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Computational Design Tool for Evaluating the Stability of Large Wood Structures

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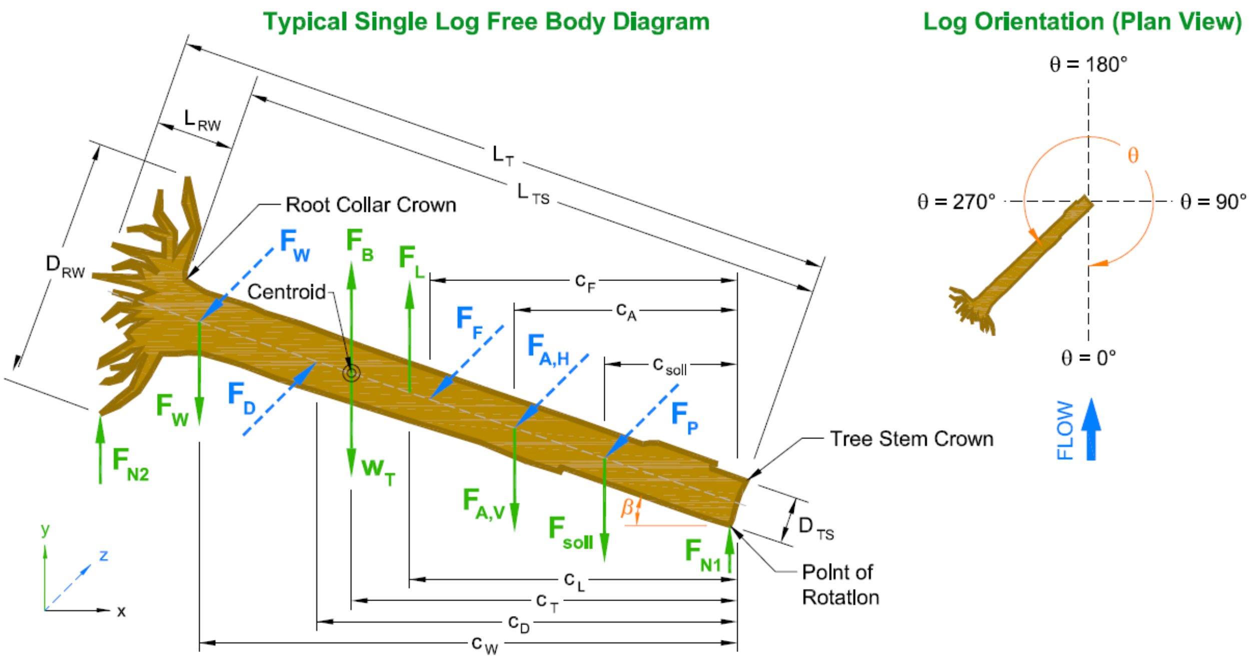

Forest Service
National Stream & Aquatic Ecology Center
Technical Note TN-103.2
April 2017

Rafferty, M. 2017. Computational Design Tool for Evaluating the Stability of Large Wood Structures**.** Technical Note TN-103.2. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, National Stream & Aquatic Ecology Center. 27 p.

ABSTRACT

Large logs are often placed in streams to benefit aquatic and riparian-dependent fish and wildlife. When specifying the type of large wood structure to be used, restoration practitioners, planners, and local residents need to be assured that the constructed structures will likely remain in place under the expected conditions. To be considered stable, a structure must be able to resist hydraulic forces with an appropriate factor of safety. The design practitioner is typically forced to perform numerous complex and time-consuming calculations to achieve the desired level of safety, resulting in additional project time and expense.

An Excel spreadsheet tool was developed that applies computational equations and design guidelines to analyze virtually any proposed configuration of small-to-medium size structures. This Large Wood Stability Analysis Tool has been made available to restoration engineers and other practitioners for evaluating and optimizing design options, such as the size and species of wood, structure configuration, and ballast and/or anchors requirements. Users are able to efficiently enter data and analyze outcomes for alternative structure designs. Methods, computations, assumptions, references, and outputs of the tool have been documented and compiled into an easy-to-understand report that can be submitted to agencies and clients for their review. Two sample applications are included to demonstrate how the tool can been applied to evaluate the stabiliy of both a single-log and multiple-log structure.

ADVISORY NOTE

Design practitioners shall take full responsibility for the final large wood structure design and performance. Designers should be qualified to work in river environments, and, depending on the State and situation, they may be required to be licensed as or supervised by a professional engineer to design large wood structures. Designers are expected to verify the calculated values and validity of the design method.

ACKNOWLEDGEMENTS

This technical note was written by Michael Rafferty, PE. It is based on his thesis (Development of a Computational Design Tool for Evaluating the Stability of Large Wood Structures Proposed for Stream Enhancements; Rafferty 2013), written in partial fulfillment of his Master's Degree in Civil Engineering at Colorado State University. Steven Yochum, of the U.S. Forest Service National Stream and Aquatic Ecology Center, converted and edited the thesis into this technical note format. This work was advised by Brian Bledsoe, of the University of Georgia (formerly of the Colorado State University), and supported by a committee additionally composed of Ellen Wohl and Peter Nelson, of the Colorado State University.

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NOTATION

A_W: wetted area of channel at design discharge [ft^2]
A_{Tp}: projected area of wood in plane perpendicular to flow [ft^2]
c_D: centroid of drag force along log axis [ft]
c_{Am}: centroid of mechanical anchor along log axis [ft]
c_{Ar}: centroid of ballast boulder along log axis [ft]
c_{Asoil}: centroid of added ballast soil along log axis [ft]
$c_{F\&N}$: centroid of friction and normal forces along log axis [ft]
c_L: centroid of the lift force along log axis [ft]
c_P: centroid of the passive soil force along log axis [ft]
c_{soil}: centroid of the vertical soil forces along log axis [ft]
$c_{T,B}$: centroid of the buoyancy force along log axis [ft]
$c_{T,W}$: centroid of the log volume along log axis [ft]
c_{WI}: centroid of wood interaction force along log axis [ft]
C_{Lrock}: coefficient of lift for submerged boulder
C_{LT}: effective coefficient of lift for submerged tree
C_{Di}: base coefficient of drag for tree, before adjustments
$C_{D:}$ effective coefficient of drag for submerged tree
C_{Di}: base coefficient of drag for tree, before adjustments
C_W: wave drag coefficient of submerged tree
$d_{b,avg}$: average buried depth of log [ft]
$d_{b,max}$: maximum buried depth of log [ft]
d_w: maximum flow depth at design discharge in reach [ft]
D_{50}: median grain size in millimeters (mm)
D_r: equivalent diameter of boulder [ft]
D_{RW}: assumed diameter of rootwad [ft]
D_{TS}: nominal diameter of tree stem (DBH) [ft]
DF_{RW}: diameter factor for rootwad ($DF_{RW} = D_{RW}/D_{TS}$)
E: void ratio of soils
$F_{A,H}$: total horizontal load capacity of anchor techniques [lbf]
$F_{A,HP}$: passive soil pressure applied to log from soil ballast [lbf]
$F_{A,Hr}$: horizontal resisting force on log from boulder [lbf]
F_{Am}: load capacity of mechanical anchor [lbf]
$F_{A,V}$: total vertical load capacity of anchor techniques [lbf]
$F_{A,Vr}$: vertical resisting force on log from boulder [lbf]
$F_{A,Vsoil}$: vertical soil loading on log from added ballast soil [lbf]
F_B: buoyant force applied to log [lbf]
F_D: drag forces applied to log [lbf]
$F_{D,r}$: drag forces applied to boulder [lbf]
F_F: friction force applied to log [lbf]
$F_{F,r}$: friction force applied to boulder [lbf]
F_H: resultant horizontal force applied to log [lbf]
F_L: lift force applied to log [lbf]
$F_{L,r}$: lift force applied to boulder [lbf]
F_N: normal force of soil on log [lbf]
$F_{N,r}$: normal force of soil on boulder [lbf]
F_P: passive soil pressure force applied to log [lbf]
F_{soil}: vertical soil loading on log [lbf]
$F_{W,H}$: horizontal forces from interactions with other logs [lbf]
$F_{W,V}$: vertical forces from interactions with other logs [lbf]
F_V: resultant vertical force applied to log [lbf]
$Fr_{L:}$ log Froude number
FS_V: factor of Safety for Vertical Force Balance
FS_H: factor of Safety for Horizontal Force Balance
FS_M: factor of Safety for Moment Force Balance
g: gravitational acceleration constant [ft/s^2]
K_P: coefficient of Passive Earth Pressure
$L_{T,em}$: total embedded length of log [ft]
L_{RW}: assumed length of rootwad [ft]
L_T: total length of tree (including rootwad) [ft]
L_{Tf}: length of log in contact with bed or banks [ft]
L_{TS}: length of tree stem (not including rootwad) [ft]
$L_{TS,ex}$: exposed length of tree stem [ft]
LF_{RW}: length factor for rootwad ($LF_{RW} = L_{RW}/D_{TS}$)
M_d: driving moment about embedded tip [lbf]
M_r: driving moment about embedded tip [lbf]
N: Blow count of standard penetration test
p_o: porosity of soil volume
Q_{des}: design discharge [cfs]
R: radius [ft]
R_c: radius of curvature at channel centerline [ft]
SG_{rock}: specific gravity of rock
SG_T: average oven dried specific gravity of wood u_{avg}: average velocity of cross section in reach [ft/s]
u_{des}: design velocity [ft/s]
u_m: adjusted velocity at outer meander bend [ft/s]
V_{dry}: volume of soils above stage level of design flow [ft^3]
V_{sat}: volume of soils below stage level of design flow [ft^3]
V_{soil}: total volume of soils over log [ft^3]
V_{RW}: volume of rootwad [ft^3]
V_S: volume of solids in soil (void ratio calculation) [ft^3]
V_T: total volume of log [ft^3]
V_{TS}: total volume of tree [ft^3]
V_V: volume of voids in soil [ft^3]

V_{Adry}: volume of ballast above stage of design flow [ft^3]
V_{Awet}: volume of ballast below stage of design flow [ft^3]
$V_{r,dry}$: volume of boulder above stage of design flow [ft^3]
$V_{r,wet}$: volume of boulder below stage of design flow [ft^3]
W_{BF}: bankfull width at structure site [ft]
W_r: effective weight of boulder [lbf]
W_T: total log weight [lbf]
x: horizontal coordinate (distance) [ft]
y: Vertical coordinate (elevation) [ft]
$y_{T,max}$: minimum elevation of log [ft]
$y_{T,min}$: maximum elevation of log [ft]
β: tilt angle from stem tip to vertical [deg]
γ_{bank}: dry specific weight of bank soils [lb/ft^3]
$\gamma_{bank,sat}$: saturated unit weight of bank soils [lb/ft^3]
$\gamma'_{bank:}$ effective buoyant unit weight of bank soils [lb/ft^3]
γ_{bed}: dry specific weight of stream bed substrate [lb/ft^3]
γ'_{bed}: effective buoyant unit weight of stream bed substrate [lb/ft^3]
γ_{rock}: dry unit weight of boulders [lb/ft^3]
γ_s: dry specific weight of soil [lb/ft^3]
γ'_s: effective buoyant unit weight of soil [lb/ft^3]
γ_{Td}: air-dried unit weight of tree (12% MC basis) [lb/ft^3]
γ_{Tgr}: green unit weight of tree [lb/ft^3]
γ_w: specific weight of water at 50^0F [lb/ft^3}
η: rootwad porosity
θ: rootwad (or large end of log) orientation to flow [deg]
μ: coefficient of friction
ν: kinematic viscosity of water at 50^0F [ft/s^2]
Σ: sum of forces
ϕ_{bank}: internal friction angle of bank soils [deg]
ϕ_{bed}: internal friction angle of stream bed substrate [deg]

INTRODUCTION

Large woody structure installations are frequently incorporated into stream enhancement projects to create physical habitat of high ecological value for aquatic species and to compensate for a deficiency of wood material. Large wood can have a profound effect on channel processes and morphology in forested streams and rivers by diverting or concentrating flow, trapping and sorting sediment, and increasing pool frequency, depth, and cover (Abbe and Montgomery, 1996; Abbe et al. 2005). Fish species depend on these features during different life stages and seasons for food, reproduction, and shelter from predators and environmental stresses (Shrivel 1990; Cederholm et al. 1997). In certain circumstances, large wood can also be used to mitigate fluvial erosional/depositional processes, manage mobile debris, and reestablish important habitat elements that benefit riparian and benthic species (Abbe et al. 2005).

Since the 1700's, the majority of watersheds in the United States have been impacted by significant anthropogenic changes which have led to habitat degradation. Two of the more common activities have been clear-cut logging through the riparian zone and the removal of instream large wood (D'Aoust and Millar, 2000). Many streamside forests no longer have mature trees that are needed to initiate stable accumulations of woody material. In recognition of the inability of natural systems to replenish the wood material that has been removed, land management strategies are increasingly recommending the direct and indirect reintroduction of woody debris to fluvial systems.

Natural stable large wood complexes are often initiated by a large immobile log that acts as a stable key member (Abbe and Montgomery 1996). However, the dimensions of wood members typically used in restoration projects are much smaller because of logistical challenges of locating and hauling wood large enough to qualify as a key piece. Therefore, when wood is placed in a stream, it typically must be evaluated for stability to improve functional performance as it relates to habitat objectives, increase the longevity of the structure, and reduce risks to public safety and infrastructure. Stable large wood structures must balance vertical, horizontal, and moment forces.

The design process often requires several iterations of complex and time-consuming analytical methods and equations. Several spreadsheet tools have previously been developed by others to facilitate these calculations, but all shared versions have at least one of the following limitations: (1) an outdated design methodology; (2) an incomplete assessment of significant hydraulic forces; (3) a narrow range of applicability for structure types, configurations, and anchoring techniques, and/or; (4) onerous data input requirements. This large wood stability analysis computational tool expands and improves on these previous versions.

This report summarizes the design rationale and methodologies that were selected to develop a comprehensive and flexible Microsoft Excel spreadsheet which can be used to efficiently evaluate and optimize design options, such as the size and species of wood, structure configurations, and ballast and/or anchors requirements. In addition, the procedure for applying the model is detailed and example applications are presented to illustrate how the tool can be used to design stable structures. The final product is available to design practitioners in the stream restoration design community to facilitate project designs, to provide additional verification of the applicability of the model, and to encourage feedback for future updates of this tool. It is available here.

Structure Types

Natural large wood accumulations can vary from a single piece in a relatively small stream to hundreds of interlocked wood members in large rivers. At either extreme, the configuration of wood is dependent on the processes that led to its placement.

Wood is naturally recruited to the channel from fallen trees, landslides, or debris flows. Depending on the characteristics of the log and the hydraulics in the channel, the wood may remain stable or mobilize during higher flows and be transported downstream until it reaches a suitable site for wood deposition. Mobilized logs may be trapped by an existing wood jam, pinned between trees or rocks, partially buried by sediment in the channel, or settle in a location of decelerating velocity and varying directional flow, such as the downstream outer bend of a meander, below a grade break, or in reaches with a high width/depth ratio. If the log is large enough to remain stable in its current position for a period of time, it may trap additional logs and form its own jam. Log jams may form along the bank, at a mid-channel bar apex, or on the floodplain. Over time, the jam may grow larger and may occasionally reach channel-spanning size. The longevity of this natural wood jam may be short-lived or last for many years.

Stream restoration practitioners should have a thorough understanding of the types of large wood structures that would be expected to naturally occur in a proposed project reach. To the extent feasible, engineered large wood structures should mimic natural accumulations of wood, although the emphasis on stability may require design adjustments, such as partially burying key logs or adding boulders for ballast weight. Engineered structures should be positioned in areas where wood would naturally be expected to accumulate and consist of an appropriate number of logs for the location in the watershed. If properly designed and placed, engineered large wood structures can provide a variety of functions, such as enhancement of aquatic habitat, streambank protection, and grade control.

The most common types of large wood structures are described in Table 1, with an emphasis on the types of structures commonly proposed in stream restoration projects.

Table 1: Common log structure types in stream restoration projects.

Configuration	Description	Function
Rootw ads	Logs buried in bank w ith rootw ads protruding into channel. Common in stream restoration projects but uncommon in nature.	Protect low banks from erosion and provide scour pools w ith w oody cover.
Log Vanes	Logs protruding from bank and angled either up- or dow nstream. This type of structure includes fallen trees w ith a portion remaining on top of the bank.	Deflect flow and create scour pools and hydraulic complexity. May also provide w oody cover if branches are intact.
Log Weirs	Channel spanning low -head w eir comprised of one or more large logs. Most applicable to smaller streams since logs have a high risk of undercutting.	Provide grade control of stream bed and create scour pools. Often configured to direct flow tow ards center of channel.
Tree Revetments	Logs placed along the bank and parallel to flow . Logs may have branches intact. Anchors often must be added to achieve stability.	Revetments protect outer banks from shear forces, reducing erosion and providing w oody cover.
Bank Flow Deflection Jams	Usually built around one or more stable key members protruding from the bank w ith stacked and w racked logs. Engineered structures are usually partially embedded in the bank.	Deflect flow and shear from banks to reduce erosion, create scour pools, and provide w oody cover. May be designed to trap additional mobile w ood.
Mid-channel Logs and Jams	Mid-channel w ood collection at the head of an island or bar. Natural formations are often mobilized during higher flow s, although this type of structure may be engineered to remain stable.	Split flow to initiate island formation, create scour pools w ith w oody cover, and trap additional mobile w ood.
Full-spanning Jams	Channel spanning jams are initiated by one or more key members (usually oriented approximately perpendicular to the channel) that constrict a large portion of the bankfull cross-sectional area and trap mobile w ood. They are inherently unstable unless engineered.	Sediment accumulates upstream of the jam and w ater flow s through and over the top creating a step in the channel profile and deep pool dow nstream.
Floodplain Logs and Jams	Fluvially deposited logs on the floodplain during high flow events, often pinned betw een trees. May require engineered design to remain stable.	Roughens up the floodplain, reduces overbank erosion, and provides high flow refuge habitat.

Risk

Risk can be generally defined as the product of the probability of failure and expected consequences, which is how flood risk is considered in the Netherlands (Jonkman et al. 2009). In regard to adding large wood to streams, restoration planning should account for both the probability of wood moving and the consequence of such movement. Large wood installation projects must thoughtfully manage risk in order to be successful.

Risk is related to uncertainties, such as predicting flood frequencies, sediment influx, future collection of mobile wood, natural variability of the system, and material deterioration of logs and anchors (Cramer, 2012). Uncertainties also exist due to experimental design techniques, particularly related to engineered log jams, which need additional research to address risk management, monitoring, and post-construction maintenance (Abbe et al., 2005).

The level of acceptable risk and definition of failure is dependent on the project setting, as well as the goals and objectives. In urban settings, large wood structures are usually intended to remain stable through the design life, which may exceed 50-100 years depending on the species of wood. A stable piece of wood is one that forms a flow obstruction that infrequently, if ever, moves downstream. Mobile wood may block culverts, collect on bridge piers leading to scour, cause damage to personal property, and threaten human life. Therefore, in an urban setting mobilized large wood is often considered a failure, and lack of habitat creation is an important, but often secondary concern. In more remote settings, it may be appropriate to allow the large wood to occasionally mobilize and reposition. In this case, the creation of high-quality habitat is the primary goal.

Mechanical anchors may also be a concern in the event of a structure failure. Anchors may prevent mobilized wood members from separating from each other, increasing the risk of the resulting "raft" collecting on downstream infrastructure. In addition, mechanical anchors and cables often persist long beyond the functional life of the structure. Steel bars and pins can pose a threat when exposed, and cables can form traps for recreational users and often have sharp ends.

Other consequences that should be assessed include the potential for increasing the frequency of flooding, the potential for channel avulsions, and the possibility of harming critical habitat, especially if sensitive species are present. In general, the further a structure protrudes into flow, the greater the potential for failure. A properly designed structure deflects water around it instead of allowing flow to move through it (Abbe et al., 2005), to minimize threats to stream recreationists by strainers.

The level of design analysis and post-construction effort is proportional to the degree of acceptable risk of the project. In many cases, detailed large wood stability analyses are essential to reduce the chance of the wood mobilizing. Additional data collection, public education, monitoring, and adaptive management may also be necessary to manage risk.

Objectives

The restoration design community would benefit from a user-friendly, widely distributed tool that offers design flexibility for single log and small to medium-sized multiple log structures. The principle objective of this project was to develop a computational large wood material stability analysis tool that integrates the latest design guidelines and science, and documents the tool for use by practitioners. The spreadsheet tool was developed to facilitate the work of design practitioners by having the following features:

- Efficient design optimization
- Ability to assess the stability of nearly every type of single log structure configuration coupled with various types of ballast and/or anchoring techniques
- Capability to address interactions between logs in small to medium-sized multiple log structures, since this type of structure is common and previously-developed spreadsheet tools that address these configurations are not known to exist
- Flexibility to account for the physical characteristics of different stream systems and geographic regions, including common riparian tree species, bed substrate gradations, bank materials, and hydrologic and hydraulic properties
- Clarity of input screens and reference information incorporated into the model to make it quick and easy to enter data for each project to which it is applied
- Automated to the extent possible, but still allow the user the option to manually override the calculated values as necessary

This technical note serves as a reference guide to describe how the model works, summarize the selected design methodology and rationale, and document the procedure for applying this large wood stability analysis tool.

DESIGN METHOD

Large wood pieces in riverine systems are subject to a combination of hydrodynamic, frictional, and gravitational forces (D'Aoust, 1999). Stable large wood structures must have resisting forces that exceed the driving forces that act to destabilize the log. The stability of a single log (or in theory an entire large wood jam) can be evaluated by a force balance, although analyzing the stability of a large log jam can only be done for a greatly simplified geometry (Abbe et al., 2005). The computational procedure to assess log stability described herein follow the force balance analysis method proposed in NRCS (2007, TS14J).

The typical forces acting on a single log and the log orientation with respect to flow are shown (Figure 1). The vertical forces that are usually considered in a force balance analysis are highlighted in "green." The primary driving vertical forces are buoyancy and lift, and these are resisted by soil ballast forces and/or anchoring forces. If the vertical driving forces exceed the resisting forces, the structure will become unstable and float. The horizontal forces are displayed in "blue." Drag forces are the primary driving force in the horizontal direction, and resisting forces include friction between the woody structure and the bed, passive soil pressures on buried members, and/or anchoring forces. If the drag forces exceed the resisting forces, then the structure would be at risk of sliding downstream. The magnitude and centroid of each driving and resisting force can then be used to perform a moment force analysis along the horizontal log axis. If the driving moment forces exceed the resisting moment forces, the structure will have the propensity to pivot downstream, roll over, or shift upwards from the embedded end of the log.

A factor of safety is often implemented in the design of large wood structures to account for uncertainties in hydraulic characteristics, channel response, and potential of the structure trapping additional mobile wood material. The factor of safety is defined as the ratio of resisting forces to imposing forces, with a multiplier typically ranging from 1 to 2 depending on the level of risk posed by structure failure.

Data Requirements

At a minimum, the following data is necessary for the design of large wood structures.

Channel Geometry

Topographic field surveys are required at each site to define the channel geometry and planform characteristics. This information can be used to identify opportunities and constraints for large wood placement, and to develop a hydraulic model of the study reach. Channel cross section surveys are required at each structure site and several positions both upstream and downstream. The cross sections should be aligned perpendicular to the stream and should extend beyond the limits of the proposed structure. A longitudinal survey will also be required to determine the stream gradient.

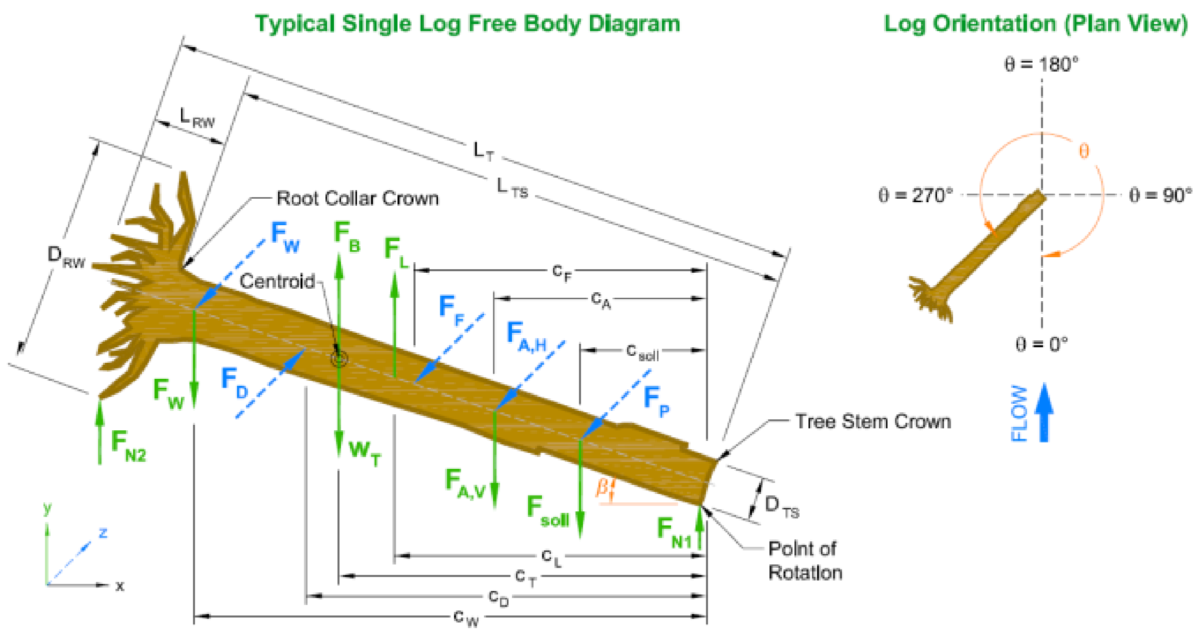

Figure 1: Typical Single Log Free Body Diagram and Log Orientation.

Hydrologic and Hydraulic Characteristics

The hydrologic and hydraulic characteristics of the study reach must be defined for a range of flows to properly assess the hydraulic forces applied on large wood structures. Low flow conditions must be assessed to understand the minimum water elevations within the project reach. High flow conditions at a specified design discharge must be analyzed to find the design flow depth, velocity, and wetted area of the channel. The structure is designed to withstand the hydraulic forces imposed by the design flood.

The design discharge is typically associated to a flood that recurs at a specified average return interval, and it is primarily related to the level of risk and consequences of structure failure. Structures that are located in remote areas and pose minimal risk to infrastructure may be allowed to mobilize at relatively frequent floods (e.g., bankfull discharge). However, the selected average return interval for urban structures sites with high risk to infrastructure is usually greater or equal to the desired life of the structure. Depending on the durability of the selected wood species and the level of risk, urban sites may require a design discharge associated with infrequent large floods (e.g., 50 to 100-years). Discharge magnitude/frequency data can be gathered from field measurements, nearby stream gages, regional flow rating curves, and/or basin hydrology assessments.

A 1-D hydraulic model, such as HEC-RAS, may be used to develop water surface profiles and assess flow conditions at the design discharge. In rare cases, a more sophisticated 2-D or 3-D model may be required. The hydraulic model outputs will include the width, depth, velocity, and wetted area of the channel. For structures located on the outside of meander bends, the cross-sectional mean velocity, u_{avg}, should be adjusted to allow for higher velocities on the outside of bends. The U.S. Department of Transportation Hydraulic Engineering Circular No. 23 v2 (Lagasse et al. 2009) presents an equation for calculating the maximum velocity at meander bends, u_m:

$$u_m = u_{avg}\left[1.74 - 0.52\log\left(\frac{R_c}{W_{BF}}\right)\right]$$

$$\left[for\ \frac{R_c}{W_{BF}} \leq 26\right]$$

where:

R_c = radius of curvature of the channel centerline [ft]

W_{BF} = bankfull width [ft]

Substrate and Bank Soil Properties

Field data must also be gathered for channel substrate and bank soils to assess the geotechnical forces acting on the structure. A particle gradation analysis can be used to define grain size classes, unit weights, friction angles, and soils classes. Table 2 displays typical alluvial soil properties compiled from Julien (2010), Shen and Julien (1993), and NRCS (2007, TS14E).

Table 2: Substrate and Soil Properties.

Grain size (mm)	Sediment Class	Average Dry Unit Weight, γ (lb/ft^3)	Internal Friction Angle, ϕ (deg)	Soil Class
Bedrock	Bedrock	165	-	1
256-2048	Boulder	146	42	4
128-256	Large Cobble	142.6	42	4
64-128	Small Cobble	137	41	4
32-64	Very coarse gravel	131.4	40	5
16-32	Coarse gravel	125.7	38	5
8-16	Medium gravel	120.1	36	5
4-8	Fine gravel	114.5	35	5
1-2	Very fine gravel	108.8	33	6
0.5-1	Very course sand	103.2	32	6
0.5-1	Coarse sand	98	31	6
0.25-0.5	Medium sand	94	30	7
0.125-0.25	Fine sand	93	30	7
0.063-0.125	Very fine sand	92	30	7
0.004-0.063	Silt	82	30	7
< 0.004	Clay	78	25	7

The angle of friction, ϕ, represents the basic parameter that accounts for the frictional resistance of a mass of granular soil.

The average dry unit (specific) weight of soil, γ_{soil}, can be approximated by using the following equation (Julien, 2010):

$$\gamma_{soil} = 1{,}600 + 300 \log D_{50} \quad [kg/m^3]$$

where:

D_{50} = median grain size in millimeters

1 $kg/m^3 \approx 0.062$ lb/ft^3

The average saturated unit (specific) weight of soils, γ', can be calculated using the following equation (Bowles 2001):

$$\gamma' = \gamma_{sat} - \gamma_w$$

where:

γ_w = specific weight of water (62.4 lb/ft^3)

γ_{sat} = specific weight of saturated soils (with pore water weight), which is found by:

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

where:

SG_{rock} = specific gravity of soils (assumed to be 2.65 for quartz particles)

e = void ratio, which is found by:

$$e = \left(\frac{SG_{rock} \times \gamma_w}{\gamma_{soil}}\right) - 1$$

If the gradation of the bank soils is not known, visual observations may be used to estimate a grain size class, and then Table 2 and the above equations can be used to calculate the soil properties.

The NRCS soil classification system, as defined by NRCS (2007, TS14E, Table 2) is typically used by the manufacturers of soil anchors for determining the rating capacity of their products.

Large Wood Properties

The species of wood, orientation angle, tilt angle, and log dimensions should be specified during design.

The species of wood is usually selected from common riparian species that exist in the region of the project. Species that are resistant to decay are commonly chosen. The decay rate of untreated woody debris depends on a wide range of factors such as the type of wood, moisture content, size of the debris, and type of decay agent. Generally, larger tree boles will last longer because of their greater mass, greater proportion of heartwood relative to sapwood, and denser wood (Abbe et al. 2005).

The log orientation with respect to the direction of flow and tilt angle are used to determine the projected area of the log in the wetted cross section. The orientation angle, θ, for the proposed method is shown in Figure 1 and defined as follows:

- $\theta = 0^0$ = Large end of bole (or rootwad) is pointed upstream, parallel with the channel
- $\theta = 90^0$ = Large end of bole is pointed towards right bank (looking downstream) and perpendicular to the channel
- $\theta = 180^0$ = Large end of bole is pointed downstream, parallel with the channel
- $\theta = 270^0$ = Large end of bole is pointed towards left bank (looking downstream) and perpendicular to the channel

The tilt angle from log to vertical, β, is also shown in Figure 1 and defined as follows:

- $\beta = +90^0$ = Small end of bole is tilted up from stream bed; rootwad tilted down
- $\beta = 0^0$ = Log is lying flat and parallel to stream bed
- $\beta = -90^0$ = Small end of bole is tilted down towards the stream bed; rootwad tilted up

The density of the wood is dependent on the species. The portion of the log above the thalweg is conservatively assumed to be dry prior to the introduction of high flow. The dry specific weight of the tree is the average unit weight of wood after exposure to air on a 12% moisture content volume basis. Using the dry specific weight will also better represent the timber as it decays through time because of microbial attack and becomes less dense (Brooks et al, 2006). The density of air-dried timber at 12% moisture content, γ_{Td}, can be calculated as follows:

$$\gamma_{Td} = SG_T \times \gamma_w \times 1.12$$

where:

SG_T = average oven dried specific gravity of wood

γ_w = specific weight of water (62.4 lb/ft^3)

The specific green weight of the tree is used to approximate the weight for the portion of the structure that is embedded below the channel thalweg since this zone is likely to remain in contact with base flow in all but the most extreme circumstances. The specific green weight is the average unit weight of freshly sawn wood at a typical species-dependent moisture content. Even if the base flow level drops below the thalweg, this assumption is still valid if *high* flows are unlikely to return within a very short period of time (perhaps in less than a 12 hour period). This assumption may not be valid for extremely flashy ephemeral streams. In most cases, the specific green weight is a conservative estimate of the saturated weight of a log when exposed to water for long periods, but the green weight is the only readily available estimate for moist conditions of most wood species. For comparison, Thevenet et al. (1998) determined wood unit weight typically increases by more than 100% after less than 24 hours of submergence. The density of green timber, γ_{Tgr}, can be calculated as follows:

$$\gamma_{Tgr} = SG_T \times \gamma_w \times MC$$

where:

SG_T = average oven dried specific gravity of wood

MC = typical moisture content of freshly sawn timber

Table 1A in Miles and Smith (2009), *Specific Gravity and Other Properties of Wood and Bark for 156 Tree Species Found in North America*, provides the unit weight of air-dried timber and the typical moisture content of green timber for common US tree species.

Wood structures have complex geometries which makes determination of volume difficult. For simplicity, force balance methods assume that the wood members have a single straight bole without taper or limbs. The bole and rootwad are treated as separate elements, with the volume of the bole approximated a cylinder, and the rootwad approximated as a frustum (truncated cone). The total volume of a single log, V_T, is estimated by:

$$V_T = \pi \left(\frac{D_{TS}}{2}\right)^2 L_{TS}$$

$$+ \frac{\pi L_{RW}}{3}\left[\left(\frac{D_{RW}}{2}\right)^2 + \left(\frac{D_{RW}}{2}\right)\left(\frac{D_{TS}}{2}\right) + \left(\frac{D_{TS}}{2}\right)^2\right](1-\eta)$$

where:

D_{TS} = diameter of the tree stem (bole) [ft]

L_{TS} = length of the tree stem (not including rootwad) [ft]

L_{RW} = length of the rootwad (generally assumed to be 1.5*D_{TS}) [ft]

D_{RW} = diameter of the rootwad (generally assumed to be 3*D_{TS}) [ft]

η = rootwad porosity (generally assumed to be 0.20)

Vertical Forces

The equations used to quantify vertical forces for a log stability analysis are summarized below.

Buoyancy Force

Buoyancy is the primary driving vertical force that causes a large wood structure to move and become unstable (Shields et al, 2004). Buoyancy decreases a log's net submerged weight and thus its stability.

The buoyant force, F_B, acting on the structure is equal to the weight of displaced water:

$$F_B = \sum_n \gamma_W V_{T\downarrow WSE}$$

where:

n = number of logs

$V_{T\downarrow WSE}$ = volume of tree below the water surface elevation, WSE [ft^3]

γ_w = specific weight of water [62.4 lb/ft^3 at 50°F]

Gravity Force

The gravity force from the weight of the structure resists buoyancy. The weight of a structure, W_T, is found by:

$$W_T = \sum_n \left(\gamma_{Td} V_{Td} + \gamma_{Tgr} V_{Tgr}\right)$$

where:

γ_{Td} = specific dry weight of tree [lb/ft^3]

V_{Td} = volume of tree above channel thalweg [ft^3]

γ_{Tgr} = specific green weight of tree [lb/ft^3]

V_{Tgr} = volume of tree below channel thalweg [ft^3]

A fully submerged log will float if the specific weight of the log is less than the specific weight of water. Most common species of wood used in stream restoration projects in the United States have a specific weight less than the specific weight of water. A partially submerged log will be more stable since the weight of displaced water is reduced compared to a fully submerged log.

The presence of a rootwad can improve a log's resistance to buoyancy. A fluvially deposited log with an attached rootwad will generally have two points of contact with the bed: the end of the stem and the bottom of the rootwad mass. The trunk of the log will tilt upwards towards the rootwad end, causing the center of gravity to be elevated. Consequently, the flow depth will need to be greater before the log floats.

In addition, rootwads often contain soil and rock, which increase the specific weight, and further increase the resistance to buoyancy. However, rootwads installed for stream restoration projects often are partially embedded which alters the tilt angle, and the bulk of the soil and rock is removed prior to transport. In effect, the resistance to buoyancy is nullified, and in some circumstances, the risk of floating is increased.

Lift Force

Large wood members may be subject to upward lift forces due to the pressure distribution around the surface exposed to flow. The lift force, F_L, on a large wood structure may be computed using the following equation:

$$F_L = \frac{C_{LT} A_{T_p} \gamma_w u_{des}^2}{2g}$$

where:

C_{LT} = lift coefficient for a submerged tree

A_{Tp} = projected area of large wood in the plane perpendicular to flow [ft^2]

u_{des} = design velocity of flow [ft/s]

g = gravitational acceleration constant [32.2 ft/s^2]

The lift coefficient on a cylinder placed perpendicular to the flow is greatest (~0.45) when the cylinder is in contact with the bed and declines to near zero when the gap between the bottom of the cylinder and the bed exceeds one half times the cylinder diameter (Alonso 2004).

Lift force may be neglected in most cases in the design of large wood structures, because it rapidly diminish as patterns of scour and deposition reshape the local topography (Wallerstein et al. 2001). However, a conservative model would include lift in the force balance analysis.

Ballast Force

Bank soil and stream bed substrate on top of a log can significantly increase its overall resistance to transport. The vertical loading from the sediment burying the log is ballasting it to an extent equivalent to the weight of the overlying sediment (in fact it will be greater than this due to the friction between the particles; Brooks et al, 2006). The ballast force, F_{soil}, counteracts buoyancy and lift forces, and may be found by:

$$F_{soil} = V_{soil,dry}\gamma_s + V_{soil,sat}\gamma_s'$$

where:

$V_{soil,dry}$ = volume of dry soil above the water surface elevation, WSE [ft^3]

γ_s = dry unit weight of soil [lb/ft^3]

$V_{soil,sat}$ = volume of saturated soil below the water surface elevation, WSE [ft^3]

γ_s' = effective buoyant (saturated) unit weight of soil [lb/ft^3]

For this analysis, the ground water table in the bank is assumed to be equal to the water surface elevation in the stream at the design discharge. The volumes of dry and saturated soil ballast are both approximated using the following equation:

$$V_{soil} = L_{T,em} D_{TS} d_{b,avg}$$

where:

$L_{T,em}$ = embedded length of the tree [ft]

D_{TS} = diameter of the tree stem (bole) [ft]

$d_{b,avg}$ = average burial depth to crown of the log [ft]

Vertical Anchor Force

If the sum of the gravity and ballast forces are less than the sum of the buoyancy and lift force, then the large wood structure will require additional anchoring forces to resist transport. Whenever feasible, natural materials (e.g., soil ballast, boulders, and wood piles) are preferred for anchoring to reduce hazards to recreational users. There are several techniques for anchoring, as summarized in Table 3.

The magnitude of the vertical anchor force, $F_{A,V}$, varies depending on the type of technique applied.

Table 3: Anchor Techniques.

Technique	Description
Added soil ballast	Add coarse material soil lifts on top of structure to increase burial depth
Boulder ballast	Place boulder on top of structure. Alternatively, secure structure to boulder located beside or beneath structure.
Wood piles	Drive or bury vertical w ood piles into the bed or banks to brace structure (not included in version 1 of the tool). Alternatively, brace structure against existing large tree.
Mechanical anchors	Secure structure to soil anchor w hich uses overlying soil to resist pullout. Alternatively, secure the structure to bedrock using a rock anchor.

Soil Ballast: The formula to calculate the anchor force for added soil ballast, $F_{A,Vsoil}$, is as follows:

$$F_{A,Vsoil} = V_{soil,dry}\,\gamma_s + V_{soil,sat}\,\gamma_s'$$

Boulder Ballast: The resisting anchor force from boulder ballast requires a force balance analysis of the proposed boulder. First the weight of the boulder, W_r, must be determined:

$$W_r = V_{r,dry}\,\gamma_{rock} + V_{r,wet}(\gamma_{rock} - \gamma_w)$$

where:

$V_{r,dry}$ = volume of rock above the water surface elevation, WSE [ft^3]

γ_{rock} = specific weight of rock [165 lb/ft^3 for quartz particles]

$V_{r,wet}$ = volume of rock submerged below the water surface elevation, WSE [ft^3]

For simplicity, the volume of rock is approximated as a sphere, and calculated as follows:

$$V_r = \frac{\pi}{6} D_r^3$$

where:

D_r = equivalent diameter of rock below the water surface elevation, WSE [ft]

The submerged volume of the boulder is found by the following equation:

$$V_{r,wet} = \frac{\pi}{3}\left(D_r - d_{r,dry}\right)^2\left[1.5D_r - \left(D_r - d_{r,dry}\right)\right]$$

where:

$d_{r,dry}$ = depth of rock above water surface elevation, WSE [ft]

The dry volume of the boulder is then calculated by:

$$V_{r,dry} = V_r - V_{r,wet}$$

The portion of the boulder that is exposed to flow will be subject to lift forces. The lift force on the boulder, $F_{L,r}$, is found by:

$$F_{L,r} = \frac{C_{Lrock} A_{Pr} \gamma_w u_{des}^2}{2g}$$

where:

C_{Lrock} = lift coefficient for large roughness elements (0.17) (D'Aoust and Millar, 2000)

A_{Pr} = projected area of rock in the plane perpendicular to flow [ft^2]

u_{des} = design velocity of flow [ft/s]

The resultant vertical anchor force from boulder ballast, $F_{A,Vr}$, is found by:

$$F_{A,Vr} = W_r - F_{L,r}$$

In order for the boulder ballast to resist vertical forces, the boulder must either be placed on top of the structure or the log must be attached to the boulder with a chain and pin connection.

Mechanical Anchors: If natural materials are not feasible for anchoring, mechanical soil and bedrock anchors may be considered. Driven-type soil anchors are available in different configurations and sizes. Some of the more common trade names are (NRCS 2007, TS14E):

- Duckbill® (low capacity)
- Platipus Stealth® (low capacity)
- Manta Ray® (medium capacity)
- Platipus Bat® (medium capacity)
- Stingray® (high capacity)

The pullout capacity of specific driven anchors can be determined from manufacturer tables. It is important to note that soil anchors are rated for static loads rather than dynamic loads. When attached to a flexible cable in fast flowing water, the cable tends to vibrate, which may allow the anchor to work its way to the surface in unconsolidated sediment (Brooks et al. 2006). It is also important to consider the expected scour depths when selecting the burial depth of soil anchors.

The pullout capacity of driven soil anchors and bedrock anchors, F_{Am}, depends on the manufacturer's rating. The resistance force of soil anchors is effectively the same for both vertical and horizontal forces since the anchor can only fail in one direction (along the anchor axis).

$$F_{Am} = Manufacturer's\ Rating\ Capacity$$

Vertical Force Balance

The sum of vertical forces, ΣF_V, acting on the large wood structure is found by subtracting the driving forces (buoyancy and lift) from the resisting forces (log weight, ballast weight, and anchor forces). It is calculated as follows:

$$\sum_n F_V = \left(W_T + F_{soil} + F_{A,V}\right) - \left(F_B + F_L\right)$$

A multiple log structure may also include interaction forces between its members. These forces may either act as driving forces or resisting forces according to a separate force balance on the other log members.

If the sum of forces in the vertical direction is positive, the structure is likely to be stable at the design discharge. The resulting weight of the structure will exert a force on the bed and/or banks, and the resisting force is referred to as the normal force, F_N. The normal force is assumed to be distributed over the length of the log that is in contact with the bed and/or banks.

If the sum of the vertical forces is negative, the structure will likely float, and F_N will equal 0. If this is the case, additional anchoring forces must be applied to an engineered structure to ensure the structure is stable.

Engineered structures typically implement a factor of safety to manage the uncertainties in the design methodology and channel response. The vertical factor of safety, FS_V, can be computed by:

$$FS_V = \frac{W_T + F_{soil} + F_{A,V}}{F_B + F_L}$$

A minimum factor of safety of 1.5 is recommended for most low-energy locations, and a minimum of 2.0 is recommended in high-energy systems or where hazard to public safety or infrastructure may exist (Cramer, 2012). Factors of safety closer to 1 may be appropriate for enhancement projects in remote areas. Professional judgment is necessary.

Horizontal Forces

The equations used to quantify horizontal forces for a stability analysis are summarized below.

Drag Force

The dynamic fluid forces, or drag, are the primary driving horizontal forces that may cause a large wood structure to become unstable and slide (Shields et al, 2004). For a single log structure the drag force, F_D, is calculated by the empirical relationship:

$$F_D = \frac{C_D^* A_{Tp} \gamma_W u_{des}^2}{2g}$$

where:

C_D^* = effective drag coefficient for a submerged tree

A_{Tp} = projected area of large wood in the plane perpendicular to flow [ft^2]

u_{des} = design velocity of flow [ft/s]

The effective drag coefficient, C_D^*, is a function of the orientation to flow, wood shape (bole without rootwad versus bole with rootwad), and boundary conditions. Gippel et al. (1992) determined the effective drag coefficient to be equal to:

$$C_D^* = 0.997(C_{Di} + C_w)\left(1 - \frac{A_{Tp}}{A_W}\right)^{-2.06}$$

where:

C_{Di} = drag coefficient of wood in a flow of infinite extent (no boundary)

C_W = wave drag coefficient of wood

A_W = wetted area of channel at design discharge [ft^2]

The term A_{Tp}/A_W represents the blockage ratio as defined by Gippel et al. (1992). The blockage ratio affects the drag imposed on a log, especially for significant flow constrictions.

Gippel et al. (1992) used a series of laboratory experiments to quantify the relations between the drag coefficient (no boundary), C_{Di}, and the angle of orientation to the flow for wood. Typical C_{Di} values for a bole only (no rootwad) range from 0.55 to 1.12. The relationship for a bole with no rootwad is:

$$C_{Di} = 1.1173 - 5.2800 \times 10^{-2}\theta + 1.4385 \times 10^{-3}\theta^2 - 9.7668 \times 10^{-6}\theta^3$$

where:

θ = orientation angle of log with respect to flow, with θ ranging from 0° for a log oriented parallel to flow, and 90° (max) for a log perpendicular to flow

Gippel et al. (1992) also did laboratory tests on a bole with a rootwad, but he did not develop an empirical relationship (although he did create one for a bole with a rootwad *and* branches). Typical C_{Di} values range from 0.75 to 1.25.

Streamwise drag increases sharply whenever the free surface approaches the upper side of the log. This increase is attributed to the formation of surface deformations also known as standing waves, and it is referred to as wave drag (Abbe et al. 2005). Alonso (2004) presented the following formula for the wave drag coefficient, C_W, for a cylinder:

$$C_w = \frac{\pi^2}{32} Fr_L^{-6} exp\left(-\left(z_{T,CL\downarrow WSE} / D_{TS}\right)/2Fr_L^2\right)$$

where:

$z_{T,CL\downarrow WSE}$ = Distance to large wood centerline from the water surface elevation [ft]

Fr_L = Log Froude number

The log Froude number measures the impact of standing surface waves on drag, and is found by:

$$Fr_L = \frac{u_{des}}{\sqrt{gD_{TS}}}$$

Alonso's (2004) equation is a rewrite of Lamb's formula (1945). Lamb showed C_w peaked at log Froude numbers near 0.60, and exponentially decreased at smaller and larger log Froude numbers. He also showed that the peak values of the wave drag coefficient are near 0.43.

Prior to adjustments for the blockage ratio, drag coefficients for a single log typically range from ~0.7 to 0.9 (NRCS 2007, TS14J). Drag coefficients for cylinders placed perpendicular to the flow reach values as high as 1.5 for cylinders that are barely submerged due to forces associated with the formation of standing waves (Alonso 2004). Drag coefficients for geometrically complex objects like large wood structures vary less with angle of orientation to the flow than for simple cylinders and tend to fall in the range of 0.6 to 0.7 (Gippel et al. 1996), before adjustments for the blockage ratio. Similar to lift forces, Wallerstein et al (2001) suggests that drag forces are expected to rapidly diminish with time during the first few high-flow events as patterns of scour and deposition reshape the local topography.

Adjustments to the projected area of the structure may also be necessary to account for the expected trapping efficiency of mobile wood, particularly for structures located on the outside of a meander bend or at site where the channel gradient flattens.

Friction Force

The movement of large wood structures by sliding along the bed will be resisted by a frictional force, with magnitude equal to the normal force multiplied by the coefficient of friction between the woody material and the bed (NRCS 2007, TS14J). The friction force, F_F, is equal to:

$$F_F = \mu_{bed} F_N$$

where:

F_N = normal force of soil on structure [lbf]

μ_{bed} = Coefficient of friction, which in the absence of measured data, Castro and Sampson (2001) assumed was equal to:

$$\mu_{bed} = tan\phi$$

where:

ϕ = Internal friction angle of soils (stream substrate or bank soils) [deg]

A similar methodology is used to find the coefficient of friction for the bank soils, μ_{bank}.

It is important to note that if the normal force equals 0 (i.e., the resultant vertical force is away from the bed) then the friction force may effectively be zero for design conditions.

Passive Soil Pressure Force

The resistive forces due to passive soil pressure acting on buried portions of logs are direct reactions to fluid forces. This passive earth pressure must be overcome in order for the wood structure to move downstream. The analysis herein of the passive soil pressure force has the following assumptions:

- The bank is composed of homogeneous, isotropic soil.
- The ground water table elevation in the bank is approximately equal to the stream surface elevation.
- The friction between the soil and the log can be ignored (friction is included in the friction force section above).
- The rootwad diameter is conservatively estimated to equal the log diameter
- The soils are conservatively assumed to be granular and thus cohesion, c, is equal to 0 (Note: $c \approx 0$ for saturated cohesive soils as well; NRCS 2007).

The passive soil pressure force, F_P, is given by:

$$F_P = 0.5 K_p F_{soil}$$

where:

F_{soil} = soil ballast force, as defined in the ballast force section of this technical note

K_P = coefficient of passive earth pressure, which is given by

$$K_P = \tan^2\left(45 + \frac{\phi}{2}\right)$$

where:

ϕ = Internal friction angle of soils (stream substrate or bank soils) [deg]

The passive soil resistance distribution is assumed to be triangular with its maximum value at the bank face and decreasing linearly to zero at the embedded tip of the log. This implies that the resultant passive resistance force acts on the log a distance of $2/3L_{T,em}$ from the embedded tip. The active earth pressure force is assumed to be small relative to the passive force (NRCS 2007, TS14J).

Horizontal Anchor Force

If the drag forces are greater than the sum of the friction force and passive soil force, then the large wood structure will require additional anchoring forces to resist transport. An overview of common anchoring techniques is included in the Vertical Anchor Force section of this technical note and in Table 3. The horizontal resisting anchor forces are summarized below.

Soil Ballast: The formula to calculate the horizontal passive soil pressure force for added soil ballast, $F_{A,HP}$, is as follows:

$$F_{A,HP} = 0.5K_p F_{A,Vsoil}$$

Boulder Ballast: Three boulder configurations can provide a resisting horizontal force: (1) A boulder placed behind the log will have a friction force with the bed which provides sliding resistance, (2) a boulder placed on top of the log can increase the normal force between the bed and the structure, and increase the frictional resistance between the log and the bed, and (3) a deadman boulder that is buried and chained to the log provides both horizontal and vertical resistance similar to a soil anchor. The resisting anchor force from boulder ballast requires a force balance analysis of the proposed boulder. In addition to the buoyancy, gravity, and lift forces covered in the "Vertical Anchor Forces" section, the boulder is also subject to drag and friction forces.

The portion of the boulder that is exposed to flow will be subject to drag forces. The drag force on the boulder, $F_{D,r}$, is found by:

$$F_{D,r} = \frac{C_{Drock} A_{Tr} \gamma_W u_{des}^2}{2g}$$

where:

C_{Drock} = drag coefficient for boulder (Schultz et al 1954), estimated a C_{Drock} of 0.85 for coarse particles with a shape factor between 0.80 and 0.99.

A_{Pr} = projected area of rock in the plane perpendicular to flow [ft^2]

u_{des} = design velocity of flow [ft/s]

The resisting friction force between the boulder and the bed is dependent on the effective weight of the boulder, W_r, found in the "Vertical Anchor Forces" section. The effective weight creates a normal force from the bed, and the friction force can then be found by:

$$F_{F,r} = \mu_{bed} F_{N,r}$$

where:

$F_{N,r}$ = normal force of soil on boulder, which equals W_r [lbf]

μ_{bed} = coefficient of friction

The resulting friction force for boulders placed behind the structure is equal to:

$$F_{A,Hr} = F_{F,r} - F_{D,r}$$

The resulting friction force for boulders placed on top of the structure is calculated by finding the new normal force of the bed acting on the new total structure weight, and then the equation in the "Friction Force" section above is recalculated.

Embedded deadman structures provide both vertical and horizontal resisting forces since the structure can only fail in one direction (along the axis of the chained connection). Thus, the W_r force found in the "Horizontal Vertical Anchor" section can be partially or fully applied to resisting horizontal forces.

Mechanical Anchors: As described in the "Vertical Anchor Force" section, if natural materials are not feasible for anchoring, mechanical soil and bedrock anchors may be considered. A portion of the total resisting force, F_{Am}, can also be applied to resist horizontal forces. Refer to the "Vertical Anchor Force" section for more information.

Horizontal Force Balance

The sum of horizontal forces, ΣF_H, acting on the large wood structure is found by subtracting the driving forces (drag) from the resisting forces (friction, passive soil pressure, and anchor forces). It is calculated as follows:

$$\sum_n F_H = (F_F + F_P + F_{A,H}) - F_D$$

Similar to the vertical force balance, a multiple log structure may also include interaction forces between its members. These forces may either act as driving forces or resisting forces according to a separate force balance on the other log members.

If the sum of forces in the horizontal direction is positive, the structure is likely to be stable at the design discharge. If the sum of the vertical forces is negative, the structure will be at risk of sliding. If this is the case, additional anchoring forces must be applied to an engineered structure to ensure the structure is stable.

The horizontal factor of safety, FS_H, can be computed by:

$$FS_H = \frac{F_F + F_P + F_{A,H}}{F_D}$$

NRCS (2007, TS14J) recommends a horizontal factor of safety of at least 2. However, the NRCS TS14J equations for calculating the drag force do not include adjustments to the drag coefficient (wave drag and blockage ratios), resulting in a calculated drag force that is often underestimated by a factor of 1.25 to 2.5. The proposed model includes these drag coefficient adjustments, so the calculated drag force will typically be significantly larger than the drag force calculated using the NRCS TS14J equations. Thus, it can reasonably be assumed that a horizontal factor of safety of 1.5 may be appropriate, particularly in low energy streams. In most cases, despite using a lower factor of safety, the proposed model will still result in a more conservative design. As an example, if the adjustments to the drag coefficient result in a calculated drag force that is 1.5 times larger and a factor of safety of 1.5 is applied, the model will require a resisting force that is 12.5% larger than the NRCS TS14J value.

$NRCS\ TS14J$

$$\rightarrow (1{,}000\ lbf\ drag\ force)\ x\ (2.0\ FS) = 2{,}000\ lbf\ required$$

$Model$

$$\rightarrow (1{,}500\ lbf\ adjusted\ drag\ force)\ x\ (1.5\ FS) = 2{,}250\ lbf\ required$$

$$\frac{2{,}250\ lbf\ \text{(Model)}}{2{,}000\ lbf\ \text{(NRCS)}} = 1.125 \text{ or } 12.5\% \text{ larger}$$

A factor of safety of 2 is recommended in high-energy systems or where hazard to public safety or infrastructure may exist (Cramer, 2012) Professional judgment is necessary to determine the appropriate factor of safety.

Moment Forces

The magnitude and centroid of each driving and resisting force can then be used to perform a moment force analysis. If the driving moment forces exceed the resisting moment forces, the structure will have the propensity to pivot downstream, "roll" over, or perhaps shift upwards from the embedded end of the log. If the log is not embedded, the moment force can be calculated about the rootwad or the centroid of the log.

The driving moment, M_D, about the buried tip of the embedded log is given by:

$$M_D = \left[F_B c_{T,B} + F_L c_L + F_D c_D\right] \cos\beta$$

The resisting moment, M_R, will act opposite the driving moment and is given by:

$$M_R = \left[W_T c_{T,W} + F_{soil} c_{soil} + (F_F + F_N) c_{F,N} + F_P c_P + (F_{A,H} + F_{A,V}) c_A\right] \cos\beta$$

where:

$c_{T,B}$ = centroid of buoyancy force along log axis [ft]
c_L = centroid of lift force along log axis [ft]
c_D = centroid of drag force along log axis [ft]
β = tilt angle from stem tip to vertical [deg]
$c_{T,W}$ = centroid of the log volume along log axis [ft]
c_{soil} = centroid of vertical soil forces along log axis [ft]
$c_{F\&N}$ = centroid of friction and normal forces along log axis [ft]
c_P = centroid of passive soil force along log axis [ft]
c_A = centroid of each anchor at the log axis [ft]

M_R acts opposite M_D, and both vectors act along a horizontal axis through the embedded tip of the log. Therefore, the factor of safety with respect to moments, FS_M, is simply the ratio of their magnitudes:

$$FS_M = \frac{M_R}{M_D}$$

A minimum factor of safety of 1.5 is recommended for the moment force analysis and NRCS (2007, TS14J) recommends that anchoring systems should be designed to achieve factors of safety greater than 2 due to the high level of uncertainty in computations for the imposed force.

COMPUTATIONAL MODEL DEVELOPMENT

The large wood computational tool was developed using Microsoft Excel 2010. This tool implements the design methodology described above. The focus of the model is single log structure analysis, although a method was devised to allow the model to also be applied to small to medium-size multiple log structures.

Model Layout

Each worksheet of the spreadsheet has a specific function related to the design process, as described below. Example output of the model is available here.

Intro – Directions for LW Stability Analysis Tool: The worksheet begins with directions for applying the LW Stability Analysis Tool. This sheet offers a brief introduction to the large wood model. A more thorough procedure for applying the model is included in the Application Procedures section.

Worksheet 1 – Cover Sheet: A cover sheet has been pre-formatted, with the project title linked throughout the remaining worksheets to save the user the effort of updating this information on the subsequent pages.

Worksheet 2 – Factors of Safety and Design Constants: This is the first design sheet, although user inputs are optional. Default factors of safety and design constants are already included in the worksheet and the user is allowed to update these values. At a minimum, the user will need to closely review the factors of safety since these are critical parameters for design. A "reset defaults" button is included on this sheet to return the inputs to the default values.

Worksheet 3 – Hydrologic and Hydraulic Inputs: The hydrologic and hydraulic inputs sheet is more data heavy than any other sheet; this is information that cannot be assessed within the model. A hydraulic model can be used to compute the required data. The information typed into this sheet will be linked to lookup tables in the stability analysis worksheet. A "clear inputs" button is also provided for this sheet.

Worksheet 4 – Stream Bed Substrate Properties: This is another background data worksheet that will be referenced by several lookup tables in the stability analysis worksheet. However, the required data input for this sheet is relatively minor. For each design site, the user is required to provide a median grain size for bed substrate and an estimation of the bank material. If the gradation of the bank soils is known, there are two custom input sections in a reference table located on the far right of the worksheet. Multiple soil parameters are automatically calculated for the design. Like all of the worksheets in the model, the spreadsheet is not locked and every cell can be manually edited, if necessary. A "clear inputs" button is provided on this sheet.

Worksheet 5 – Large Wood Properties: The large wood properties worksheet has a large database of wood properties for common riparian zone species in the United States. The information is sorted into eight geographic regions: West Coast, Intermountain West, Great Plains, Upper Midwest, South Central, New England, Mid-Atlantic, and Southeast. The user only needs to select the region of the proposed project and then choose from the list of species in a dropdown menu. A total of 10 species can be selected for comparison, and these inputs can also be edited later if necessary. If the preferred species is not included in the list, the user can input a "custom" tree species at the bottom of the reference table for the region. A "clear inputs" button is provided to quickly reset the sheet.

Worksheet 6 – Single Log Design: The single log design worksheet contains relatively few user input prompts, as the bulk of the calculations are automated using the guidelines presented in the Design Method section. However, there are four critical user input sections on this sheet: (1) site location and channel geometry; (2) wood species and structure geometry; (3) anchor selection (optional); and (4) multiple log structure interaction forces (optional). The first three sections are supported by a cross section plot that helps the user check for inputs errors. It should be noted that the channel topography on the profile is smoothed for aesthetics, although the calculations assume a straight line link between each cross section point. This sheet also has several error and check messages that pop up if the user has entered information that is likely inaccurate or beyond the capacity of the code.

The user will first select the Site ID from a dropdown list and then the spreadsheet will automatically populate with the data entered in previous worksheets. The user can then identify the type of proposed structure (optional) and its general location within the channel cross section. Next, the user will need to input the channel cross section geometry. The channel geometry input is limited to the cross section distance (x-coordinate) and elevation (y-coordinate) at seven key points (looking downstream):

1. A representative point on the left floodplain
2. Top of the left bank
3. Toe of the left bank
4. Channel thalweg

5. Toe of the right bank
6. Top of the right bank
7. A representative point on the right floodplain

The cross section geometry will need to extend beyond the limits of the proposed structure. The data input into the model should reflect the proposed topography, with considerations for expected scour depths, sediment deposition, and potential bank erosion caused by the proposed structure.

It is expected that these seven points will be sufficient to estimate the channel geometry for the vast majority of sites, since single log and small multiple log structures are generally proposed in relatively small stream systems (first to third-order streams). Unfortunately, additional points cannot be added to the current version of the model due to the complexity of the geometry calculations. If the simplified geometry is considered inaccurate for a specific site, the user will need to manually enter the related design parameters.

After the channel geometry is entered, the user will select the wood species for analysis from a list of trees that were identified on the "Wood Properties" worksheet. Then, the structure orientation, size, and geometry will be manually added. The wood geometry requires the user to input a single (x,y) coordinate and then the spreadsheet will calculate the remaining key points on the log. The user will have the option of entering the crown (top) or bottom coordinates for one of the following: the rootwad, the root collar, or the stem tip. All of this information can be adjusted throughout the design process.

The model automatically calculates several complex geometry calculations to determine various design parameters (e.g., volume of log above high water, volume of log below the thalweg, burial lengths and depths, projected area of log, spacing between the log and the water surface, spacing between the log and the channel bed, and many more). Given the complex geometry of the log's position within the channel, some mathematical approximations (e.g., slice method, partial area method) are used to perform certain calculations. The user can review these background calculations by scrolling to the right on the worksheet.

At this point, the model will have enough information to analyze the stability of the log with respect to vertical, horizontal, and moment forces. The worksheet has visual aids to help the user quickly understand several key design variables, including a typical single log free body diagram and an orientation layout diagram. Both are these diagrams are intended to further clarify the notation and parameters for the force balance analysis. The force balance calculations have color-coded visual aids as well. The driving and vertical forces outputs have adjacent cells that are formatted by a representative color, and these cells contain arrows to indicate the relative direction of the force. The output that displays the computed factor of safety is compared to the design factor of safety, and the worksheet has symbology that clearly displays if the design criteria have been met.

If the structure does not meet the design criteria, the user has the option of editing the structure geometry, or applying three major anchor techniques: (1) add soil ballast; (2) add large boulders above, behind, or tethered below in the form a deadman anchor; and (3) selecting from a list of mechanical anchors. A total of 3 boulders, 2 mechanical anchors, and 1 soil ballast volume can be input into the anchor force section. The user will need to continue to adjust the design until the factors of safety have been met or exceeded.

Finally, the user has the option to add interactive forces between adjacent logs in a structure. A total of four adjacent logs can be added within this section. The recommended procedure for multiple log analysis is described in the Application Procedures section.

A "clear inputs" button is included to delete the input data on the sheet. Please note that this button does not reset the coded formulas. The user would need to open an unaltered spreadsheet if they wish to reset any formulas that have been manually edited or overwrote.

Worksheet 7 – Notation, Units, and List of Symbols: This worksheet is a quick reference for notation, units, abbreviations, and symbols found elsewhere in the design model. This is also essential information for the final design report since the descriptions of variables in other cells within the worksheet are provided in embedded comments, which are not set to print.

Reference Worksheet – Large Wood Anchor Techniques: This reference sheet lists descriptions for common anchoring techniques and manufacturer's rating capacities for various soil anchors. There is also a custom input option on the far right end of the table for other types of anchors (e.g., bedrock anchors). All of the information provided in this sheet is for reference only, and it is the designer's responsibility to verify the information.

Limits of Applicability

Although the spreadsheet is intended to be applicable for a wide range of site conditions and design configurations, the methodology is not applicable for all design scenarios. Limitations include, but are not limited to, the following scenarios:

- Stream reaches with highly turbulent flow
- Stream reaches with a highly unstable geometry (e.g., actively eroding banks, aggrading/eroding bed), unless the design also addresses these issues
- High-energy stream reaches that are actively transporting material larger than cobbles
- Streams subject to debris flows
- Larger streams that have complex geometry that cannot be approximated using the channel geometry inputs in the model
- Very complex wood structures since the multiple log analysis method proposed for this model is likely too cumbersome

There are also scenarios when the design methodology may apply, but the model may require manual modifications. These special design cases include, but are not limited to, the following:

- Large wood members with complex geometry (e.g., multiple trunks, partial rootwads)
- Stream reaches with significant changes in longitudinal gradient or cross section geometry immediately upstream or downstream of the structure may require the calculated embedded length of the log to be adjusted to reflect the actual embedded length of the log
- Multi-thread channels will need geometry and hydraulic inputs that only reflect the section of the stream where the structure is positioned

APPLICATION PROCEDURE

This Large Wood Stability Analysis Tool is organized in a manner consistent with the design process. The first worksheet has directions for applying the model, which are also summarized in this section.

The user should input data beginning with the *Cover* worksheet, and then proceeding through the worksheets from left to right. Within each worksheet, the user should update cells from left to right, and top to bottom. The designer should gather all information necessary to complete each worksheet before proceeding to the next. The cells are color-coded according to their function, as described (Figure 2). Input values should be in English units, with one exception: D_{50} for the bed substrate gradation (mm). The *Single Log Design* worksheet has several error checks, which prompt a warning message to inform the user if an incorrect value has been entered. The general form of the error messages is shown (Figure 2**Error! Reference source not found.**). The spreadsheet is not locked and therefore every cell can be manually edited. However, the user is encouraged to exercise caution to avoid unintended consequences due to reference formulas. The user should also be very careful when removing or adding cells (at least scroll over and down to see what other cells and supporting calculations may be impacted). As a best practice, the designer should hide rows instead of deleting them.

Single-Log Structure

The general procedure for applying the tool for a single log stability analysis can be summarized in 12 steps (Figure 3):

Step 1: Fill out the project name in the *1-Cover* worksheet. This information will then automatically populate in the heading of each subsequent page.

Step 2: Review the design factors of safety and constant values in the *2-Constants* worksheet.

Step 3: Input hydrologic and hydraulic data for each potential site in the *3-H&H* worksheet

Step 4: Input stream bed substrate and bank soils properties in the *4-Soil* worksheet. If the median grain size is not known for the bed substrate, the user can estimate this value by viewing reference tables by scrolling to the right. The bank soil type is based on field observations, since it is not common to complete a pebble count or other gradation analysis for bank soils. If the user wishes to edit the values for the bank soil properties, it is recommended that they scroll over to the *Bank Soil Properties Lookup Table*, and then enter the preferred values in one of the two custom rows at the bottom of the table. Then scroll back over to the main *Bank Soil Properties* table, and use the dropdown list to select the customized name of the manually input data.

User Inputs

Cell Format	Description
Dropdown List	Select value from dropdown list
User Input	Type value into cell
User Verify	Verify value in cell (edit if necessary)

Fixed Cells or Automatic Calculations

(In most circumstances, the user should not edit these cells, although the values should be independently verified)

Cell Format	Description
Heading	Table Heading (with descriptive comments that can be read by hovering the cursor over the cell)
Automatic Value	Automatically calculated cell by programmed formulas (verify)
Key Value	Automatically calculated force value (verify)
Solution	Automatically calculated factor of safety (verify)
Background Value	Background calculation (verify – optional)
CHECK	Prompts user to check a specific input
ERROR	Prompts user to change a specific input

Figure 2: Spreadsheet color coding and warnings.

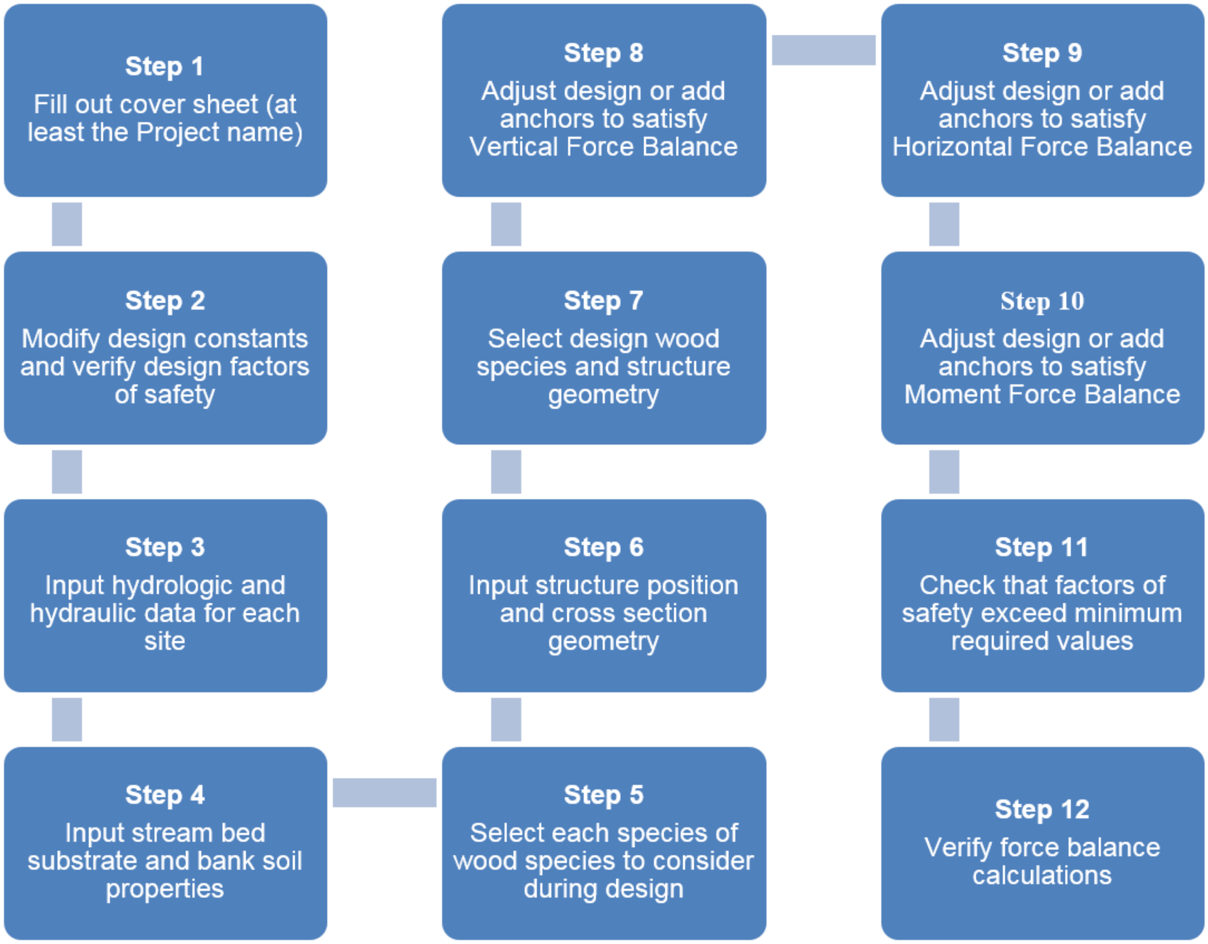

Figure 3: Single log structure design procedure.

Step 5: Select up to 10 species of large wood to consider during design in the *5-Wood* worksheet. Common riparian species are divided into 8 geographic regions in the contiguous United States: West Coast, Mountain West, Great Plains, South Central, Upper Midwest, New England, Mid-Atlantic, and Southeast. The user should first select the applicable region using the provided map, and then the dropdown lists will automatically be linked to the correct lookup table for the common trees in the region. To add a custom species, scroll over to the lookup table for the region, and then enter the custom data in the last row of the table. Return to the *Timber Unit Weights* main table, and the custom input can be found at the bottom of the dropdown list.

Step 6: In the *6-Single Log Design* worksheet, fill out the cells relating to the site and structure location, including the *Channel Geometry Coordinates* table. The geometry data is critical for the remainder of the design, so the user should take extra care when defining the coordinates. Be certain to input the proposed geometry instead of the existing conditions. A proposed cross section plot will automatically update with the input of the geometry data to help the user check for input errors.

Step 7: Select the wood species for design and input the structure geometry by specifying the coordinates for a single point on the log. Six options are given for the *fixed geometry point* on the log. Again, the plot will update with the input of the data to help the user check for errors. A figure is also provided in the spreadsheet to help the user define the orientation angle, θ. After inputting this data, the remainder of the spreadsheet will update automatically. At this point, it is a good idea to double check to make sure all of the *user input* cells in the *Single Log Stability Analysis Model Inputs* section have been filled out correctly.

Step 8: Review the *Vertical Force Analysis* section. If the log does not meet the required factor of safety, adjust the layout or add anchor forces. This should be done before working on the horizontal force balance because the friction force, F_F, is a function of the normal force, F_N. The *Anchor Forces* section can be found near the bottom of the *6-Single Log Design worksheet*.

Step 9: Review the *Horizontal Force Analysis* section. Continue to adjust the design by altering the layout or adding anchor forces until the required factor of safety for the horizontal forces has been met.

Step 10: Review the *Moment Force Analysis* section. If necessary, adjust the design by altering the layout or adding anchor forces until the factor of safety for the moment forces has been met.

Step 11: Double-check to make sure all of the factors of safety have been met or exceeded. Also, reconsider if the factors of safety still seem appropriate for the design.

Step 12: Verify all force balance equations. Make manual adjustments if necessary.

If the user wishes to design an alternative structure layout at the same site or a new single log structure at a different site, then copy and paste the *6-Single Log Design* worksheet and repeat steps 6 through 12 for each new design.

To print a completed design, highlight tabs numbered 1 through 7, and click *Print*. The pages are pre-formatted except the *Anchors* lookup sheet, which is not intended to be printed. An example of a single log structure design is included in the Sample Application section.

Multiple-Log Structure

The LW Stability Analysis Tool can also be used to design small to medium-sized multiple log structures. Multiple log structures are typically constructed of up to three primary components: (1) key members that form the foundation upon which the structure is built; (2) stacked members forming an interlocking matrix to manipulate structure size; and (3) wracked members that influence the permeability and roughness. The interaction and arrangement of key, stacked, and wracked members, as well as the debris that is naturally added over time, govern the stability of the structures (Abbe et al., 2005). For the purpose of this model, key, stacked, and wracked members are defined as follows.

Key members are logs that will serve as the primary stabilizing elements for the overall structure. Key members are often the largest logs in the proposed structure, but this is not necessarily a requirement for this model. The user should designate a log as a key member if it is likely to provide resistance (particularly vertical resistance) to other adjacent logs in the final analysis. This may be in the form of logs that will be deeply embedded in the bank, or if deemed necessary, logs that are good candidates for attaching anchors later in the design process.

Stacked members are logs that are generally unstable by themselves and will require additional stabilizing forces through interactions with adjacent key members. Stacked members are generally positioned above (or below) designated key members. On occasion, the user may decide to add an anchor to a stacked member, although this is usually only done at the end of the analysis if the designer determines that the key members will not provide enough resistance.

Wracked members are smaller wood debris that fills voids between key members and stacked logs. Generally, they are ignored during the force balance analysis since they usually consist of relatively small woody material that does not pose a significant risk if mobilized. However, they are a primary consideration when selecting an appropriate factor of safety for design, and the user does have the option of including larger wracked material in the calculations.

The design procedure directs the user to perform a preliminary analysis of each stacked log in the structure. This initial step does not involve adding interaction forces between the logs. If the designer is uncertain which logs should be designated as key members, it may be advisable to perform a preliminary analysis of all of the logs in the structure to help guide the selection of the key logs.

The overall design procedure for multiple log structures is similar in many ways to the procedure for single log structures except Steps 6 through 10 are modified as described below.

Steps 1 to 5: Same as the single log structure design procedure (see previous section)

Step 6a: Create a preliminary structure layout (in AutoCAD or similar) to define the quantity of logs, locate intersect points, and identify key, stacked, and wracked members.

Step 6b: Input the channel geometry in a blank *Single Log Design* worksheet, and then manually make a copy for each proposed log in the structure. This step is necessary because each log will need to be individually evaluated for stability. The designer is recommended to create a unique ID for each log, and then rename each worksheet accordingly.

Step 7: Complete a force balance analysis for each stacked member log, initially ignoring the *Interaction Forces with Adjacent Logs* and *Anchor Forces* sections. The user should manually record the resisting forces required to stabilize each stacked member in a table. The required vertical force can be found in cell K61 of the *Single Log Design* worksheet, and the required horizontal force can be found in cell K72. If the log is already vertically or horizontally stable, record the excess force that may be applied to resist driving forces of the adjacent log(s). This information can be found in cell K62 and K73. Note that the relative geometric layout for each individual log in the structure does not need to be exactly accurate, since the intersection points will be manually defined by the user on the *key member* worksheet(s).

Step 8a**:** Complete a force balance analysis for the key members. In the *Interaction Forces with Adjacent Logs* section on the force balance sheet, enter the relative position of each adjacent log in contact with the key member, the connection type (gravity or pinned), the intersection point, and the required vertical and horizontal forces to achieve stability for each stacked member. If the load from the adjacent stacked logs is spread over multiple key members, divide the required forces by the number of key members sharing the load. (Note: these loads do not need to be evenly distributed between key members). If an adjacent stacked log is either horizontally or vertically stable, then enter any excess force (see Step 3) value as a negative number in the key member design spreadsheet. The tool will automatically determine which loads are transferable to the next layer of logs. For instance, a non-pinned (gravity) stacked member situated above the key member will not transfer buoyancy force to the key member.

Step 8b**:** Add *Anchor Forces* as necessary to stabilize the key members. As a general rule, the design of multiple log structures should initially focus on achieving vertical stability, before moving on to horizontal stability, and finally the moment analysis.

Step 9: Return to the *stacked member* log worksheets and in the *Interaction Forces with Adjacent Logs* section, input the forces that were resisted by the stability analysis of the key members. Add additional *Anchor Forces* as necessary to stabilize the forces that were not resisted by the design of the key members.

Steps 10 to 12: Same as the single log structure design procedure (see previous section)

Note that the user must manually translate the resulting vertical and horizontal forces from one log design sheet into another. If preferred, a separate spreadsheet may be used to tally the transferred forces for each log. An example of a multiple log structure design is included in the Sample Application section. In theory, there is no limit to the number of logs that can be considered, although the force balance accounting may become cumbersome for the user beyond a few logs.

In some cases, the design procedure can be simplified for larger structures. For instance, if the structure has multiple stacked member logs with a similar size and configuration, a single worksheet can be filled out for each "layer" of stacked members. However, the user will need to take care to properly distribute the loads for all of the stacked members in the each layer. Another option for designing expansive large wood structures using this tool is to develop a repeating structure geometry that can be analyzed in manageable sub-groups of logs. For instance, a 40-log structure could consist of five similar 8-log structures that may only require one stability evaluation depending on the site characteristics.

Depending on the size and configuration of the structure, the user may wish to manually override certain design computations in the model. For instance, most design procedures for larger wood jams (engineered log jams) typically ignore the lift and moment forces, and the drag coefficient may be assumed to be between 0.6 and 0.7 for the entire structure (although these values should still be corrected for the blockage of the channel). Overall, the proposed analysis procedure described above is likely conservative for larger structures unless significant scour or wood trapping is expected. If either is the case, the user should use professional judgment to adjust the design, channel geometry, and/or the factory of safety.

SAMPLE APPLICATION – SINGLE LOG

This section steps through a sample application of the tool for a single log design. The spreadsheet for this sample application is available for download here.

Site Description

The hypothetical project site selected for this example is located at a large stream on the eastern side of the Cascade Mountains in Washington. The site is located on the outside of a slight meander in a low gradient, moderately entrenched reach. A rootwad-type structure is proposed at the left bank with the intention of stabilizing the toe of the slope. The design will emphasize the use of natural materials for anchoring and it will be engineered to remain stable during a flood with a recurrence interval of 50 years. A layout of the channel cross section showing the existing channel topography is shown (Figure 4). This cross section figure is actually a model output of the design structure, and it also shows the relative position and configuration of the proposed rootwad log.

Model Inputs

Data was input into the model following the Single Log Structure Application Procedure. A summary of the design parameters is shown in Table 5. The channel geometry is summarized in Table 5. The large wood properties and structure geometry for the rootwad log is included in Table 6. The values in these tables include all of the required user inputs and are listed in the order that they were entered into the model. The default design constants provided in the model were used for this sample project.

Table 4: Sample single log structure design parameters.

Description	Value	Units
Cover Sheet		
Project name: Sample Single Log Structure		
Factors of Safety		
Vertical force balance, FS_V	1.5	----
Horizontal force balance, FS_H	1.5	----
Moment force balance, FS_M	1.5	----
Hydrology and Hydraulics		
Site ID	Sample1	
Design discharge, Q_{des}	3700	cfs
Maximum depth, d_w	8.45	ft
Average velocity, u_{avg}	3.4	ft/s
Bankfull width, W_{BF}	94	ft
Wetted area, A_W	1650	ft^2
Radius of curvature, R_c	500	ft
Streambed and Bank Properties		
Bed D_{50}	88.8	mm
Bank soils	gravel/cobble	
Wood Properties		
Project location: West Coast		
Selected species	Interior West Douglas-fir and Western redcedar	

Table 5: Sample single log structure channel geometry.

Channel Geometry Coordinates Proposed	x (ft)	y (ft)
Floodplain left bank	0.00	99.18
Top left bank	33.00	98.59
Toe left bank	54.00	95.63
Thalweg	79.00	94.50
Toe right bank	108.00	94.94
Top right bank	127.00	98.72
Floodplain right bank	150.00	98.88

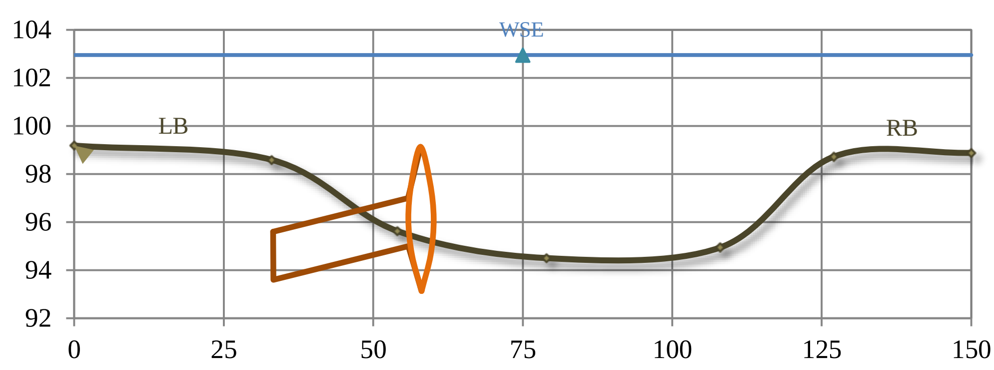

Figure 4: Model output of the single log structure cross section.

Table 6: Sample single log structure large wood properties and geometry.

Parameter	Log ID Top #1
wood species	Douglas-fir
root wad?	Yes
length, L_T (ft)	35.0
diameter, D_{TS} (ft)	2.00
<u>Structure Geometry</u>	
orientation angle, θ	45.0
tilt angle, β	-2.5
fixed point	Root collar: Bottom
x (ft)	55.90
y (ft)	95.00

Model Outputs

At this point, the computational tool automatically updated the force balance calculations for each key member and created an output of the results. The rootwad was already considered horizontally stable with a factor of safety much greater than 1.50. However, the vertical force balance resulted in a computed factor of safety of 1.19 which was well below the target value of 1.50. An additional 2,551 lbf of vertical resistance was needed to achieve stability.

For this project, additional soil ballast was selected as the preferred anchoring technique to provide the required resistance against buoyancy. An additional one foot (average depth) of soil was placed over a 15-foot long, partially embedded segment of the log. The added ballast weight provided 2,559 lbf of vertical resistance. After inputting this anchor data, the model output the revised force balance results, which indicated that the log is stable at the design discharge with regards to vertical, horizontal, and moment forces. A screenshot of the model output for the final force balance analysis of the rootwad structure is shown (Figure 5). The *Anchor Forces* section for the additional soil ballast was also included at the top of the figure.

All of the design calculations were back-checked and it was determined that no manual overrides of equations or calculated results were necessary for this example.

Anchor Forces

Additional Soil Ballast

V_{Adry} (ft³)	V_{Awet} (ft³)	c_{Asoil} (ft)	$F_{A,Vsoil}$ (lbf)	$F_{A,HP}$ (lbf)
0.0	30.0	7.5	2,559	6,161

Vertical Force Analysis

Net Buoyancy Force

Wood	V_{TS} (ft³)	V_{RW} (ft³)	V_T (ft³)	W_T (lbf)	F_B (lbf)
↑WSE	0.0	0.0	0.0	0	0
↓WS↑Thw	88.7	29.5	118.2	4,131	7,376
↓Thalweg	11.8	3.2	15.0	585	935
Total	100.5	32.7	133.2	4,715	8,312

Lift Force

C_{LT}	0.00
F_L (lbf)	0

Soil Ballast Force

Soil	V_{dry} (ft³)	V_{sat} (ft³)	V_{soil} (ft³)	F_{soil} (lbf)
Bed	0.0	0.0	0.0	0
Bank	0.0	61.0	61.0	5,202
Total	0.0	61.0	61.0	5,202

Vertical Force Balance

F_B (lbf)	8,312	↑
F_L (lbf)	0	
W_T (lbf)	4,715	↓
F_{soil} (lbf)	5,202	↓
$F_{W,V}$ (lbf)	0	
$F_{A,V}$ (lbf)	2,559	↓
Σ F_V (lbf)	4,164	↓
FS_V	1.50	✓

Horizontal Force Analysis

Drag Force

A_{Tp} / A_W	Fr_L	C_{Di}	C_W	C_D*	F_D (lbf)
0.02	0.58	1.12	0.04	1.20	651

Passive Soil Pressure / Friction Force

Soil	K_P	F_P (lbf)	L_{Tf} (ft)	μ	F_F (lbf)
Bed	4.81	0	7.69	0.87	752
Bank	4.81	12,523	29.31	0.87	2,868
Total	-	12,523	37.00	-	3,620

Horizontal Force

F_D (lbf)	651	→
F_P (lbf)	12,523	←
F_F (lbf)	3,620	←
$F_{W,H}$ (lbf)	0	
$F_{A,H}$ (lbf)	6,161	←
Σ F_H (lbf)	21,653	←
FS_H	34.27	✓

Moment Force Balance

Driving Moment Centroids			Resisting Moment Centroids			
$c_{T,B}$ (ft)	c_L (ft)	c_D (ft)	$c_{T,W}$ (ft)	c_{soil} (ft)	$c_{F\&N}$ (ft)	c_P (ft)
20.4	0.0	27.8	20.4	10.2	17.5	13.7

*Distances are from the stem tip

Point of Rotation: Stem Tip

Moment Force Balance

M_d (lbf)	187,477
M_r (lbf)	521,504
FS_M	2.78 ✓

Figure 5: Model output of force balance analysis for the single log structure.

SAMPLE APPLICATION – MULTIPLE LOG

This section steps through a sample application of the tool for a theoretical multiple log structure design. The spreadsheet for this sample application is available for download here.

Site Description

For simplicity, the same site described in the above *Sample Application – Single Log* section will be used for this design.

A bank flow deflection structure is proposed on the left bank of the stream with the intention of enhancing instream habitat and improving bank stability. Again, the design will emphasize the use of natural materials for anchoring and each log in the structure will be engineered to remain stable during a flood with a recurrence interval of 50 years. A layout of the site and structure configuration is shown (Figure 6). Given the size and function of the proposed structure, an adjustment was made in the channel cross section to account for the expected scour pool formation near the structure as shown in Figure 7.

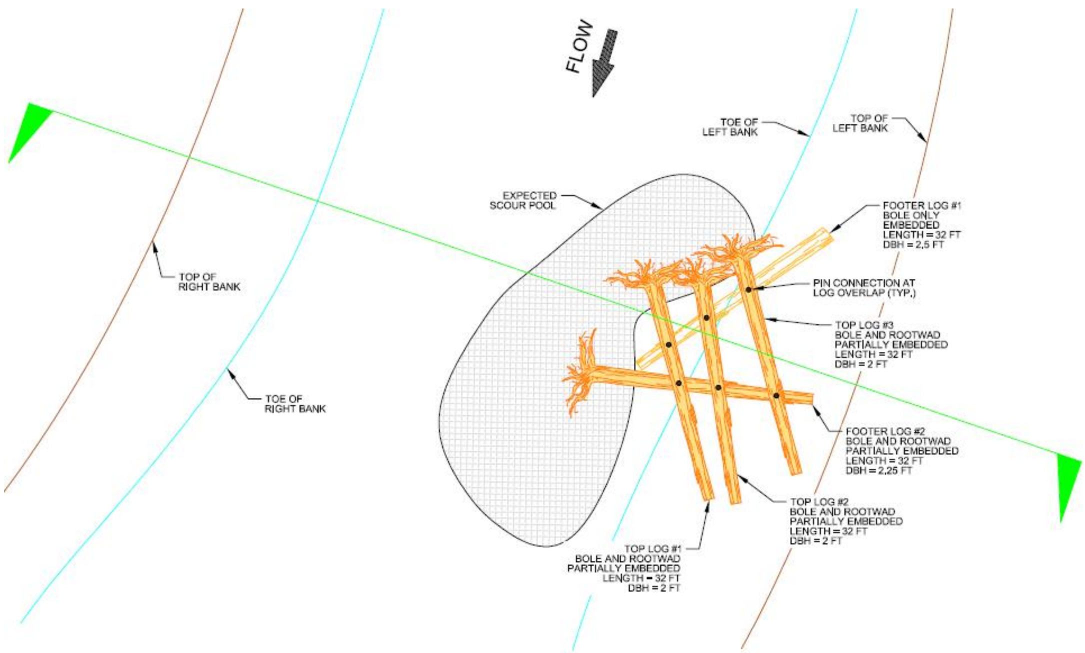

Figure 6: Sample multiple log structure layout (not to scale).

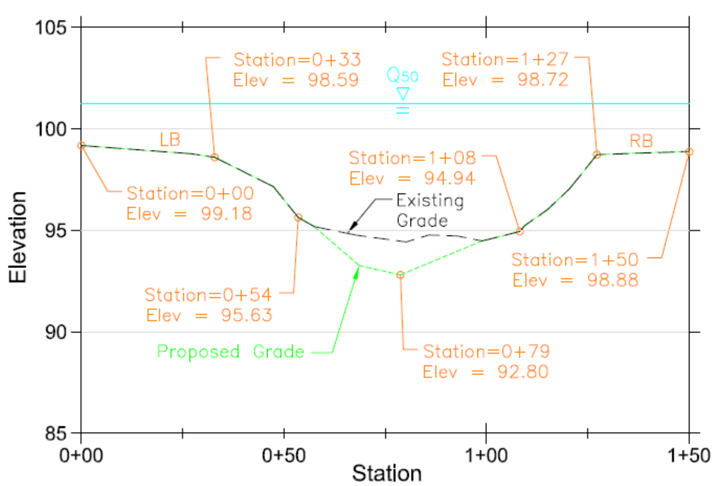

Figure 7: Sample multiple log structure cross section

Model Inputs

Data was input into the model following the Multiple-Log Structure Application Procedure. A summary of the design parameters is shown (Table 7). The channel geometry is summarized in Table 8. The large wood properties and structure geometry for each of the 5 logs are included in Table 8. The values in these tables include all of the required user inputs and are listed in the order that they were entered into the model. The default design constants provided in the model were used for this sample project.

Table 7: Sample multiple log structure design parameters.

Description	Value	Units
Cover Sheet		
Project name: Sample Multiple Log Structure		
Factors of Safety		
Vertical force balance, FS_V	1.5	----
Horizontal force balance, FS_H	1.5	----
Moment force balance, FS_M	1.5	----
Hydrology and Hydraulics		
Site ID	Sample1	
Design discharge, Q_{des}	3700	cfs
Maximum depth, d_w	8.45	ft
Average velocity, u_{avg}	3.4	ft/s
Bankfull width, W_{BF}	94	ft
Wetted area, A_W	1650	ft^2
Radius of curvature, R_c	500	ft
Streambed and Bank Properties		
Bed D_{50}	88.8	mm
Bank soils	gravel/cobble	
Wood Properties		
Project location: West Coast		
Selected species	Interior West Douglas-fir and Western redcedar	

Table 8: Sample multiple log structure channel geometry.

Channel Geometry Coordinates Proposed	x (ft)	y (ft)
Floodplain left bank	0.00	99.18
Top left bank	33.00	98.59
Toe left bank	54.00	95.63
Thalweg	79.00	92.80
Toe right bank	108.00	94.94
Top right bank	127.00	98.72
Floodplain right bank	150.00	98.88

Model Outputs

Using the model inputs described in the section above, the tool automatically performed the calculations for a force balance analysis on each large wood member in the structure. A summary of the most important outputs is described below. No manual overrides of equations or calculated results were necessary for this example.

Per the guidance described in the Multiple-Log Structure Application Procedure, the stacked members were defined and analyzed first. The stacked members for this structure layout were determined to be the top wood members (logs identified on Figure 6 as Top #1, Top #2, and Top #3). Initially, these three logs were analyzed without completing the *Interaction Forces with Adjacent Logs* and *Anchor Forces* sections of the worksheet. The forces required to stabilize each stacked member were recorded and displayed in Table 10. For this example, the forces required to stabilize the stacked members will be provided by the design of the key member logs. The log identified as Top #3[2] was already horizontally stable during this initial design phase, and the excess force that could be applied to resist driving forces of the adjacent log(s) was recorded as a negative number.

Table 9: Sample multiple log structure large wood properties and geometry.

Parameter	Log ID Top #1	Top #2	Top #3	Foot #1	Foot #2
wood species	Douglas-fir	Douglas-fir	Douglas-fir	Douglas-fir	Douglas-fir
root wad?	yes	yes	yes	no	yes
length, L_T (ft)	32.0	32.0	32.0	32.0	32.0
diameter, D_{TS} (ft)	2.00	2.00	2.00	2.50	2.25
Structure Geometry					
orientation angle, θ	33.0	27.0	33.0	324.0	102.0
tilt angle, β	0.5	0.5	0.5	0.01	0.01
fixed point	root collar:bottom	root collar:bottom	root collar:bottom	step tip:bottom	root collar:bottom
x (ft)	63.00	57.00	53.00	62.03	67.00
y (ft)	94.50	94.50	94.50	92.10	92.75

Table 10: Summary of interaction forces required for stacked members.

Log ID	F_v (lbf)	F_v (per key member)	F_H (lbf)	F_H (per key member)
Top #1	7,278	3,639	1,872	936
Top #2	7,113	3,556	1,087	543
Top #3	5,323	2,662	-3,547	-1,774
Total	19,714	9,857	-588	-294

Table 11: Boulder ballast design.

Log ID	Position	Diameter, D_R (ft)	C_{Ar} (ft)
Foot #1	deadman	4.75	8.0
	above	4.50	16.0
	above	4.50	24.0
Foot #2	above	4.75	8.0
	deadman	5.00	16.0
	deadman	5.00	24.0

Table 12: Interaction forces input into spreadsheet for key members.

Key Member	Log ID	Postion	Link	C_{WI}	$F_{W,V}$ (lbf)	$F_{W,H}$ (lbf)
Foot #1	Top #1	above	pinned	5.0	3,639	936
	Top #2	above	pinned	11.4	3,556	543
	Top #3	above	pinned	18.4	2,662	-1774
Foot #2	Top #1	above	pinned	5.0	3,639	936
	Top #2	above	pinned	13.1	3,553	543
	Top #3	above	pinned	18.6	2,662	-1774

Table 13: Results of force balance analysis for the multiple log structure.

Factor of Safety	Target	Foot #1	Foot #2	Top #1	Top #2	Top #3
vertical force balance, FS_V	1.5	1.51	1.52	1.50	1.50	1.50
horizontal force balance, FS_H	1.5	>100	88.10	4.19	4.99	10.79
momentum force balance, FS_M	1.5	2.85	3.07	2.40	2.27	2.26

For this multiple log design, the required forces and excess forces from the stacked logs will be distributed evenly between the two key members (logs identified as Footer #1, and Footer #2), so each force was divided by two.

The resisting forces required for each stacked member will be supplied by the key members. The position of the adjacent logs, type of link, and interaction forces were entered into the *Interaction Forces with Adjacent Logs* section of the design worksheet for each key member, as shown in Table 12. Because the forces were divided evenly between the logs, and each stacked member is in contact with both footer logs, the only difference between the input data for the interaction forces for each key log in Table 12 is the distance from stem tip (end of log with a smaller diameter) to the intersection between the two logs along the log axis, c_{WI}.

At this point, the computational tool automatically updated the force balance calculations for each key member and created an output of the results. Both key members were considered horizontally stable (with a factor of safety much greater than 1.50), but required additional anchoring to achieve vertical stability. Footer #1 required 15,185 lbf of additional resistance, while Footer #2 required 18,836 lbf more resistance. Anchors were then added to the key members to resist the driving forces for all of the logs in the large wood structure. All of the loads were transferable between the logs since the structure is held together by six pinned connections at log overlaps. Boulder ballast was designed in two configurations (on top of the log and deadman anchor). Three boulders are proposed for each key member to counterbalance the vertical driving forces in the structure, as shown in Table 11. The size of the boulders varied from 4.5 to 5 feet in diameter, although two or more smaller boulders may be substituted for a single larger boulder during construction, as long as the substituted boulders have an effective weight equal to or greater than the design boulder. The boulders were spaced at 8-foot intervals along the log. The large boulders closest to the bank were left exposed to stream flow to help armor the bank and fill voids between the logs.

The boulders added 15,470 lbf and 19,144 lbf of vertical resisting forces to Footer #1 and Footer #2 respectively. The model output the force balance results shown in Table 13, indicating that the key members are adequately anchored to resist the forces for the entire structure. As an optional check, the forces resisted by the key members were added into the *Interaction Forces with Adjacent Logs* section of each worksheet for the stacked members to verify that all of the logs are stable. As expected, additional *Anchor Forces* were not necessary to stabilize the stacked members. At this point, all of the logs in the structure were considered to be stable.

VALIDATION

To ensure that the model was calculating the equations correctly and producing realistic results, three separate validations were performed during development. First, each formula was double-checked by a calculator after programming it into the spreadsheet. Corrections were immediately made to address incorrect formulas. Next, numerous structure design configurations, including adjustments to individual variables, were input into the model to check to see if the model provided a reasonable response for the calculated values. Finally, a detailed validation was performed using a calculator for the log identified as Footer #2 from the sample multiple log model application described above. The maximum difference between the model and calculated values of 0.86% occurred during the check of the saturated bank soil overburden volume, $V_{sat,bank}$. This difference is likely overstated since the checked value was a rough approximation of a complex series of geometric equations. The majority of the remaining calculated values fell well below 1% difference, leading to the conclusion that the force balance calculations were handled correctly by the model. The complete validation of the calculations for the "Footer #2" log can be found in the appendix to this technical note here.

CONCLUSIONS

This Large Wood Stability Analysis Tool is a valuable resource for stream restoration design practitioners. It is available here. The simplicity and clarity of the input prompts were designed to make the model user-friendly, and the depth of calculations and design options should give the practitioner confidence that the structure design has been adequately analyzed. The tool is expected to enable designers to significantly reduce the amount of time and effort required to complete a comprehensive structure design, and the final product should be well received by reviewing agencies and clients. The addition of a method to evaluate the stability of small to medium-sized multiple log structures addresses a gap between previously developed design spreadsheets that are specialized to either analyze a single log structure or a large engineered log jam.

ACKNOWLEDGEMENTS

Steven Yochum is appreciated for hosting this tool and editing this adaptation of Rafferty (2013) as a Forest Service National Stream and Aquatic Ecology Center technical note.

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