TECHNICAL NOTES

U.S. DEPARTMENT OF AGRICULTURE NATURAL RESOURCES CONSERVATION SERVICE
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ENGINEERING – NO. 15

INCORPORATION OF LARGE WOOD INTO ENGINEERING STRUCTURES

DESCRIPTION

Large wood (LW) can be incorporated into a structure or used as a structure to (1) disperse flow energy (Buffington and Montgomery, 1999) (2) stabilize channel banks and bed forms (Bilby 1984), (3) increase aquatic habitat, (Bryant and Sedell, 1995) (4) narrow a stream and reduce the width to depth ratio (Sedell and Froggatt 1984), (5) cause localized deposition (Keller et al. 1985), (6) form pools, (Bilby and Ward 1989) (7) route flood water, (Ellis 1999) and (8) decrease costs by using on-site materials (Booth, Montgomery, and Bethel 1996). Also, LW components in engineering structures are often necessary to meet permit guidelines.

Most in-stream work with LW to date has been experiential. Unfortunately, this has resulted in very little documentation of design procedures, stability analyses, or even structure function or success (Frissell and Nawa 1992). The following guidelines provide a procedure for analyzing the stability of LW components in engineering structures. This technical note is not intended to serve as a design template for Engineered Log Jams (ELJ) (Abbe 1999). Guidance on ELJ's from the Watershed Science Institute is forthcoming.

Types of Streams

Not all streams, or locations in a single stream, are appropriate for LW placement. It is necessary to evaluate the hydraulic geometry, floodplain connectivity, channel planform, channel bed and bank material, and the associated riparian plant community of a given stream to determine the appropriateness of large wood placement. Even when a stream system seems to function without the presence of wood, there may actually be a LW component missing that would provide energy dissipation, sediment storage, and aquatic habitat. Since LW was being actively removed from streams before 1900, the perception of "that stream never had any wood in it" may be prevalent, but incorrect.

Potentially appropriate stream types are listed below for the Rosgen (1996) and Montgomery and Buffington (1993) stream classification systems and for the Channel Evolution Model (Schumm, Harvey, and Watson 1984).

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Suitability	Rosgen	Montgomery & Buffington	CEM
Suitable -- appropriate for all areas where LW is a natural component of the geomorphic landscape.	C (1 - 4) E (1 - 4) Bc (1 - 4) If BHR <1.2	Regime Pool-Riffle Plane Bed (<2%)	I IV V If BHR < 1.2
Marginally suitable -- careful evaluation of the particular stream and reach is required. These stream types tend to be higher gradient and have greater stream power.	C (5, 6) E (5, 6) Bc (5, 6) Or if BHR > 1.2 B A	Cascade Step-Pool Plane Bed (>2%)	I IV V If BHR > 1.2
Not suitable -- these are typically incised streams with very high banks or unstable braided stream systems.	G F D (consider ELJ) Any stream with BHR > 1.4	N/A The Montgomery and Buffington system primarily evaluates streams that are LW dependent	II III

Notes: BHR = Bank Height Ratio, total bank height/bankfull flow height (Rosgen 1996)
ELJ = Engineered Log Jam (Abbe 1997)

A very important aspect in determining LW placement in streams is the presence and relative size of the floodplain. Adding roughness in the form of LW to a stream system is fairly low risk in areas that are undeveloped and have a floodplain that is connected to the stream channel. If the channel is confined by valley walls, terraces, roads, or dikes, then the relative shear stress will be higher and the water will be deeper. This scenario would require a larger structure to ensure stability, and larger structures may raise the water surface elevation causing additional flooding. Gippel (1995) found that during low flow conditions in streams with large wood, average velocity was reduced on the order of 35 percent, however, during moderate and high flows, there is no difference in velocity.

ANALYSIS

The difference between a traditional engineering structure and LW placement is primarily in the lack of control of material dimension and quality and the complex dimensions of a natural tree with an attached root wad. The size of wood necessary to provide absolute stability may not be available, practical, or it may simply not exist.

Analysis for stability of wood members in any structure requires a freebody diagram, which incorporates all forces acting upon the wood member (Figure 1). If several pieces of wood are used in conjunction, additional analyses will be required to evaluate the interaction. between members. The following analysis allows for evaluation of a single wood member, LW with additional rock for ballast, and wood incorporated into structures.

Assumptions

1. The streambed slope factor is ignored for the gravity calculation.
2. Resisting force due to channel bends is ignored (making the analysis more conservative).
3. Drag on LW assumes complete submergence.
4. Rootwad porosity is approximately 20%, the solid portion of the rootwad is 80% of its area.
5. Skin friction on LW is ignored.
6. The log is parallel to the flow lines with the tip pointing downstream.
7. Center of gravity is at the contact between the bole and rootwad.
8. The force due to the flow (F_F) is not broken into component vectors because numerically there is no significant difference.
9. F_{NRW}, $F_{\mu RW}$ and $F_{\mu T}$ act through the point of rotation (0), so they have no moment arm.
10. The force due to lift (F_L) is calculated only when the rootwad is completely submerged.
11. As the depth of water approaches ½ the diameter of the rootwad, the calculated volume of tree submerged approximates total tree volume.
12. Tree has one trunk and the rootwad is circular.

Notation and Constants

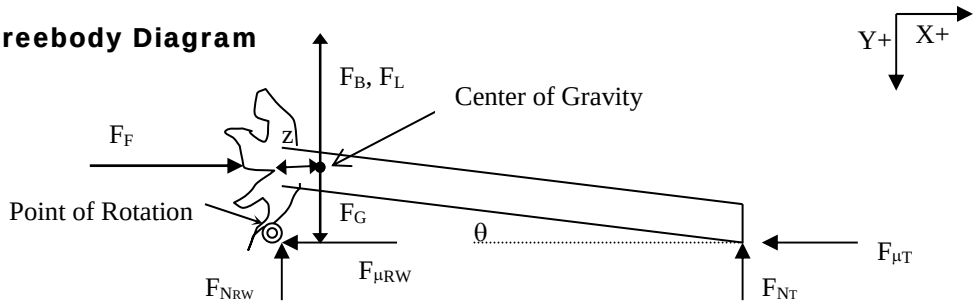
F_B	=	force due to buoyancy		
F_G	=	force due to gravity		
F_F	=	force due to flow		
F_μ	=	force due to friction between LW and bed		
F_L	=	force due to lift		
F_N	=	force normal to LW at the tip and the rootwad		
Subscripts T and RW refer to the tree and rootwad respectively				
ρ_T	=	density of the tree	See Table 2	
ρ_W	=	density of water	=	62.4 #/ft^3
S_g	=	Specific Gravity		
		Water	=	1.0
		Rock (average for quartz)	=	2.65
g	=	acceleration due to gravity	=	32.2 ft/s^2
B_R	=	ballast required (submerged weight)	=	#
v	=	velocity of flowing water	=	ft/s
d_w	=	depth of water	=	ft
η_P	=	porosity		
θ	=	angle from rootwad face to vertical	=	degrees
ϕ	=	internal angle of friction for bed material (*See Table 1*)	=	degrees
μ_{BED}	=	coefficient of friction for bed material		
z	=	distance in the x direction from the center of gravity to the point of rotation	=	ft
L_T	=	length of the tree	=	ft
D_T	=	diameter of the tree	=	ft
L_{RW}	=	thickness of the rootwad	=	ft
D_{RW}	=	diameter of the rootwad	=	ft
$\forall$	=	volume	=	ft^3
A	=	area	=	ft^2
P_{sub}	=	proportion submerged (from Figure 2)		

Subscripts T, RW, and BD refer to tree, rootwad, and boulder respectively. *Subscript SUB refers to the submerged values.*

C_D	=	coefficient of fluid drag		
		C_{DT}	=	0.3
		C_{DRW}	=	1.2
		C_{DBD}	=	0.2
C_L	=	coefficient of lift for large roughness element	=	0.18
FS_B	=	factor of safety – buoyancy		
FS_M	=	factor of safety -- momentum		

C_D and C_L values derived from: D'Aoust and Millar, 1999

Figure 1: Freebody Diagram



Required Calculations

Force Balance / Momentum

$\Sigma Fy = 0$, $F_F (\sin \theta) + F_G = F_B + F_L + F_{NT} + F_{NRW}$

$\Sigma Fx = 0$, $F_F (\cos \theta) = F_{\mu RW} + F_{\mu T}$

$\Sigma Mo = 0$, $F_{NT} (L_T \cos\theta + z) + F_B z + F_L z = (F_G + B_R) z + F_F (2/3\ d_w)$

Geometric Calculations and Forces

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

$\theta = \tan^{-1} ((½ D_{RW})/(L_T))$

$z = (½ D_{RW}) \sin \theta + (L_T/2 - (½ L_{RW})(D_{RW}^2/D_T^2) (1-\eta_P))$

$\forall_{RW} = (\pi (D_{RW})^2)/4) L_{RW} (1-\eta_P)$

$\forall_T = (\pi (D_T/2)^2) L_T$

$\forall_{Tsub} = (d_w/\sin\theta)(\pi r^2)$

$A_{Rwsub} = (A_{RW})(P_{sub})$

$\forall_{Rwsub} = A_{RWsub} L_{RW} (1-\eta_P)$

$F_G = (\forall_T + \forall_{RW}) \rho_T$

$F_B = (\forall_{Tsub} + \forall_{RWsub}) \rho_w$

STOP, CHECK FS_B →

$FS_B = F_G/F_B$

If $FS_B < 1.5$, add required ballast (B_R) to obtain $FS_B = 1.5$ before continuing calculations

$FS_B = (F_G + B_R)/F_B$

$B_R = ((FS_B)(F_B)) - F_G$

$F_F = (v^2/2g) A_{RWsub} \rho_w C_D$

$F_L = (v^2/2g) (\forall_T + \forall_{RW}) \rho_w C_L$

Sum of Moments and Factors of Safety

1. ΣFy, $F_F (\sin \theta) + (F_G + B_R) = F_B + F_L + F_{NT} + F_{NRW}$
2. ΣMo, $F_{NT} (L_T \cos\theta + z) + F_B z + F_L z = (F_G + B_R) z + F_F (2/3\ d_w)$

Solve Equation 2. for F_{NT}, substitute into Equation 1. Solve for F_{NRW}

3. $F_{\mu T} = F_{NT} \mu_{BED}$
4. $F_{\mu RW} = F_{NRW} \mu_{BED}$

$FS_M = (F_{\mu T} + F_{\mu RW}) / (F_F (\cos \theta))$

$FS_B = ((F_G + B_R) + F_F (\sin \theta)) / (F_B + F_L)$

Example calculations are located in the appendix

Table 1: Friction Angles ϕ*

Sediment	Grain Size (mm)	Dry Bulk Density, kg / m³	Saturated Bulk Density, kg / m³	Friction Angles
Coarse gravel, boulders	>192	2100-2200	1300-1400	43-46
Coarse gravel	36-144	2000-2100	1250-1300	42-45
Medium gravel	18-36	1952-1975	1175-12225	41-44
Fine gravel	9-18	1750-1800	1100-1150	40-42
Gravelly sand	4.5-9.0	1700-1750	1050-1100	38-41
Coarse sand	1.0-4.5	1600-1650	1000-1050	33-39
Medium sand	0.54-1.0	1550-1600	950-1000	29-35
Fine sand	0.06-0.54	1450-1500	900-950	22-30

*From Abbe and others, 2000

Figure 2:

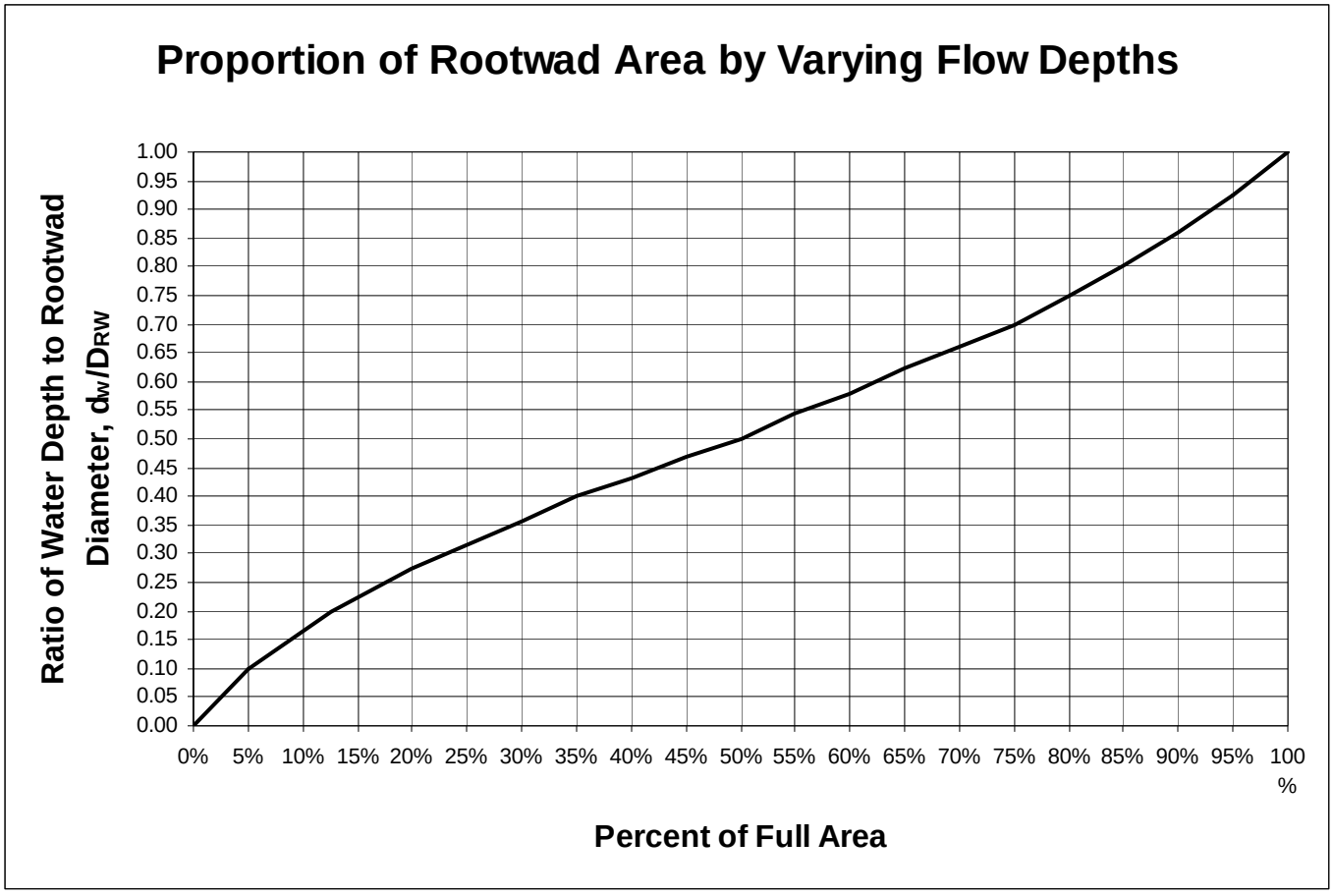


Table 2: Densities of air-dried timber*

Species	ρ_w #/ft^3
Cedar	22.5
Spruce (Sitka, White and Engleman)	26.8
Hemlock, Pine (Jack and Lodgepole), Spruce (Black)	30.0
Pine (Ponderosa)	31.8
Fir (Douglas)	33.7

* Modified from D'Aoust and Millar 1999

All projects utilizing LW require a momentum analysis.

The factor of safety of a structure with LW changes with flow depth and time. If the structure is designed to catch more LW, this must be accounted for in the initial design. The structure may initially have a porosity of 50%; after several high flow events, the porosity may be reduced to 20% due to sediment deposition and additional LW recruitment. Recognize that several different conditions exist that may alter the level of stability and factors of safety. These include the condition just after construction, the structure after several high-flow events, the seasoned structure which may be several years old, and the deteriorating structure that is nearing the end of its life span.

Bed friction conditions can change with time. Trees can embed into stream sediments increasing soil resistance. Values in Table 1 should provide a conservative analysis. Significantly higher unit densities than those shown in Table 2 have been documented in moist wood. The designer should make every effort to document realistic densities as this one variable has a large impact on the design.

If ice and debris are of concern, a higher factor of safety is necessary. In general, a stream with a lower width to depth ratio will have less likelihood of ice formation than a wide shallow channel. Upstream conditions are critical since ice formation above the structure will have the most significant impact. Ultimately, the selection of a reasonable factor of safety for different loading conditions is up to the designer who will take responsibility for the design and installation of the structure.

GENERAL MATERIAL SPECIFICATIONS

LW for instream structures should be relatively durable and of suitable quality to assure permanence for the design life of the LW component of the engineering structure (this is variable from a few years to decades) in the climate in which it is to be used.

Decay rates of wood and burial and/or exposure must also be considered for the life span of the LW. Alternate wetting and drying, or constant dampness, cause the highest rates of decay. Fully saturated wood has much greater longevity.

The density of the available material has a large impact on the analysis and on the ultimate stability of the project. Table 2 values are conservative in that they are for air-dried wood. If wood is moist, or can be soaked prior to installation, this will impact the wood density and the stability of the installation.

Cottonwood and alder have the highest decay rates with an estimated design life of 5 to 10-years. Maple is more durable, but even under saturated conditions survival is only 10 to 20-years. Conifers are generally more desirable because of slower decay rates, however, hemlock is the least desirable of the conifers. Sitka spruce is durable but is limited in availability because of its distribution and high value as lumber. Douglas fir is the most

available conifer and is very durable surviving from 25 to 50-years. Western red cedar is the most desirable because it lasts twice as long as Douglas fir, has natural rot-resistant properties, and is extremely durable (Johnson and Stypula 1993).

Trees with attached rootwads are the most desirable for incorporation into engineering structures because the rootwad can be exposed to stream flow while the bole is buried and used as a natural anchor. Rootwads also elevate the center of gravity of the tree, which are then more stable because it takes a much greater depth of water to float the tree. Trees without rootwads often result in scour beneath the log (Booth, Montgomery, and Bethel 1996).

LW sizing depends on the size of the stream, maximum depth of flow, planform, entrenchment, ice and debris loading, and available tree species. Adjustments will be necessary for your local area. If there is a limit on the size of material that you have available or the material has already been identified, use the actual wood size in your analysis to determine the amount of ballast that will be required for structure stability.

DESIGN CONSIDERATIONS

see attached figures for reference

(1) **Location** – LW is typically placed within a stream channel in locations that will enhance habitat and compliment natural stream processes – use a natural analog. For instance, placement of LW in a scour pool will increase the depth and size of the pool while providing cover for fish.

(2) **Height** – The relative height of LW near the stream bank (H) is generally determined by the elevation of channel-forming discharge (approximately a 1.5-year event). For ungaged streams, channel-forming discharge can be determined using field indicators such as bed features and the presence or absence of vegetation. The channel-forming flow elevation is not necessarily the top of the bank; for most streams, the channel-forming flow elevation is equal to or slightly above average annual peak flow. LW below the channel-forming flow level will be saturated on a regular basis and will provide in-stream habitat. LW that is located above the channel-forming flow elevation will trap sediment and debris, and may also support vegetation.

If the intent is to have a semi-permanent structure that accumulates more debris, then the top of the structure must be at or above the channel-forming flow level. If it is below, scour over the top of the structure may occur reducing the factor of safety, and resulting in greater buoyancy.

(3) **Angle and Offset** – The LW portion of a structure should be oriented such that the forces acting upon the LW increase its stability. If a rootwad is left exposed to the flow, the bole placed into a streambank should be oriented downstream parallel to the flow direction so that the pressure on the rootwad pushes the bole into the streambank and bed. Wood members that are oriented parallel to flow are more stable than members oriented at 45° or 90° to the flow. The most common mode of LW movement is for a piece oriented other than parallel to flow to rotate and slide until it assumes a position parallel to flow, and then becomes stable (Braudrick and Grant 2000).

(4) **Profile** – Structures with a lower profile will have fewer forces acting upon them. Design flow should be the channel-forming flow level (1.5-year flow). Banks that are

frequently overtopped will require a more extensive key that extends further back into the bank. Bank material will also need to be considered when designing the dimensions of the key.

(5) **Anchoring and Ballast** – Anchoring is a major concern when designing a structure with LW. Determine whether you need anchoring based upon calculations in the analysis section of this technical note. Anchoring is not always necessary.

Maintaining flexibility is the primary concern for structural stability in a stream channel. The less flexible the structure, the more potential damage if a failure occurs. Instead of traditional anchoring, such as cable and deadmen, consider increasing the mass of the LW. This can be accomplished by anchoring two or more logs together, or by using rebar or cable to attach large rock to the log near its center of gravity. The structure will then be comprised of several individual members rather than one large structure that is cabled into place.

When using ballast to increase the mass of the structure, use the stability analysis to determine how much material is needed. A factor of safety of 2 is recommended for all structures incorporating LW. For streams that are entrenched (Rosgen types F, G, A, and potentially B), or for streams with very low width to depth ratios (<12) an additional 60% ballast weight may be necessary due to greater flow depths and higher velocities. The factor of safety for ballast should be a minimum of 1.5 (D'Aoust and Millar 2000).

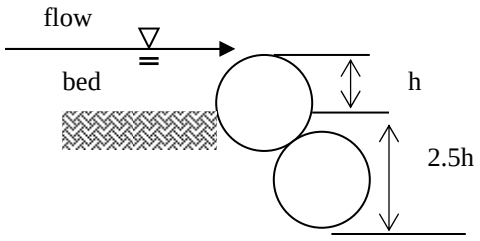
When using cable to anchor LW, keep in mind that disturbing the channel banks can lead to a rapid failure if the cable comes loose. Vibration of the cable due to flowing water and movement of the LW can cause bank destabilization and failure. When anchoring with cable, consider anchoring into the streambed or at a 45-degree angle into the bed and bank. This will reduce damages if there is a failure.

For a bole with attached rootwad, bury the bole end in the downstream direction with channel gravel or cobble. There is some evidence that this ballast and subsequent low velocity zone stabilizes the LW (Braudrick and Grant 2000).

Buried cut-off logs or rocks can be used in conjunction with a streambank structure to reduce the risk of flanking. The buried log or rock should be oriented perpendicular to the direction of flood flows. Left over rock, or rock that is too small for the instream portion of the structure can be used in the cut-off trench.

(6) **Depth of the Bed Key** -- The bed key depth should be determined by calculating expected scour hole depth downstream of a proposed structure. Note that scour depth will likely exceed the depth of the thalweg (deepest part of the channel). Scour depths will be greater in streams that are relatively deep or have higher gradients.

In lieu of a scour analysis, scour depth can be estimated using the following:



Expected scour depth for gravel or cobble bed streams can be estimated by:

Scour = 2.5*h

Where h = height of exposed rootwad to bed elevation.

For sand, use 3 to 3.5*h

To reduce scour depths, decrease the structure height. Higher structures cause greater flow convergence, and thus greater scour depths. The use of LW can help reduce scour depth by dissipating energy, replacing the need for a downstream apron.

(7) **Construction** – Construction should occur during low flow conditions to minimize instream disturbances. LW should be placed with the proper equipment to insure that the wood is interlocked and stable. It is CRITICAL that the designer or an inspector experienced in these structures be present during installation.

EXAMPLE ANALYSES

Attached are two specific examples (see Appendix), which illustrate how LW stability is evaluated using the calculations presented earlier in this technical note.

1. Single tree with rootwad – fully submerged
2. Single tree with rootwad – partially submerged
3. Single boulder – fully submerged

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APPENDIX

Sample Calculations

Single Tree with Rootwad, Fully Submerged, v = 5 ft/s, D_T = 2 ft, L_T = 20 ft, D_{RW} = 6 ft, L_{RW} = 3 ft, d_W = 8 ft, ϕ = 43° (from Table 1), η_P = 0.2, ρ_T = 31.2 #/ft^3

$\mu_{BED} = \tan \phi = \tan 43 = 0.933$

$\theta = \tan^{-1}((½D_{RW})/(L_T)) = \tan^{-1}((3)/(20)) = \tan^{-1}(.15) = 8.53°$

$z = (½ D_{RW}) \sin \theta + (L_T/2 – (½L_{RW})(D_{RW}^2/D_T^2)(1-\eta_P)) = (3)\sin 8.53° + (20/2 – (3/2)(6^2/2^2)(1-0.2)) =$ - 0.355 ft (note minus sign)

$\forall_{RW} = (\pi (D_{RW})^2/4) L_{RW} (1-\eta_P) = (\pi 6^2)/4(3)(1-0.2) = (28.3)(2.4) = 67.9$ ft^3

$\forall_T = \pi (D_T/2)^2 L_T = \pi (20) = 62.8$ ft^3

$F_G = (\forall_T + \forall_{RW}) \rho_T = (62.8 + 67.9)\ 31.2 = 4078$ #

$F_B = (\forall_{Tsub} + \forall_{RWsub}) \rho_w = (62.8 + 67.9)(62.4) = 8156$ #

$FS_B = F_G/F_B = 4078/8156 = 0.50$ Structure floats, add ballast (B_R)
$FS_B = (F_G + B_R)/F_B$
$1.5 = (4078 + B_R)/8156$
$B_R = ((1.5)(8156)) – 4078 = 8156$ #

$F_F = (v^2/2g) A_{RWsub} \rho_w C_{DRW} = (5^2/64.4)(28.27)(62.4)(1.2) = 822$ #

$F_L = (v^2/2g) (\forall_T + \forall_{RW}) \rho_w C_L = (5^2/64.4)(62.8 + 67.9)(62.4)(0.18) = 570$ #

1. ΣFy, $F_F (\sin \theta) + (F_G + B_R) = F_B + F_L + F_{NT} + F_{NRW}$
   $822(\sin 8.53) + (4078 + 8156) = 8156 + 570 + F_{NT} + F_{NRW}$
   $F_{NRW} = 822(\sin 8.53) + 12234 - 8156 - 570 - F_{NT}$
   $F_{NRW} = 3630 - F_{NT}$

Solve Equation 2. for F_{NT}, substitute into Equation 1. Solve for F_{NRW}

2. ΣMo, $F_{NT} (L_T \cos\theta + z) + F_B z + F_L z = (F_G + B_R) z + F_F (2/3\ d_w)$
   $F_{NT} (20\cos 8.53 - 0.355) + ((8156)(-0.355)) + ((570)(-0.355)) =$
   $((4078 + 8156)(-0.355)) + (822)((2/3)(8))$
   $F_{NT} (19.4) + (-2894) + (-202) = (-4343) + (4384)$
   $F_{NT} = 162$ #

   $F_{NRW} = 3630 - F_{NT} = 3630 – 162 = 3468$ #

3. $F_{\mu T} = F_{NT} \mu_{BED} = (162)(0.933) = 151$ #

4. $F_{\mu RW} = F_{NRW} \mu_{BED} = (3468)(0.933) = 3236$ #

$FS_M = (F_{\mu T} + F_{\mu RW}) / (F_F (\cos \theta)) = (151 + 3236) / (822(\cos 8.53)) = 4.2$

$FS_B = (F_G + B_R + F_F (\sin \theta)) / (F_B + F_L) = (4078 + 8156 + 822\sin 8.53)/(8156 + 570) = 1.4$

Sample Calculations

Single Tree with Rootwad, Partially Submerged (ignore lift), v = 5 ft/s, D_T = 2 ft, L_T = 20 ft, D_{RW} = 6 ft, L_{RW} = 3 ft, d_w = 1 ft, ϕ = 43° (from Table 1), η_P = 0.2, ρ_T = 31.2 #/ft^3

$\mu_{BED} = \tan \phi = \tan 43 = 0.933$

$\theta = \tan^{-1}((½D_{RW})/(L_T)) = \tan^{-1}((3)/(20)) = \tan^{-1}(.15) = 8.53°$

$z = (½ D_{RW}) \sin \theta + (L_T/2 – (½L_{RW})(D_{RW}^2/D_T^2)(1-\eta_P) = (3)\sin 8.53°°+(20/2 – (3/2)(6^2/2^2)(1-0.2)) =$ - 0.355 ft (note minus sign)

$\forall_{RW} = \pi (D_{RW}/2)^2 L_{RW} (1-\eta_P) = (\pi 3^2)(3)(1-0.2) = 67.8$ ft^3

$\forall_T = (\pi r^2)L_T = \pi (D_T/2)^2(20) = (3.1416(2/2)^2)(20) = 62.8$ ft^3

$\forall_{Tsub} = (d_w/\sin\theta)(\pi r^2) = (1/\sin 8.53)(3.1416(D_T/2)^2) = (6.7)(3.1416(2/2)^2) = 21.0$ ft^3

$A_{RWsub} = A_{RW}P_{sub} = \pi (D_{RW}/2)^2 P_{sub} = (3.1416)(9)(0.075) = 2.12$ ft^2

$\forall_{RWsub} = A_{RWsub}L_{RW}(1-\eta_P) = (2.12)(3)(1-0.2) = 5.1$ ft^3

$F_G = (\forall_T + \forall_{RW}) \rho_T = (62.8 + 67.8)\ 31.2 = 4075$ #

$F_B = (\forall_{Tsub} + \forall_{RWsub}) \rho_w = (21.0 + 5.1)62.4 = 1629$ #

$FS_B = F_G / F_B = 4075 / 1629 = 2.5$ No ballast required

$F_F = (v^2/2g) A_{RWsub} \rho_w C_{DRW} = (5^2/64.4)(2.12)(62.4)(1.2) = 62$ #

1. ΣFy, $F_F (\sin \theta) + F_G = F_B + F_{NT} + F_{NRW}$
   $62(\sin 8.53) + 4075 = 1629 + F_{NT} + F_{NRW}$
   $F_{NRW} = 62(\sin 8.53) + 4075 - 1629 - F_{NT}$
   $F_{NRW} = 2455 - F_{NT}$

Solve Equation 2. for F_{NT}, substitute into Equation 1. Solve for F_{NRW}

2. ΣMo, $F_{NT} (L_T\cos\theta + z) + F_B z = F_G z + F_F (2/3\ d_w)$
   $F_{NT}(20\cos 8.53 - 0.355) + ((1710)(-0.355)) = ((4075)(-0.355)) + (62)((2/3)(1))$
   $F_{NT}(19.4) + (-607) = (-1447) + (41)$
   $F_{NT} = -41$ # very light in the tip. All the force is on the RW.

$F_{NRW} = 2374 - F_{NT} = 2374 – \sim 0 = 2374$ #

3. $F_{\mu T} = F_{NT}\ \mu_{BED} = (\sim 0)(0.933) = \sim 0$ #

4. $F_{\mu RW} = F_{NRW}\ \mu_{BED} = (2374)(0.933) = 2215$ #

$FS_M = (F_{\mu T} + F_{\mu RW}) / (F_F (\cos \theta)) = (\sim 0 + 2215)/(62\cos 8.53) = 36$

$FS_B = (F_G + F_F (\sin \theta)) / (F_B) = (4075 + 62\sin 8.53)/(1710) = 2.4$

Sample Calculations

Single Boulder, Fully Submerged, 3-foot diameter, v = 5 ft/s, $\phi = 43°$

$\mu_{BED} = \tan \phi = \tan 43 = 0.933$

$\forall_B = \pi D^3/6 = (3.1416)(3^3/6) = (3.1416)(4.5) = 14 \text{ ft}^3$

$\rho_B = (\rho_w)(S_{gR}) = (62.4)(2.65) = 165 \text{ \#/ft}^3$

$\forall_{Bsub} = \forall_B = 14 \text{ ft}^3$ (since boulder is fully submerged)

$F_G = \forall_B \rho_B = (14)(165) = 2310 \text{ \#}$

$F_B = (\forall_{Bsub}) \rho_w = (14)(62.4) = 874 \text{ \#}$

$F_F = (v^2/2g)(\pi D^2) \rho_w C_{DBD} = (5^2/2(32.2))(3.1416)(3^2)(62.4) C_{DBD} = (.388)(3.1416)(9)(62.4)C_{DBD}$

$= 685 C_{DBD} = 685(0.2) = 137 \text{ \#}$

$F_L = (v^2/2g)(\forall_B) \rho_w C_L = (.388)(14)(62.4) C_L = 339 (0.18) = 61 \text{ \#}$

$F_{\mu B} = (F_G - F_B - F_L) \tan\phi = 1375 (\tan 43°) = 1282 \text{ \#}$

$FS_M = F_{\mu B} / F_F = 1282 / 137 = 9.4$

$FS_B = F_G / (F_B + F_L) = 2310 / (874 + 61) = 2.5$