above log 3	
σ_{v3}		lb/ft^2		
$\sigma_{v3} * L_{eb3} * \gamma_{soil}$		lb		
$F_{passive}$	**-53,050**	**lb**	**Eqn 31**	

**** Eqns 33 through 35 represent the case where passive forces act**

$$F_{passive} = -0.5 * K_p * \sum_i^n \sigma_{v_i} * L_{em_i} * d_{log_i}$$ Equ

$$K_p = \frac{1+\sin\phi}{1-\sin\phi}$$ Equ

$$\sigma_{v_i} = D_{sub_i} * (\gamma_{sat} - \gamma_{water}) + D_{dry_i} * \gamma_{soil}$$ Equ

D_{subi} = depth of submerged soil above log i
D_{dryi} = depth of dry soil above log i
L_{emi} = embedded length of log i
d_{logi} = diameter of log i

Sliding Calculations

Project: Tucannon
Project No.: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

6. Lateral Resistance from Piles ($F_{piles\text{-}h}$)

N_{piles}			Number of piles (Design)
d_{piles}	0.83	ft	Diameter of piles (Design)
L_{piles}	8	ft	Embedded length of piles below scour (Design)
Placement Method	Excavated		Method of pile placement
Placement Multiplier	0.25		See RBDG (P. 52)
Pile Placement Location	Bed		Bed or Bank
γ_{water}	62.4	lb/ft^3	Unit weight of water
γ_{soil}	137	lb/ft^3	Unit weight of soil
γ_e	74.6	lb/ft^3	Eqn 37
ϕ_{soil}	0.72	radians	Calculated for material pile is located
K_p	4.81		Eqn 38
h_{load}**	2.5	ft	Height above scour depth load is applied
$F_{piles\text{-}h}$		**lb**	**Eqn 15**

$$F_{piles-h} = -N_{piles} * \frac{L_{pile}^3 * \frac{1}{2} * \gamma_e * d_{pile} * K_p}{h_{load} + L_{pile}} \qquad \text{Equation 36}$$

N_{piles} = number of piles
L_{pile} = length of pile embedded below potential scour depth

$$\gamma_e = \gamma_s - \gamma_w \qquad \textit{effective unit weight of soil} \qquad \text{Equation 37}$$

γ_s = dry unit weight of the soil

γ_w = unit weight of the soil
d_{pile} = diameter of the pile
h_{load} = height above the potential scour depth the load is applied

$$K_p = \frac{1+\sin\phi}{1-\sin\phi} \qquad \text{Equation 38}$$

*** Top 2' of pile embedment disregarded for calculation to account for vortex shedding.**
**** Analysis also assumes that the resultant force is located at half of the flow depth on the upstream side of the LWM structure to produce a conservative moment on the pile.**

Factor of Safety

$FOS_{sliding}$ =	$(F_{hd} + F_f + F_{piles\text{-}h} + F_{passive}) / (F_d + F_{hu} + F_i)$		
F_d	4,606	lb	
F_{hu}		lb	
F_{hd}		lb	
F_i	5,207	lb	
F_f	-12,413	lb	
$F_{passive}$	-53,050	lb	
$F_{piles\text{-}h}$		lb	
$FOS_{sliding}$	**6.67**		**STABLE FOR SLIDING**

Summary Comments:

Rotation Calculations

Project: Tucannon
Project Number: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

Spreadsheet Description

Purpose: The spreadsheet below is used to calculate the Factor of Safety against LWM structure horizontal rotation.

Assumptions:
1) The LWM structue behaves as a single structure under the design load.
2) The effect of soil in back of the structure is negligible.
3) The structure will be submerged during the design event
4) This LWM structure experiences the largest loads. All LWM structures on site will be designed based on this LWM structure's loadings

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells requiring input from a dropdown list)
Input (Cells automatically populated from Input to Interface Tab)
Output (Cells that are automatically updated are this color)
Output (Cells that are automatically updated with previously calculated values are this color)

FBD and Equations:

$$FOS_{rotation} = \frac{MR_{rotation}}{MD_{rotation}}$$ **Equation 45**

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design Rotation Factor of Safety ($FOS_{rotation}$) for this structure is #.# per Table 4 "Minimum Recommended Factors of Safety".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{bouyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Resistance to Rotation ($MR_{rotation}$ and $MD_{rotation}$)

$$MD_{rotation} = (F_i + F_d + F_{hu}) * \left(\frac{L_{sp}+L_{ebp}}{2}\right)$$ **Equation 42**

L_{sp} = *length of wood structure from tip to point of rotation measured perpendicular to flow*
L_{ebp} = *embedded length of wood structure measured perpendicular to flow*

$$MR_{rotation} = \left| F_{hd} * \left(\frac{L_{sp}+L_{ebp}}{2}\right) + F_{passive} * \frac{L_{ebp}}{2} + F_f * \frac{L_{sp}}{2} + \sum_{i}^{n} F_{pile-h_i} * L_{ph_i} \right|$$

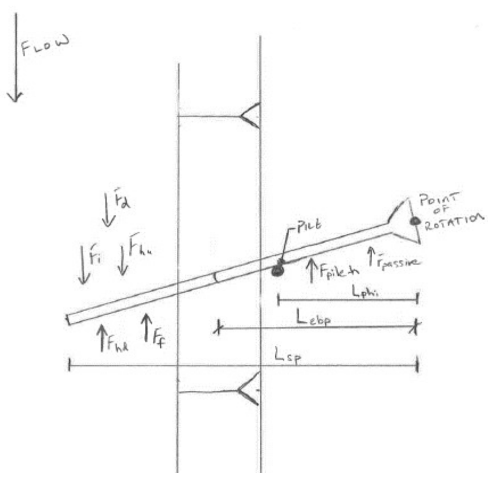
Equation 43

$$F_{pile-h_i} = \frac{F_{piles-h}}{N_{piles}}$$ **Equation 44**

L_{phi} = *distance from pile 'i' to the point of rotation measured perpendicular to flow*

Driving:

L_{sp}	12	ft	Length of wood structure from tip to point of rotation measured perpendicular to flow
L_{ebp}	7	ft	Embedded length of wood structure measured perp. to flow
F_i	5,207	lb	Impact Forces (Calc'd in Sliding)
F_d	4,606	lb	Drag Forces (Calc'd in Sliding)
F_{hu}		lb	Upstream Hydrostatic Forces (Calc'd in Sliding)
$MD_{rotation}$	**93,220**	**lb*ft**	**Eqn 42**



Resisting:

F_{hd}		lb	Downstream Hydrostatic Forces (Calc'd in Sliding)
$F_{passive}$	-53,050	lb	Passive Forces (Calc'd in Sliding)
F_f	-12,413	lb	Friction Forces (Calc'd in Sliding)
F_{pile-h}		lb	Lateral Resistance from Piles (Calc'd in Sliding)
$F_{pile-hi}$		lb	Lateral Resistance from Piles (Calc'd in Sliding)
N_{piles}			Number of Piles (Design)
L_{phi}	25	ft	Distance from pile to the point of rotation measured perp. to flow.
$MR_{rotation}$	**260,153**	**lb*ft**	**Eqn 43**

Factor of Safety

$FOS_{rotation}$ =	$MR_{rotation}$ / $MD_{rotation}$		
$MD_{rotation}$	93,220	lb	
$MR_{rotation}$	260,153	lb	
$FOS_{rotation}$	**2.79**		**STABLE FOR ROTATION**

Summary Comments:

Rotation Calculations

Project: Tucannon
Project Number: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: #########

Overturning Calculations

Project: Tucannon
Project Number: Project Number

Analyst: ASD
Calculations Checked By: ALJ
Latest Revision: 2/28/2023

Spreadsheet Description

Purpose: The spreadsheet below is used to calculate the Factor of Safety against vertical overturning.

Assumptions:
1) The LWM structure behaves as a single structure under the design load.
2) The effect of soil in back of the structure is negligible.
3) The structure will be submerged during the design event
4) This LWM structure experiences the largest loads. All LWM structures on site will be designed based on this LWM structure's loadings

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells requiring input from a dropdown list)
Input (Cells automatically populated from Input to Interface Tab)
Output (Cells automatically updated are this color)
Output (Cells automatically updated with previously calculated values are this color)

FBD and Equations:

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$ **Equation 49**

*** PROJECT NAME has a "XXXX" Public Safety Risk Factor and a "XXXX" Property Damage Risk Factor. The Design Overturn Factor of Safety ($FOS_{overturn}$) for this structure is #.# per Table 4 "Minimum Recommended Factors of Safety".**

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{buoyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

$$MD_{overturn} = F_i * (Y_u + d_{bury}) + F_d * \left(\frac{Y_u}{2} + d_{bury}\right) + F_{hu} * \left(\frac{Y_u}{3} + du_{bury}\right) + |F_L| * L_s$$

Equation 46

du_{bury} = *depth at the upstream side of the structure from channel bottom to point of rotation measured perpendicular to flow*
Ls = *length of structure measured parallel to flow*

$$MR_{overturn} = |F_{hd}| * \left(\frac{Y_d}{2} + dd_{bury}\right) + |F_{passive}| * (dd_{bury}) + (F_b - F_L - F_{piles-v}) * \frac{L_s}{2} + \sum_i^n F_{pile-v_i} * Lpv_i$$ **Equation 47**

$$F_{pile-v_i} = \frac{F_{piles-v}}{N_{piles}}$$ **Equation 48**

L_{pvi} = *distance from pile 'i' to the point of rotation measured parallel to flow*

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$ **Equation 49**

1. Resistance to Overturn ($MR_{rotation}$ and $MD_{rotation}$)

Driving:

F_i	5,207	lb	Impact Forces (Calc'd in Sliding)
F_d	4,606	lb	Drag Forces (Calc'd in Sliding)
F_{hu}		lb	Upstream Hydrostatic Forces (Calc'd in Sliding)
F_L	-1,382	lb	Lift Forces (Assumed Zero in Buoyancy Calcs)
Y_u	3.5	ft	Upstream water elevation from model
d_{ubury}		ft	Depth at upstream side of structure from channel bottom to point of rotation measured perp to flow
L_s		ft	Length of structure parallel to flow
$MD_{overturn}$	**26,285**	**lb*ft**	**Eqn 46**

Resisting:

F_{hd}		lb	Downstream Hydrostatic Forces (Calc'd in Sliding)
$F_{passive}$	-53,050	lb	Passive Forces (Calc'd in Sliding)
F_b	14,279	lb	Buoyancy Forces (Calc'd in Sliding)
F_{pile-v}		lb	Lateral Resistance from Piles (Calc'd in Sliding)
Y_d	3.5	ft	Downstream water elevation
d_{dbury}	6	ft	Depth at downstream side of structure from channel bottom to point of rotation measured perp to flow
N_{piles}			Number of Piles (Design)
L_{pvi}		ft	Distance from pile to the point of rotation measured parallel to flow.
$F_{pile-vi}$		lb	Eqn 48
$MR_{overturn}$	**318,303**	**lb*ft**	**Eqn 47**

Factor of Safety

$FOS_{overturnon}$ = $MR_{overturn}$ / $MD_{overturn}$			
$MD_{overturn}$	26,285	lb	
$MR_{overturn}$	318,303	lb	
$FOS_{overturn}$	**12.11**		**STABLE FOR OVERTURN**

Overturning Calculations

Project:	Tucannon	**Analyst:**	ASD
Project Number:	Project Number	**Calculations Checked By:**	ALJ
		Latest Revision:	2/28/2023

Summary Comments:

Factor of Safety Summary

Project:	Tucannon	**Analyst:**	ASD
Project Number:	Project Number	**Calculations Checked By:**	ALJ
		Latest Revision:	2/28/2023

Spreadsheet Description

Purpose: The spreadsheet below summarizes the factors of safety for the LWD structure.

Assumptions:

Input (Cells Requiring Input from Structure Detail)
Input (Cells requiring Input from Hydraulic Model)
Input (Cells automatically populated from Input to Interface Tab)
Output (Cells automatically updated are this color)
Output (Cells automatically updated with previously calculated values are this

Tables and Equations:

$$FOS_b = \frac{F_{LWMd}+F_{boulders}+F_{soil}+F_{piles-v}}{|F_{LWMs}+F_L|}$$

FOS_b = buoyancy factor of safety

Equation 18

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

Equation 41

$$FOS_{rotation} = \frac{MR_{rotation}}{MD_{rotation}}$$

Equation 45

$$FOS_{overturn} = \frac{MR_{overturn}}{MD_{overturn}}$$

Equation 49

Table 4. Minimum recommended factors of safety.

Public Safety Risk	Property Damage Risk	Stability Design Flow Criteria	$FOS_{sliding}$	$FOS_{buoyancy}$	$FOS_{rotation}$ $FOS_{overturning}$
High	High	100-year	1.75	2.0	1.75
High	Moderate	50-year	1.5	1.75	1.5
High	Low	25-year	1.5	1.75	1.5
Low	High	100-year	1.75	2.0	1.75
Low	Moderate	25-year	1.5	1.75	1.5
Low	Low	10-year	1.25	1.5	1.25

1. Factors of Safety Summary

Project Public Safety Risk	*High*
Project Property Damage Risk	*Low*

Safety Factors		Minimum Recommended Safety Factor	Calculated Safety Factor	Result
Buoyancy	FOS_b	1.5	2.62	**OK!**
Sliding	$FOS_{sliding}$	1.25	6.67	**OK!**
Rotation	$FOS_{rotation}$	1.25	2.79	**OK!**
Overturn	$FOS_{overturn}$	1.25	12.11	**OK!**

Summary Comments: