HYDRAULIC FORCES SUMMARY

Debris Loading Case	WSEL U/S (ft)	Debris Thickness (ft)	Hydrostatic Force U/S (lbs)	Hydrostatic Force D/S (lbs)	Total Hydrostatic Force (lbs)	Drag Force (lbs)	Total Force (lbs)	Total Force Each Pier (kips)	Elevation Resultant Force (ft)
Single Pier Loading	594.54	9	240,084	194,468	45,616	143,170	188,786	**189**	590.0
Nine-Pier Loading	596.24	9	240,084	121,405	118,679	34,444	153,123	**153**	591.3
All-Pier Loading									
Piers 1-6 (left overbank)	603.42	18.52	1,547,744	344,699	1,203,045	13,652	1,216,698	**1,217**	592.0
Piers 7-11 (channel)	603.42	25.42	2,915,871	1,103,801	1,812,070	18,739	1,830,809	**1,831**	588.5
Piers 12-18 (right overbank)	603.42	14.92	1,004,511	119,218	885,293	10,999	896,292	**896**	593.9

ASSUMPTIONS: Single, 12-foot diameter circular piers
2850-foot bridge
9-pier loading scenario assumes 9 piers with debris accumulations 95 feet wide by 9 feet deep (maintenance scenario)
All-pier loading scenario assumes 18 piers with debris accumulations 95 feet wide and to the full depth of flow (no-maintenance scenarios)
100-year flood discharge of 127,900 cfs

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Task	Single Pier Debris -Pier #8	Sheet	1	Of	1

Assume: Debris accumulation only on single pier
Superstructure is not submerged
Ineffective flow areas from the debris defined by 1:1 contraction and 2:1 expansion
Depth of debris is 9 ft

Data:

Left station of debris=		ft	Right station of debris=	ft
Upstream water surface elevation, Ws_{us}=	594.54	ft	RS 9395.42	
Downstream water surface elevation, WS_{DS}=	593.64	ft	RS 9255.50	
Debris Bottom, DB_{EL}=	585.54	ft	(9' debris depth)	
Width of debris accumulation, W_D=	95	ft		
γ=	62.4	lbs/ft^3		
g=	32.2	ft/s^2		

Horizontal hydrostatic force

A_{hu}= Area of the debris accumulation below the upstream water surface
A_{hu}= $(WS_{us}\text{-}DB_{EL})*W_D$
A_{hu}= 855 ft^2

A_{hd}= Area of the debris accumulation below the downstream water suface
A_{hd}= $(WS_{DS}\text{-}DB_{EL})*W_D$
A_{hd}= 769.5 ft^2

hcu= Vertical distance to centroid of Ahu =$0.5(WS_{US}\text{-}DB_{EL})$
hcu= 4.5 ft

hcu= Vertical distance to centroid of Ahd =$0.5(WS_{DS}\text{-}DB_{EL})$
hcu= 4.05 ft

F_{hu}= Hydrostatic force upstream = $\gamma h_{cu} A_{hu}$
240,084 lbs

F_{hd}= Hydrostatic force downstream = $\gamma h_{cd} A_{hd}$
194,468 lbs

F_h= Total hydrostatic force on pile = F_{hu} - F_{hd}
45,616 lbs

Blockage ratio

$$B = \frac{A_d}{A_d + A_c}$$

$$F_r = \frac{V_r}{\sqrt{g y_r}}$$

$$F_D = C_D \gamma A_D \frac{V_r^2}{2g}$$

A_d= 855 ft^2
A_c= 17,283.28 ft^2 Flow area at BR US
B= 0.05

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Hydrodynamic drag force

V_r= Reference velocity, see discussion in Subsection 4.3.3.1, m/s (ft/s)

If B>30%, Vr is based on the maximum average veloctity in the contracted section of the entire bridge opening

If B<30%, Vr is based on the maximum local average velocity near the pier and debris accumulation

i.e., maximum average flow velocity in the main channel for piers located in the main channel

maximum average flow velocity in the left overbank for piers located in the left overbank

V_r=	9.98	ft/s	Maximum local channel velocity from flow distribution RS 9395.42
y_r=	16.54	ft	Maximum channel depth from RS 9395.42
F_r=	0.432		

On Piles

C_D= Drag coefficient, see Tables 4.1 and 4.2

C_D= 1.74

F_D= Drag force, (lbs)

143,170 lbs

Total Force on Single Pier Accumulation

F= Total segment force = F_h+F_D

F= **188,786** lbs

Location of Forces on Single Pier Accumulation

F_{hEL} = Elevation of hydrostatic force = $$DB_{EL}+\frac{F_{hu}(\frac{WS_{US}-DB_{EL}}{3})-Fhd(\frac{WS_{DS}-DB_{EL}}{3})}{F_h}$$

F_{hEL} = 589.82 ft

F_{DEL} = Elevation of drag force = 0.5(WS_{US}+DB_{EL})

590.04 ft

F_{EL}= Elevation of total force = $$\frac{F_D F_{DEL}+F_h F_{hEL}}{F}$$

F_{EL}= 589.99 ft

F_{hST}= Station of hydrostatic force = 0.5(Left station of debris + right station of debris)

F_{DST}= Station of drag force = F_{hST}

F_{ST}= Station of total force = F_{DST}=F_{hST}

F_{hST}=F_{DST}=F_{ST}= - ft

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Task	9 Pier Debris - Pier 1-5 & Pier 7-10	Sheet	1	Of	1

Assume: Debris accumulation on nine piers
Superstructure is not submerged
Ineffective flow areas from the debris defined by 1:1 contraction and 2:1 expansion
Depth of debris is 9 ft

Data: **Pier 1-5** in the left overbank

Left station of debris=		ft	Right station of debris=	ft
Upstream water surface elevation, Ws_{us}=	596.24	ft	RS 9395.42	
Downstream water surface elevation, WS_{DS}=	593.64	ft	RS 9255.50	
Debris Bottom, DB_{EL}=	587.24	ft	(9' debris depth)	
Width of debris accumulation, W_D=	95	ft		

Pier 7-10 in the channel

Left station of debris=		ft	Right station of debris=	ft
Upstream water surface elevation, Ws_{us}=	596.24	ft	RS 9395.42	
Downstream water surface elevation, WS_{DS}=	593.64	ft	RS 9255.50	
Debris Bottom, DB_{EL}=	587.24	ft	(9' debris depth)	
Width of debris accumulation, W_D=	95	ft		
γ=	62.4	lbs/ft^3		
g=	32.2	ft/s^2		

Horizontal hydrostatic force

A_{hu}= Area of the debris accumulation below the upstream water surface
A_{hu}= $(WS_{us}-DB_{EL})*W_D$

Pier 1-5	A_{hu}=	855	ft^2	Pier 7-10	A_{hu}=	855	ft^2

A_{hd}= Area of the debris accumulation below the downstream water suface
A_{hd}= $(WS_{DS}-DB_{EL})*W_D$

Pier 1-5	A_{hd}=	608	ft^2	Pier 7-10	A_{hd}=	608	ft^2

hcu= Vertical distance to centroid of Ahu =$0.5(WS_{US}-DB_{EL})$

Pier 1-5	hcu=	4.5	ft	Pier 7-10	hcu=	4.5	ft

hcu= Vertical distance to centroid of Ahd =$0.5(WS_{DS}-DB_{EL})$

Pier 1-5	hcu=	3.2	ft	Pier 7-10	hcu=	3.2	ft

F_{hu}= Hydrostatic force upstream = $\gamma h_{cu} A_{hu}$

Pier 1-5	F_{hu}=	240,084	lbs	Pier 7-10	F_{hu}=	240,084	lbs

F_{hd}= Hydrostatic force downstream = $\gamma h_{cd} A_{hd}$

Pier 1-5	F_{hd}=	121,405	lbs	Pier 7-10	F_{hd}=	121,405	lbs

F_h= Total hydrostatic force on pile = F_{hu} - F_{hd}

Pier 1-5	F_h=	**118,679**	lbs	Pier 7-10	F_h=	**118,679**	lbs

Blockage ratio

$$B = \frac{A_d}{A_d + A_c}$$

$$F_r = \frac{V_r}{\sqrt{g y_r}}$$

$$F_D = C_D \gamma A_D \frac{V_r^2}{2g}$$

Pier 1-10	A_d=	7,695	ft^2
	A_c=	11,951.80	ft^2 Flow area at BR US
	B=	0.39	

Hydrodynamic drag force

V_r= Reference velocity, see discussion in Subsection 4.3.3.1, m/s (ft/s)
If B>30%, Vr is based on the maximum average velocity in the contracted section of the entire bridge opening
If B<30%, Vr is based on the maximum local average velocity near the pier and debris accumulation
i.e., maximum average flow velocity in the main channel for piers located in the main channel
maximum average flow velocity in the left overbank for piers located in the left overbank

Pier 1-5	V_r=	4.96	ft/s	Pier 7-10	V_r=	4.96	ft/s	Total bridge opening velocity at RS 9395.42 (active flow within limits of bridge opening)
	y_r=	8.98	ft		y_r=	8.98	ft	Total bridge opening hydraulic depth at RS 9395.42 (top width active flow / flow area)
	F_r=	0.292			F_r=	0.292		

On Piles

C_D= Drag coefficient, see Tables 4.1 and 4.2

C_D=	1.69		C_D=	1.69	
F_D= Drag force, (lbs)			F_D= Drag force, (lbs)		
34,444	lbs		**34,444**	lbs	

Total Force on Single Pier Accumulation

F= Total segment force = F_h+F_D

Pier 1-5	F=	**153,123**	lbs	Pier 7-10	F=	**153,123**	lbs

Location of Forces on Single Pier Accumulation

F_{hEL} = Elevation of hydrostatic force =

$$DB_{EL} + \frac{F_{hu}\left(\frac{WS_{US} - DB_{EL}}{3}\right) - Fhd\left(\frac{WS_{DS} - DB_{EL}}{3}\right)}{F_h}$$

Pier 1-5	F_{hEL} =	591.13	ft	Pier 7-10	F_{hEL} =	591.13	ft

F_{DEL} = Elevation of drag force = $0.5(WS_{US}+DB_{EL})$

F_{DEL} =	591.74	ft	F_{DEL} =	591.74	ft

F_{EL}= Elevation of total force =

$$\frac{F_D F_{DEL} + F_h F_{h_{EL}}}{F}$$

F_{EL}=	591.26	ft	F_{EL}=	591.26	ft

$F_{hST=}$ Station of hydrostatic force = 0.5(Left station of debris + right station of debris)
F_{DST}= Station of drag force = F_{hST}
F_{ST}= Station of total force = F_{DST}=F_{hST}

F_{hST}=F_{DST}=F_{ST}=	-	ft	F_{hST}=F_{DST}=F_{ST}=	-	ft

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Assume: Debris accumulation on all 18 piers
Superstructure is not submerged
Ineffective flow areas from the debris defined by 1:1 contraction and 2:1 expansion
Depth of debris is full-flow depth

Data:

Pier 1-6 in the left overbank

Left station of debris=		ft	Right station of debris=	ft
Upstream water surface elevation, Ws_{us}=	603.42	ft	RS 9395.42	
Downstream water surface elevation, WS_{DS}=	593.64	ft	RS 9255.50	
Debris Bottom, DB_{EL}=	584.9	ft	Average bottom left overbank	
Width of debris accumulation, W_D=	95	ft		

Pier 7-11 in the channel

Left station of debris=		ft	Right station of debris=	ft
Upstream water surface elevation, Ws_{us}=	603.42	ft	RS 9395.42	
Downstream water surface elevation, WS_{DS}=	593.64	ft	RS 9255.50	
Debris Bottom, DB_{EL}=	578	ft	Bottom channel	
Width of debris accumulation, W_D=	95	ft		

Pier 12-18 in the right overbank

Left station of debris=		ft	Right station of debris=	ft
Upstream water surface elevation, Ws_{us}=	603.42	ft	RS 9395.42	
Downstream water surface elevation, WS_{DS}=	593.64	ft	RS 9255.50	
Debris Bottom, DB_{EL}=	588.5	ft	Average bottom right overbank	
Width of debris accumulation, W_D=	95	ft		
g=	32.2	ft/s^2		

Horizontal hydrostatic force

A_{hu}= Area of the debris accumulation below the upstream water surface
A_{hu}= $(WS_{us}-DB_{EL})*W_D$

Pier 1-6	A_{hu}=	1759.4 ft^2	Pier 7-11	A_{hu}=	2414.9 ft^2	Pier 12-18	A_{hu}=	1417.4 ft^2

A_{hd}= Area of the debris accumulation below the downstream water suface
A_{hd}= $(WS_{DS}-DB_{EL})*W_D$

Pier 1-6	A_{hd}=	830.3 ft^2	Pier 7-11	A_{hd}=	1485.8 ft^2	Pier 12-18	A_{hd}=	488.3 ft^2

hcu= Vertical distance to centroid of Ahu =$0.5(WS_{US}-DB_{EL})$

Pier 1-6	hcu=	9.26 ft	Pier 7-11	hcu=	12.71 ft	Pier 12-18	hcu=	7.46 ft

hcu= Vertical distance to centroid of Ahd =$0.5(WS_{DS}-DB_{EL})$

Pier 1-6	hcu=	4.37 ft	Pier 7-11	hcu=	7.82 ft	Pier 12-18	hcu=	2.57 ft

F_{hu}= Hydrostatic force upstream = $\gamma h_{cu} A_{hu}$

Pier 1-6	F_{hu}=	1,547,744 lbs	Pier 7-11	F_{hu}=	2,915,871 lbs	Pier 12-18	F_{hu}=	1,004,511 lbs

F_{hd}= Hydrostatic force downstream = $\gamma h_{cd} A_{hd}$

Pier 1-6	F_{hd}=	344,699 lbs	Pier 7-11	F_{hd}=	1,103,801 lbs	Pier 12-18	F_{hd}=	119,218 lbs

F_h= Total hydrostatic force on pile = $F_{hu} - F_{hd}$

Pier 1-6	F_h=	**1,203,045** lbs	Pier 7-11	F_h=	**1,812,070** lbs	Pier 12-18	F_h=	**885,293** lbs

Blockage ratio

$$B = \frac{A_d}{A_d + A_c}$$

$$F_r = \frac{V_r}{\sqrt{g y_r}}$$

$$F_D = C_D \gamma A_D \frac{V_r^2}{2g}$$

Pier 1-18	A_d=	32,553 ft^2	
	A_c=	16,186.42 ft^2	Flow area at BR US
	B=	0.67	

Hydrodynamic drag force

V_r= Reference velocity, see discussion in Subsection 4.3.3.1, m/s (ft/s)
If B>30%, Vr is based on the maximum average veloctity in the contracted section of the entire bridge opening
If B<30%, Vr is based on the maximum local average velocity near the pier and debris accumulation
i.e., maximum average flow velocity in the main channel for piers located in the main channel
maximum average flow velocity in the left overbank for piers located in the left overbank

Pier 1-6	V_r=	2.75 ft/s	Pier 7-11	V_r=	2.75 ft/s	Pier 12-18	V_r=	2.75 ft/s	Total bridge opening velocity at RS 9395.42 (active flow within limits of bridge opening)
	y_r=	16.16 ft		y_r=	16.16 ft		y_r=	16.16 ft	Total bridge opening hydraulic depth at RS 9395.42 (top width active flow / flow area)
	F_r=	0.121		F_r=	0.121		F_r=	0.121	

C_D= Drag coefficient, see Tables 4.1 and 4.2

On Piles	C_D=	0.70		C_D=	0.70		C_D=	0.70
	F_D=	Drag force, (lbs)		F_D=	Drag force, (lbs)		F_D=	Drag force, (lbs)
		13,652 lbs			**18,739** lbs			**10,999** lbs

Total Force on Single Pier Accumulation

F= Total segment force = F_h+F_D

Pier 1-6	F=	**1,216,698** lbs	Pier 7-11	F=	**1,830,809** lbs	Pier 12-18	F=	**896,292** lbs

Location of Forces on Single Pier Accumulation

F_{hEL} = Elevation of hydrostatic force =

$$DB_{EL} + \frac{F_{hu}\left(\frac{WS_{US} - DB_{EL}}{3}\right) - Fhd\left(\frac{WS_{DS} - DB_{EL}}{3}\right)}{F_h}$$

Pier 1-6	F_{hEL} =	592.01 ft	Pier 7-11	F_{hEL} =	588.46 ft	Pier 12-18	F_{hEL} =	593.91 ft

F_{DEL} = Elevation of drag force = $0.5(WS_{US}+DB_{EL})$

	F_{DEL} =	594.16 ft		F_{DEL} =	590.71 ft		F_{DEL} =	595.96 ft

F_{EL}= Elevation of total force = $\dfrac{F_D F_{DEL} + F_h F_{hEL}}{F}$

	F_{EL}=	592.03 ft		F_{EL}=	588.48 ft		F_{EL}=	593.94 ft

F_{hST}= Station of hydrostatic force = 0.5(Left station of debris + right station of debris)
F_{DST}= Station of drag force = F_{hST}
F_{ST}= Station of total force = $F_{DST}=F_{hST}$

	$F_{hST}=F_{DST}=F_{ST}$=	**0.00** ft		$F_{hST}=F_{DST}=F_{ST}$=	**0.00** ft		$F_{hST}=F_{DST}=F_{ST}$=	**0.00** ft

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Reference: Debris Control Structures Evaluation and Countermeasures, Third Edition, FHWA-IF-04-016

Hydrodynamic drag force

$$F_D = C_D \gamma A_D \frac{V_r^2}{2g}$$

where:

F_D= Drag force, N (lbs)

C_D= Drag coefficient, see Tables 4.1 and 4.2

γ= Specific weight of water, N/m^3 (lbs/ft^3)

A_D= Area of wetted debris based on the upstream water surface elevation projected normal to the flow direction, m^2 (ft^2)

V_r= Reference velocity, see discussion in Subsection 4.3.3.1, m/s (ft/s)

g= Acceleration of gravity, 9.81 m/s^2 (32.2 ft/s^2)

Blockage ratio

$$B = \frac{A_d}{A_d + A_c}$$

where:

B= Blockage ratio

A_d= Cross-sectional flow area blocked by debris in the contracted bridge section, m^2 (ft^2)

A_c= Unobstructed cross-sectional flow in the contracted section, m^2 (ft^2)

Froude number

$$F_r = \frac{V_r}{\sqrt{g y_r}}$$

where:

F_r= Froude number

V_r= Reference velocity, see discussion in Subsection 4.3.3.1, m/s (ft/s)

g= Acceleration of gravity, 9.81 m/s^2 (32.2 ft/s^2)

y_r= Average flow depth corresponding with the reference velocity, m (ft)

Horizontal hydrostatic force

$$F_h = \gamma (h_{cu} A_{hu} - h_{cd} A_{hd})$$

where:

F_h= Horizontal hydrostatic force on area A_n, N (lbs)

γ= Specific weight of water, N/m3 (lbs/ft^3)

h_{cu}= Vertical distance from the upstream water surface to the centroid of area Ahu, m (ft)

A_{hu}= Area of the vertically projected, submerged portion of the debris accumulation below the upstream water surface, m2 (ft2)

h_{cd}= Vertical distance from the downstream water surface to the centroid of area Ahd, m (ft)

A_{hd}= Area of the vertically projected, submerged portion of the debris accumulation below the downstream water surface, m2 (ft2)