PENDULUM TESTING OF GUARDRAIL POSTS ON BOX CULVERTS

INTRODUCTION

The objective of this project was to develop a guardrail design for typical box culverts that will meet the safety performance guidelines set forth in National Cooperative Highway Research Program (NCHRP) *Report 350*. Low-speed pendulum tests were performed on a prototype guardrail post on a simulated box culvert as a surrogate for full-scale crash testing.

PENDULUM FACILITY

The guardrail post on box culvert was tested at Texas Transportation Institute (TTI) outdoor pendulum testing facility. The pendulum bogie, built according the specifications of the Federal Outdoor Impact Laboratory's (FOIL) pendulum, and the testing area are shown in the adjacent figure. Frontal crush of the aluminum honeycomb nose of the bogie simulates the crush of an actual vehicle and the sweeper plate, constructed of steel angles and a steel plate, is attached to the body of the pendulum with a ground clearance of 4 inches to replicate roughly an automobile's undercarriage. The crushable nose configuration is the FOIL ten stage bogie nose. Cartridges of expendable aluminum honeycomb material of differing densities are placed in a sliding nose. The pendulum impacts the guardrail post on box culvert at a target speed of 22 mph and at a height of 21 inches above the ground, which represents the bumper height of a pickup truck. After a test, the honeycomb material is replaced and the bogie is reused. A sketch of the honeycomb configuration used for the pendulum bogie is shown in Appendix A. Testing was performed in accordance with *NCHRP Report 350* and a brief description of the procedures is presented in Appendix B.

TEST INSTALLATION

TTI received simulated concrete box culvert details from Michael Elle of Minnesota Department of Transportation (MnDOT). Two W6x9 guardrail post were anchored to two simulated concrete deck specimens. Each specimen was crash tested using a dynamic pendulum surrogate vehicle. Each post was anchored to a 9-inch thick concrete deck to simulate a typical box culvert installation. The concrete deck specimens were 8 feet-3½ inches wide and 8 feet-4½ inches long. The concrete decks constructed and tested for this project were 9 inches thick. Reinforcement in the top of each deck consisted of #3 transverse bars spaced on 12-inch centers. Longitudinal reinforcement in each deck consisted of #3 bars spaced on 6-inch centers. Reinforcement in the bottom layer consisted also of #3 bars spaced on 12-inch centers with #5 bars spaced on 4½-inch centers in the longitudinal direction. To further simulate the anchorage to a typical concrete box culvert installation, the posts were anchored 2 ft-4 inches from the edge of the culvert. Additional details are shown in Appendix C.

A detailed design of the W6x9 post anchorage and base plate tested was performed. A second design utilizing W8x21 posts was also performed. However, based on the proposed frequent use, only the system utilizing W6x9 posts was tested. Based on the information provided by the participating states in this pooled fund project, the preferred anchoring system for post anchorage to the top of the box culvert system was Hilti's RE 500 Adhesive Anchoring System. The W6x9 posts were welded to 12 inch x 12 inch x 7/8-inch thick base plates and anchored to the 9-inch thick concrete box culvert decks utilizing 7/8-inch diameter super Hilti Anchoring System (HAS) rods. These rods were embedded a minimum of 6 inches into 1-inch diameter drilled holes in the concrete decks and anchored to the deck using Hilti RE 500 Epoxy Anchoring System. A larger base plate utilizing deeper adhesive anchors was designed for the W8x21 posts to simulate anchorage to the top of a concrete footing. The base plate and anchorage designs were based on the minimum strengths to cause plastic failure in the posts. These designs can be utilized for the direct anchorage to either the box culvert or concrete footing without any contribution from soil embedment above the box culvert or footing. The anchorage and base plate designs for both the W6x9 and the W8x21 posts are provided in Appendix D.

TEST RESULTS

Test P1

The pendulum bogie, traveling at an impact speed of 21.7 mi/h, impacted the guardrail post at a height of 21 inches. At 0.012 s, the post began to deflect toward the field side, and at 0.017 s, the post returned to its upright position. The post began to deflect toward the field side again at 0.022 s, and the pendulum began to ride up the face of the post at 0.091 s. Forward motion of the pendulum stopped at 0.157 s.

The top of the post was deformed toward field side 10.8 inches. Total crush of the honeycomb nose was 14.0 inches. Photographs of the post before and after the test are shown in Appendix E.

Longitudinal occupant impact velocity was 8.9 m/s, longitudinal occupant ridedown acceleration was -3.9 g's, and the maximum 50-ms average acceleration was -10.0 g's. Graphs for this test are shown in Appendix F.

Test P2

The pendulum bogie, traveling at an impact speed of 21.1 mi/h, impacted the guardrail post at a height of 21 inches. At 0.010 s, the post began to deflect toward the field side, and at 0.015 s, the post returned to its upright position. The post began to deflect toward the field side again at 0.020 s, and the pendulum began to ride up the face of the post at 0.067 s. The post began to shear at the front of the base at 0.106 s.

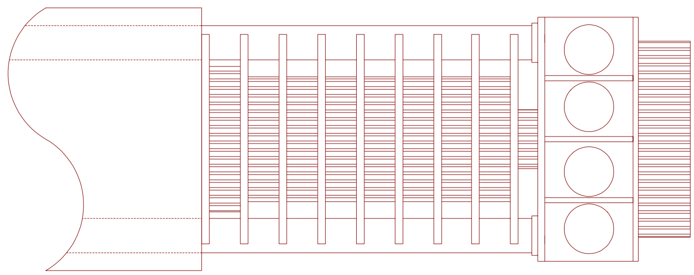
The top of the post was deformed toward field side 10.8 inches. Total crush of the honeycomb nose was 13.7 inches. Photographs of the post before and after the test are shown in Appendix E.

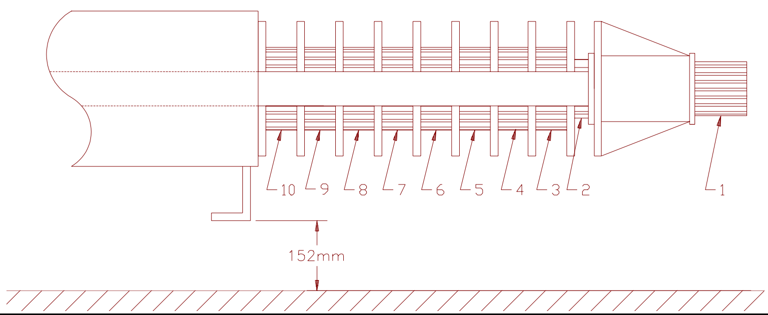
Longitudinal occupant impact velocity was 6.3 m/s, longitudinal occupant ridedown acceleration was -0.6 g's, and the maximum 50-ms average acceleration was -9.6 g's. Graphs for this test are shown in Appendix F.

CONCLUSIONS

TTI performed low-speed pendulum tests as a surrogate for full-scale crash testing. The W6x9 post and baseplate design using 7/8-inch high strength anchor rods and anchored using the Hilti RE 500 Adhesive System and presented herein performed well in the full scale tests. Based on the testing results, the W6x9 post and anchorage details presented in this report are recommended for full-scale crash testing.

APPENDIX A. PENDULUM BOGIE DETAILS





Cartridge Number	Size (mm)	Area Effectively Removed by Pre-Crushing (mm^2)	Static Crush Strength (kPa)	Total Crush Force for Each Cartridge (kN)
1	69.9 × 406 × 76		896.3	25.4
2	102 × 127 × 51		172.4	2.2
3	203 × 203 × 76	13549	896.3	24.8
4	203 × 203 × 76	9678	1585.8	50.0
5	203 × 203 × 76	3871	1585.8	59.2
6	203 × 203 × 76		1585.8	65.3
7	203 × 203 × 76	13549	2757.9	76.3
8	203 × 203 × 76	7742	2757.9	92.3
9	203 × 203 × 76		2757.9	113.6
10	203 × 254 × 76		2757.9	142.3

Configuration of pendulum nose and honeycomb.

APPENDIX B. PENDULUM TEST PROCEDURES AND DATA ANALYSIS

The pendulum test and data analysis procedures were in accordance with guidelines presented in *NCHRP Report 350*. Brief descriptions of these procedures are presented as follows.

ELECTRONIC INSTRUMENTATION AND DATA PROCESSING

The bogie was instrumented with two accelerometers mounted at the rear of the bogie to measure longitudinal acceleration levels. The accelerometers were strain gage type with a linear millivolt output proportional to acceleration.

The electronic signals from the accelerometers were amplified and transmitted to a base station by means of constant bandwidth FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Calibration signals were recorded before and after the test and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive switches on the nose of the bogie were actuated by wooden dowel rods and initial contact to produce speed trap and "event" marks on the data record to establish the exact instant of contact with the installation, as well as impact velocity.

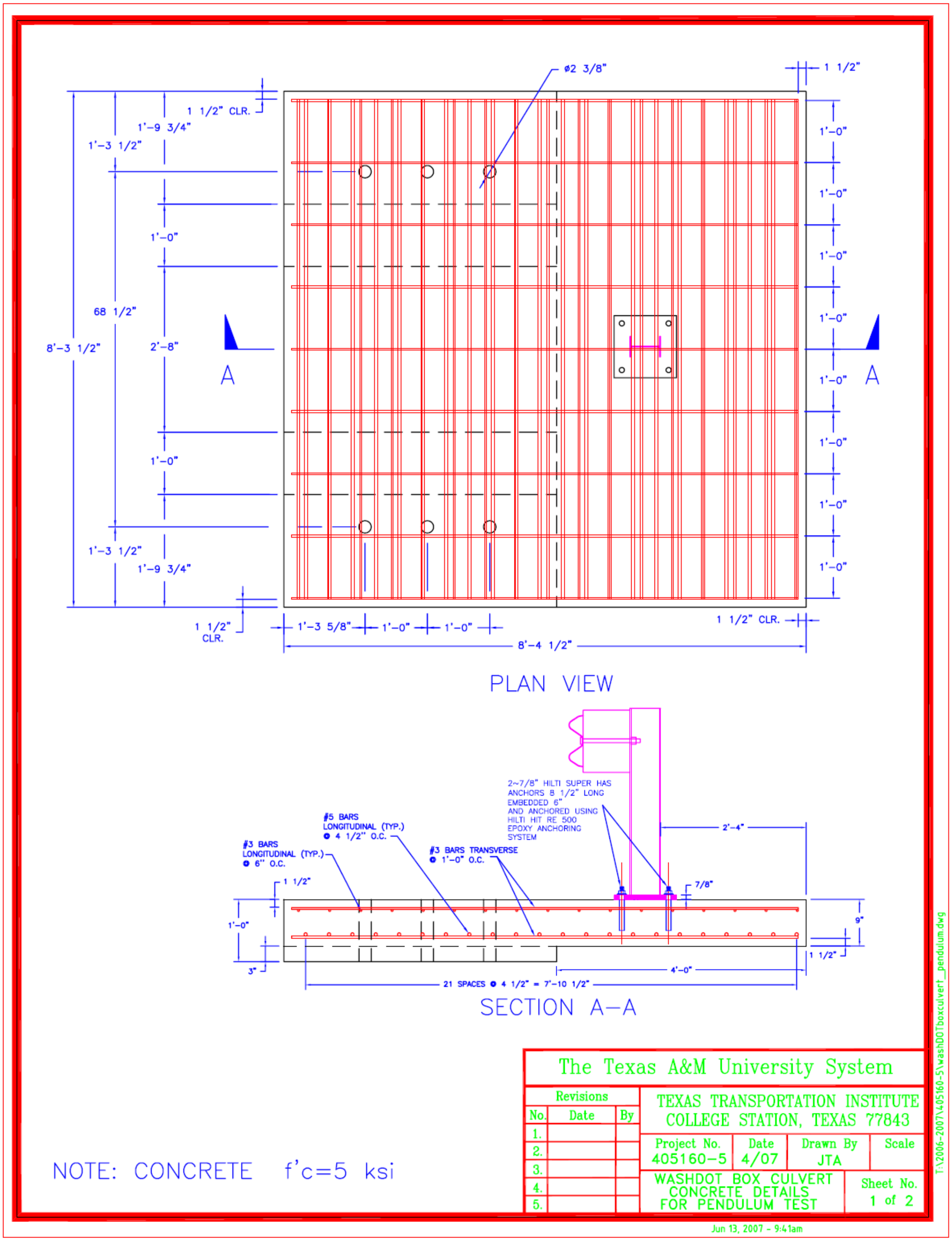
The multiplex of data channels, transmitted on one radio frequency, is received and demultiplexed onto TEAC® instrumentation data recorder. After the test, the data are played back from the TEAC® recorder and digitized. A proprietary software program (WinDigit) converts the analog data from each transducer into engineering units using the R-cal and pre-zero values at 10,000 samples per second, per channel. WinDigit also provides Society of Automotive Engineers (SAE) J211 class 180 phaseless digital filtering and bogie impact velocity.

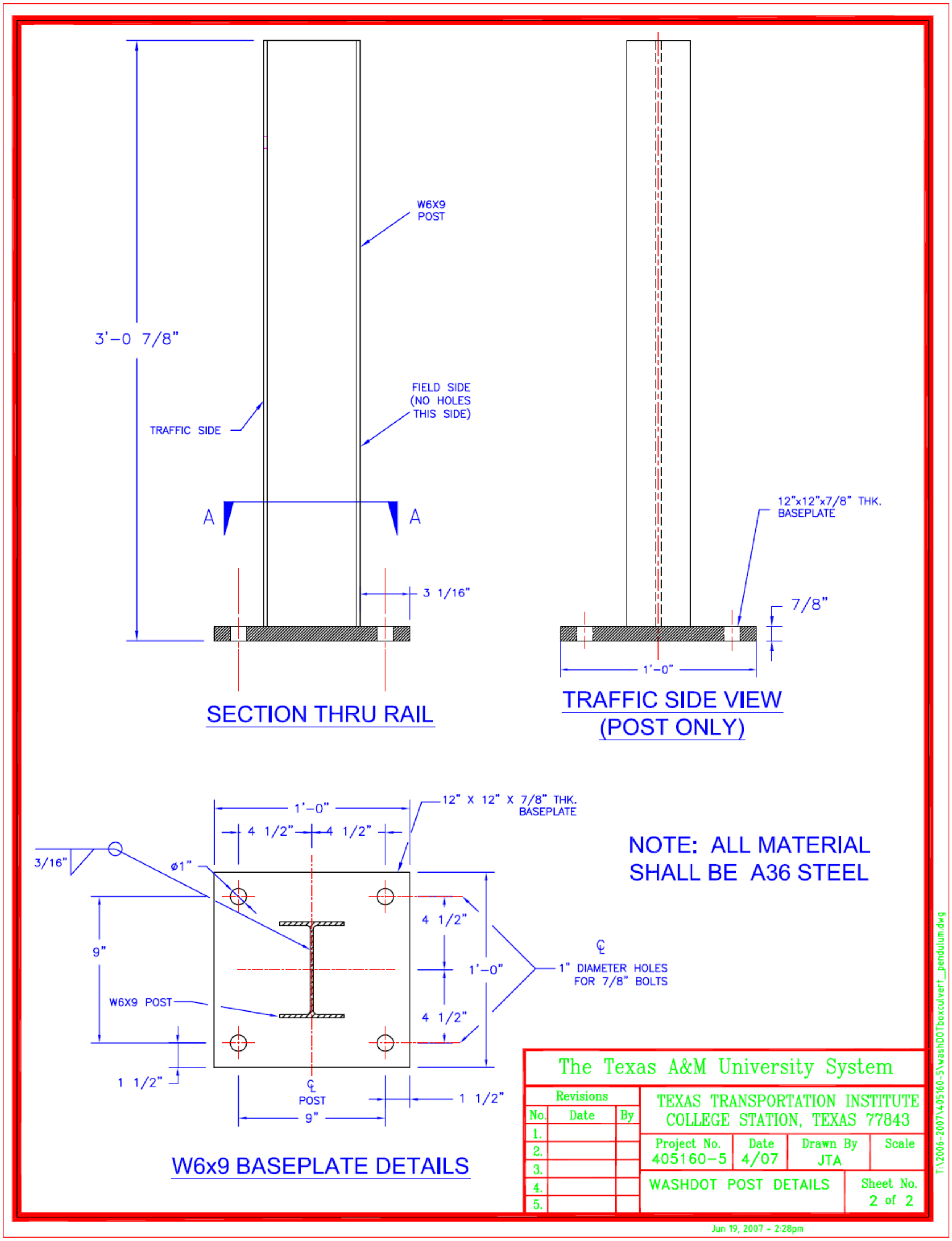
The Test Risk Assessment Program (TRAP) uses the data from WinDigit to compute occupant/compartment impact velocities, time of occupant/compartment impact after bogie impact, and the highest 10-ms average ridedown acceleration. WinDigit calculates change in bogie velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms are computed. For reporting purposes, the data from the bogie-mounted accelerometers were then filtered with a 180 Hz digital filter and plotted using a commercially available software package (Microsoft EXCEL).

PHOTOGRAPHIC INSTRUMENTATION

A high-speed digital camera, positioned perpendicular to the path of the pendulum bogie and the test article, was used to record the collision period. The film from this high-speed camera was analyzed on a computer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A Betacam camera and still cameras were used to document the crushable pendulum nose and the test article before and after the test.

APPENDIX C. DETAILS OF TEST ARTICLES




W6X9 POST
3'-0 7/8"
FIELD SIDE (NO HOLES THIS SIDE)
TRAFFIC SIDE
A
A
3 1/16"
12"x12"x7/8" THK. BASEPLATE
7/8"
1'-0"
SECTION THRU RAIL
TRAFFIC SIDE VIEW (POST ONLY)
1'-0"
12" X 12" X 7/8" THK. BASEPLATE
4 1/2"
4 1/2"
3/16"
ø1"
NOTE: ALL MATERIAL SHALL BE A36 STEEL
4 1/2"
9"
1'-0"
1" DIAMETER HOLES FOR 7/8" BOLTS
W6X9 POST
4 1/2"
1 1/2"
POST
9"
1 1/2"
W6x9 BASEPLATE DETAILS
The Texas A&M University System
Revisions
No.
Date
By
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TEXAS TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS 77843
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APPENDIX D. DESIGN CALCULATIONS

W6x9 DESIGN

Texas Transportation Institute

Project #: 405160-00005

W6x9 Design

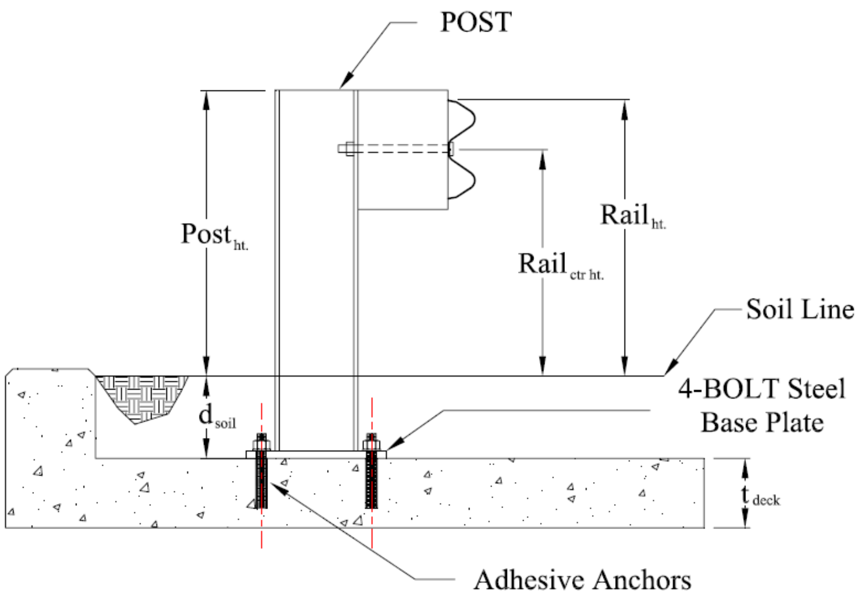
Subject: Box Culvert Guardrail - Task AE Calculations

Hilti RE 500 Anchor System

Sponsor: Washington DOT Pooled Fund

7/8" Dia. Anchors Embed. 6" Max

Given the following general latout of a box culvert guardrail post anchored to a concrete box culvert section using an epoxy adhesive anchoring system. Find the limiting ultimate strength of the post design considering the different variables used in the design.



GUARDRAIL ON BOX CULVERT TYPICAL CROSS-SECTION

depth of soil (in.)

$d_{soil} := 0in$

Thickness of Deck (in.)

$t_{deck} := 9in$

1.) Design Information:

****** Rail Geometry ******

$Rail_{ctrht} := 21in$ Center Height of Rail (in.)

$Rail_{ht} := Rail_{ctrht} + 6.125in$ Height to top of rail (in.)

$Post_{ht} := 27in$ Height of Post above grade (in.)

$Post_{load} := 12kips$ Load applied to Rail center (kips) $M_{load} := Post_{load} \cdot (Rail_{ht} + d_{soil})$

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Define Mathcad units ORIGIN := 1

$kips \equiv kip$ $ksi \equiv \frac{kips}{in^2}$

Steel Beam Yield Strength: $F_y := (50) \cdot ksi$

Beam Nominal Depth: NOMINAL_DEPTH := (6)

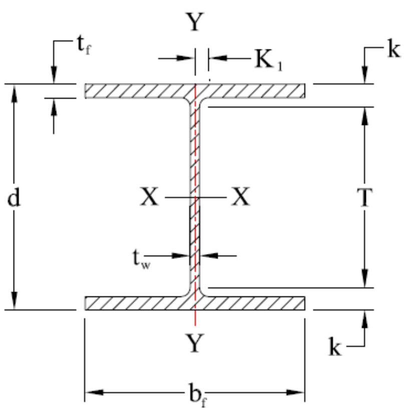
Beam weight per foot: WEIGHT_PER_FOOT := (9)

Beam Data - Fri Sep 15 09:13:04 2006

***** **Post Information** *****

Post Data for: Nominal_depth = 6·in

$Wt\_per\_foot = 9\,ft^{-1} \cdot lb$ $F_y = 50 \cdot ksi$



POST DETAILS

$Wt\_per\_foot = 9\,ft^{-1} \cdot lb$	Wt. per foot of length (lb/ft)
$d_n = 6$	Nominal Depth of member
$Area = 2.68 \cdot in^2$	Area (in^2)
$d = 5.9 \cdot in$	Actual Depth of Member (in.)
$t_w = 0.17 \cdot in$	Thickness of Web (in.)
$b_f = 3.94 \cdot in$	Width of Flange (in.)
$t_f = 0.215 \cdot in$	Thickness of Flange (in.)
$k = 0.56 \cdot in$	Distance to toe of fillet (in.)
$I_x = 16.4 \cdot in^4$	Moment of Inertia (Stg. Axis (in^4))
$S_x = 5.56 \cdot in^3$	Section Modulus (Stg. Axis (in^3))
$Z_x = 6.23 \cdot in^3$	Plastic Modulus (Strong Axis (in^3))
$Z_y = 1.72 \cdot in^3$	Plastic Modulus (Weak Axis (In^3))
$A_f = 0.85 \cdot in^2$	Area Flange (in^2)
$r_x = 2.47 \cdot in$	radius of gyration with respect to X-X Axis (in.)
$I_y = 2.19 \cdot in^4$	Moment of Inertia (Weak Axis (in^4))
$S_y = 1.11 \cdot in^3$	Section Modulus (Weak Axis (in^3))

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***** Steel & Concrete Material properties *****

$F_{ysteel} := 50ksi$ Yield Strength of Steel Material (ksi)

$F_{yrebar} := 60ksi$ Yield Strength of rebar (ksi)

$F_u := 65ksi$ Rupture Strength of Steel Material (ksi)

$f'_c := 4000psi$ Compressive Strength of Concrete)psi)

****** Anchor Bolt Properties *******

$F_{ubolts} := 125ksi$ High Strength Super HAS Rod Material, ASTM A193, Grade B7 Material (ksi)

$Dia_{bolt} := \frac{7}{8} in$ Dia. of anchor bolts (in.) $Area_{bolt} := \pi \, Dia_{bolt}^2 \cdot 0.25$ $Area_{bolt} = 0.6 \cdot in^2$

$\phi_{bolt} := 1.0$ Strength Reduction Factor For Bolts

$E_s := 29 \cdot 10^6 \cdot psi$ Modulus of Elasticity (in.) $N_t := 2$ 2 bolts on the tension face

$A_s := \frac{\pi \cdot Dia_{bolt}^2}{4} \cdot N_t$ Area of tension bolts $A_s = 1.203 \cdot in^2$

$E_c := 57000 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi$ $E_c = 3604996.533 \cdot psi$ $n := \frac{E_s}{E_c}$ $n = 8.04$

***** Weld Properties *****

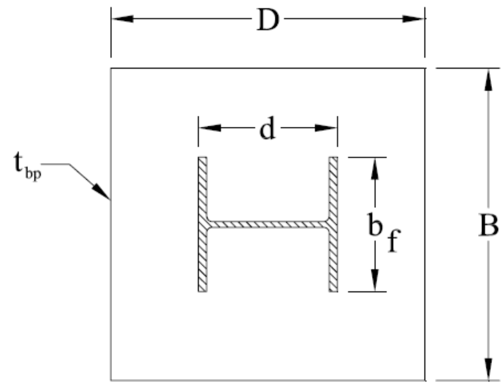
$F_{EXX} := 70ksi$ Weld Material Strength (ksi)

$t_{weld} := \frac{1}{4} in$ Weld Size (in.)

$\phi_{weld} := 1.0$ Reduction Factor for Weld

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**



BASEPLATE DETAILS

******** Baseplate Properties ********

$D := 12in$ Baseplate Length (in.)

$B := 12in$ Baseplate width (in.)

$t_p := 1.000in$ Approx. Baseplate thickness (in.)

$d = 5.9 \cdot in$ Depth of Post (in.)

$b_f = 3.94 \cdot in$ Width of Post (in.)

$Hole_{edgedist} := 1.5in$ Distance to plate edge to hole center (in.)

******* Hilti Anchor Properties *******

1.) As per page 163, 2006 Hilti Product Technical Guide,
HIT RE 500 Epoxy System, Average values for 4000 psi concrete:

$Tension := \begin{pmatrix} 22670 \\ 63495 \\ 64730 \end{pmatrix} lbf$ $\quad Shear := \begin{pmatrix} 16365 \\ 48455 \\ 79020 \end{pmatrix} lbf$

$Depth_{embed} := \begin{pmatrix} 4 \\ 7.875 \\ 10.5 \end{pmatrix} in$

Actual Embedment Depth (inches)
, see Hilti guide

$h_{ef} := 6.00in$

Use Hilti Hight Strength Super HAS, 7/8" Dia. Rod:

$HIT_{ultimatetensile} := linterp(Depth_{embed}, Tension, h_{ef})$

$HIT_{ultimateshear} := linterp(Depth_{embed}, Shear, h_{ef})$

Interpolate for Embedment Depth, h_{ef}

$HIT_{ultimatetensile} = 43.741 \cdot kips$ Ultimate Bond Strength
(see pg 112 Hilti 2002 Tech. Guide)

$HIT_{ultimateshear} = 32.928 \cdot kips$ Ulitmate shear strength of
anchor (see pg 112)

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$Temperature := 110\,°F$ Max Temperature for Temperature Reduction

Check Load Adjustment Factors for Anchor Spacings & Clearance:

From page 119, Hilti 2002 Technical Guide

$S_{act} := 9.0in$ Actual anchor spacing (inches)

$C_{act} := 24in$ edge distance (inches) from concrete edge to Centerline of bolts

$h_{nom} := 7.875in$ Standard embedment depth (inches), see page 110

$h_{ef} = 6 \cdot in$ Actual embedment depth (in.)

$S_{min} := 0.5 \cdot h_{ef}$ $S_{min} = 3 \cdot in$

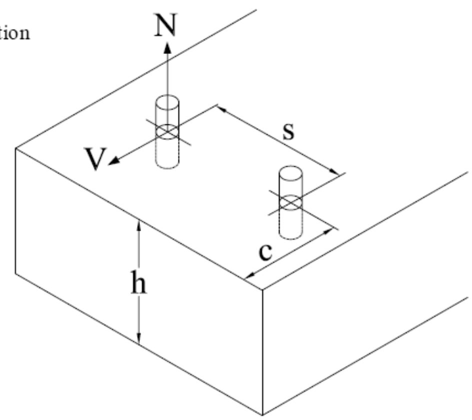
$S_{cr} := 1.5 \cdot h_{ef}$ $S_{cr} = 9 \cdot in$

$C_{min} := 0.5 \cdot h_{ef}$ $C_{min} = 3 \cdot in$

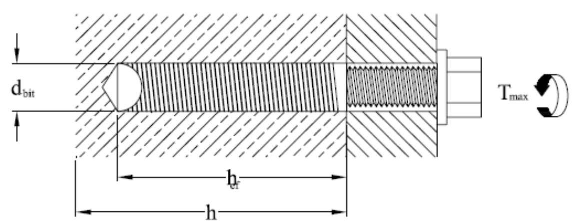
$C_{cr} := 1.5 \cdot h_{ef}$ $C_{cr} = 9 \cdot in$

$h := t_{deck}$ Thickness of slab, (in)

$h = 9 \cdot in$



ANCHOR DETAILS



ANCHOR GEOMETRY

Texas Transportation Institute

**** Calculate Hilti Reduction Factors for Spacing Tension & Shear ******

$$f_A := \begin{cases} f_A \leftarrow 0.3\cdot\left(\frac{S_{act}}{h_{ef}}\right) + 0.55 \ \text{ if } S_{cr} \geq S_{act} \geq S_{min} \\ f_A \leftarrow 1.0 \ \text{ if } S_{act} \geq S_{cr} \\ f_A \leftarrow 0 \ \text{ if } S_{act} < S_{min} \end{cases}$$

$f_A = 1$

***** Calculate Reduction Factors for Edge Distance Tension, "f_{RN}" *******

$$f_{RN} := \begin{cases} f_{RN} \leftarrow 0.3\cdot\left(\frac{C_{act}}{h_{ef}}\right) + 0.55 \ \text{ if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RN} \leftarrow 1.0 \ \text{ if } C_{act} \geq C_{cr} \\ f_{RN} \leftarrow 0 \ \text{ if } C_{act} < C_{min} \end{cases}$$

$f_{RN} = 1$

5.) Calculate Reduction Factors for Edge Distance Shear, "f_{RVperp}"

$$f_{RVperp} := \begin{cases} f_{RVperp} \leftarrow 0.54\cdot\left(\frac{C_{act}}{h_{ef}}\right) - 0.09 \ \text{ if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RVperp} \leftarrow 1.0 \ \text{ if } C_{act} \geq C_{cr} \\ f_{RVperp} \leftarrow 0 \ \text{ if } C_{act} < C_{min} \end{cases}$$

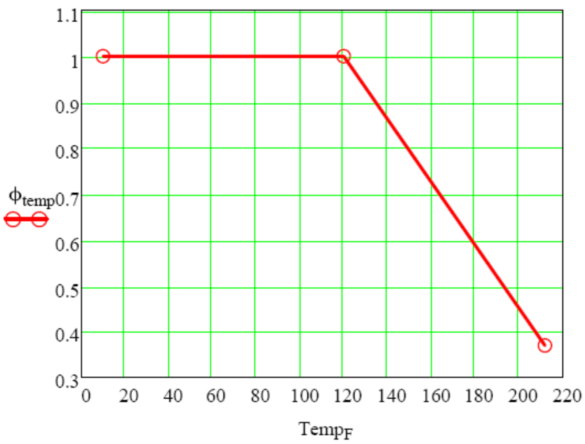
$f_{RVperp} = 1$

6.) Calculate total combined Reduction Factors for tension & shear:

$f_{RVperp} = 1$ $f_A = 1$ $f_{RN} = 1$

$\phi_{temp} := \begin{pmatrix} 1.0 \\ 1.0 \\ 0.37 \end{pmatrix}$ $Temp := \begin{pmatrix} 10 \\ 120 \\ 212 \end{pmatrix} °F$ $F := Temp$ $Temp = \begin{pmatrix} 260.93 \\ 322.04 \\ 373.15 \end{pmatrix} K$ $Temp = \begin{pmatrix} 260.93 \\ 322.04 \\ 373.15 \end{pmatrix} K$

$$Temp_F := \frac{\left[(Temp - 273.15K)\cdot\frac{9}{5}\right] + 32K}{K}$$ Temperature conversion



$\phi_{tempreduce} := \text{linterp}(Temp, \phi_{temp}, Temperature)$

$\phi_{tempreduce} = 1$

$\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN} \cdot \phi_{tempreduce})}$ $\phi_{shear} := \overrightarrow{(f_A \cdot f_{RVperp})}$

$\phi_{tension} = 1$ $\phi_{shear} = 1$

$\phi R_{tension} := \phi_{tension} \cdot HIT_{ultimatetensile}$ $\phi R_{shear} := \phi_{shear} \cdot HIT_{ultimateshear}$

$\phi R_{tension} = 43.74 \cdot kips$ $\phi R_{shear} = 32.93 \cdot kips$ Hilti Factored Anchor Strengths for $h_{ef} = 6.00 \cdot in$

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7. Calculate the Plastice Strength of the Post:

$F_y = 50 \cdot ksi$ Yield Strength of Steel

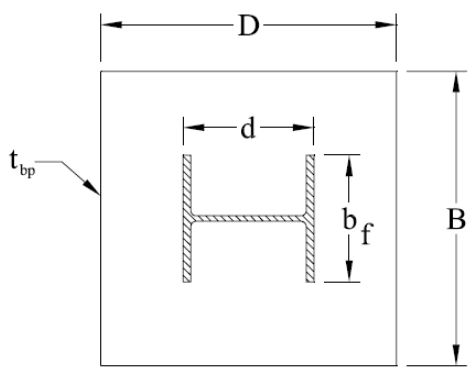
$Z_x = 6.23 \cdot in^3$ Plastic Section Modulus of Post

$M_{xplastic} := F_y \cdot Z_x$

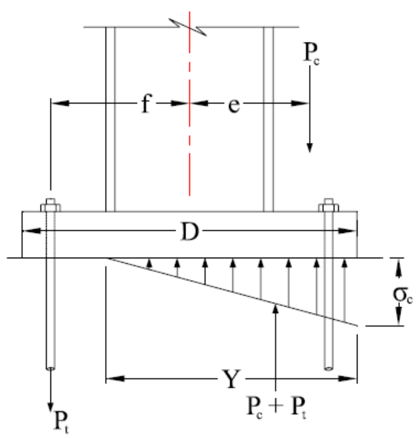
$M_{xplastic} = 25.96 \cdot kip \cdot ft$ Plastic Moment

$M_{load} = 27.12 \cdot kip \cdot ft$ Moment from Post Load

8.) Check Baseplate details & calculate anchor bolt forces:



BASEPLATE DETAILS



Given Basic Uplift Procedure as shown in Blodgett, "Design of Welded Structures" pages 3-3-8 through 10. and sketch w/ nomenclature showing Baseplate Geometry and distribution of force.

Find: Maximum Stress (σ_c), "Y", and force in the bolts (P_t) for applied force as shown.

This basic uplift procedure as shown in Blodget's "Design of Welded Structures" pages 3-3-8 through 10. It solves three equations for three unknowns for any combination of vertical & applied moment to the column. You have to combine the vertical load and moment to a single vertical load at some eccentricity "e". (Input Items in Yellow):

4 Bolts are used in he deign with 2 bolts located on the tension face

$P_c := .10 \cdot kips$ Vertical Load on Column (kips)

Select Design Moment from Above:

$M_1 := M_{xplastic}$ Applied Moment (k-ft.)

$e := \frac{M_1}{P_c}$ $e = 3115 \cdot in$ eccentricity (in.)

$D = 12 \cdot in$ BP Length (in.) $B = 12 \cdot in$ BP Width (in.) $f'_c = 4000 \cdot psi$

$d = 5.9 \cdot in$ Post Depth (in.) $D = 12 \cdot in$ BP Length (in.) $N_t = 2$ # Tension Bolts

$b_f = 0.33\,ft$ Post Flange Width (in.)

$f := \frac{d}{2} - Hole_{edgedist}$ Distance from Col. Centerline to tension bolts.

From static, there are Three Equations & Three Unknowns, P_t, "Y", & s_c:

Use Mathcad's Solve Block to find solutions. Solve Block requires "Initial guesses and uses these guesses to converge on solutions for the three unknowns, s_c, Y, P_t:

Initial Guesses for unknowns: $\sigma_c := 1000 \cdot psi$ $Y := .3 \cdot ft$ $P_t := 10 \cdot kip$

Given

$$\frac{1}{2} \cdot Y \cdot \sigma_c \cdot B - P_t - P_c = 0$$ **Equation 1**

$$P_t \cdot f + (P_c + P_t) \cdot \left(\frac{D}{2} - \frac{Y}{3}\right) - P_c \cdot e = 0$$ **Equation 2**

$$\sigma_c = \frac{P_t \cdot Y}{A_s \cdot n \cdot \left(\frac{D}{2} - Y + f\right)}$$ **Equation 3**

$$\begin{pmatrix} Y \\ \sigma_c \\ P_t \end{pmatrix} := Find(Y, \sigma_c, P_t)$$

$Y = 2.7545 \cdot in$

$\sigma_c = 2887 \cdot psi$ Compressive stress @ the Edge of the Baseplate on Compression side.

$P_t = 48 \cdot kips$ Tension Force in (N_t) Anchor Bolts

$P_{Bolt} := \frac{P_t}{N_t}$ $P_{Bolt} = 23.81 \cdot kips$ Tension per Bolt (kips)

... o.k. less than Factored Hilti Ultimate for $h_{ef} = 6 \cdot in$ $\phi R_{tension} = 43.74 \cdot kips$

9.) Check Baseplate bending/thickness using forces & stress above separately.

Calculate moment in baseplate on bearing side:

$Y = 2.75 \cdot in$ $\qquad d_{edge} := \frac{D}{2} - \frac{b_f}{2}$ $\qquad d_{edge} = 4.03 \cdot in$

$$M_{plate1} := \frac{\sigma_c \cdot Y}{2} \cdot \left[\left(d_{edge} + \frac{t_f}{2} \right) - \frac{Y}{3} \right]$$

$$M_{plate1} = 12.8 \cdot \frac{kip \cdot in}{in}$$

Calculate moment in baseplate on Tension Bolt Side:

$P_{Bolt} = 23.81 \cdot kips$

$Hole_{edgedist} = 1.5 \cdot in$

$d_{edge} = 4.03 \cdot in$ Distance from Baseplate Edge to Post Edge

$$Bolt_{dist} := d_{edge} - Hole_{edgedist} + \frac{t_f}{2}$$

$Bolt_{dist} = 2.64 \cdot in$ Distance from center of bolt to centerline of post flange

$M_{plate2} := \frac{P_{Bolt} \cdot Bolt_{dist}}{Bolt_{dist} \cdot 2}$ $\qquad M_{plate2} = 11.9 \cdot \frac{kip \cdot in}{in}$

$$M_{plate} := \begin{cases} M_{plate1} & \text{if } M_{plate1} > M_{plate2} \\ M_{plate2} & \text{otherwise} \end{cases}$$

Select worst case bending moment in plate bearing or anchor bolt tension

$M_{plate} = 12.8 \cdot \frac{kip \cdot in}{in}$ Design moment in the baseplate for thickness calculations

Substract 1/8" since procedure is little conservative

Therefore: $t_{prequired} := \sqrt{\frac{4 \cdot M_{plate}}{F_y}}$ $\qquad t_{prequired} = 1.01 \cdot in$ $\qquad t_{plate} := \left(t_{prequired} - 0.125 in\right)$

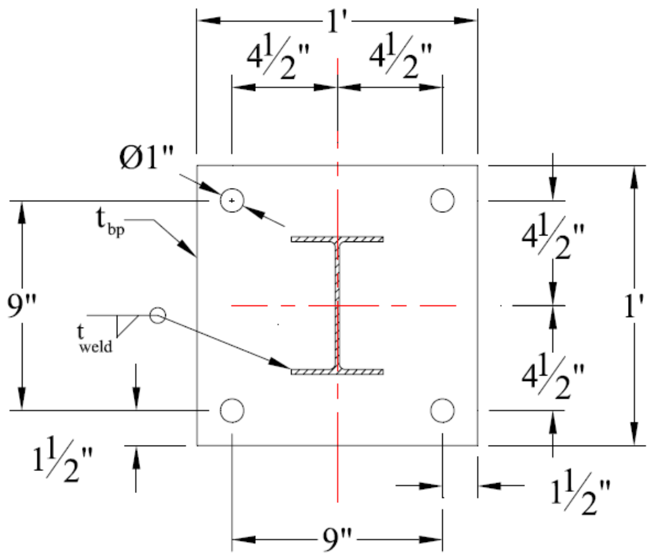
$t_{bp} := Round\left(t_{plate}, 0.125 in\right)$ $\qquad t_{bp} = 0.875 \cdot in$ Final Baseplate Design Thickness (in.)

$t_{bp} = 0.875 \cdot in$

$F_y = 50 \cdot ksi$

$t_{weld} = 0.25 \cdot in$

RECOMMENDED BASEPLATE DETAILS



W6x8.5 & 9
BASEPLATE DETAILS

Anchor Bolts: 7/8" Dia. A193 Threaded Rods 8 inches long, embedded 6 inches minimum

Anchorage System: Hilti RE 500 Anchoring System

W8x21 DESIGN

Texas Transportation Institute

Project #: 405160-00005

W8x21 Design

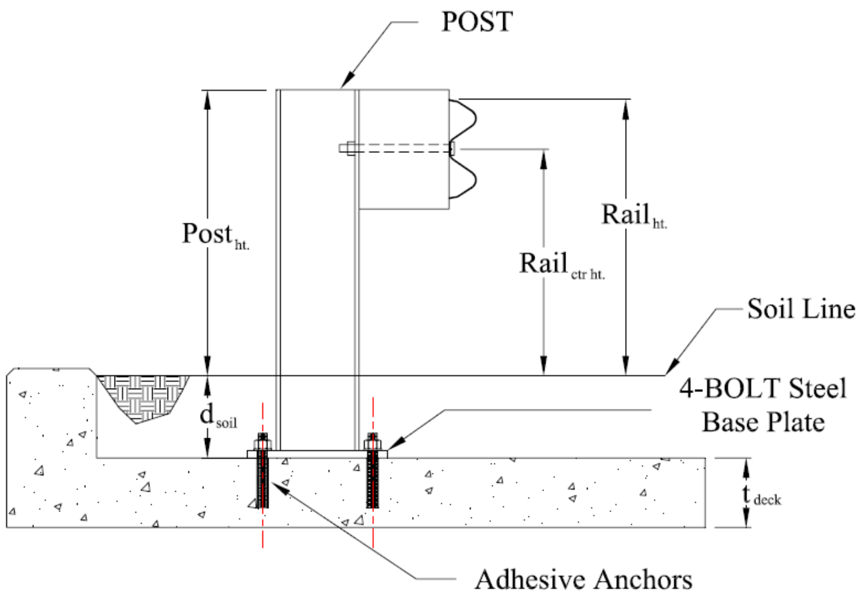
Hilti RE 500 Anchor System

7/8" Dia. Anchors Embed. 10" Max

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Given the following general latout of a box culvert guardrail post anchored to a concrete box culvert section using an epoxy adhesive anchoring system. Find the limiting ultimate strength of the post design considering the different variables used in the design.



GUARDRAIL ON BOX CULVERT TYPICAL CROSS-SECTION

depth of soil (in.)

$d_{soil} := 18in$

Thickness of Deck, Slab or Footing (in.)

$t_{deck} := 14in$

1.) Design Information:

****** Rail Geometry ******

$Rail_{ctrht} := 21in$ Center Height of Rail (in.)

$Rail_{ht} := Rail_{ctrht} + 6.125in$ Height to top of rail (in.)

$Post_{ht} := 27in$ Height of Post above grade (in.)

$Post_{load} := 20kips$ Load applied to Rail center (kips) $M_{load} := Post_{load} \cdot (Rail_{ctrht} + d_{soil})$

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

Define Mathcad units ORIGIN := 1

$kips \equiv kip$ $ksi \equiv \frac{kips}{in^2}$

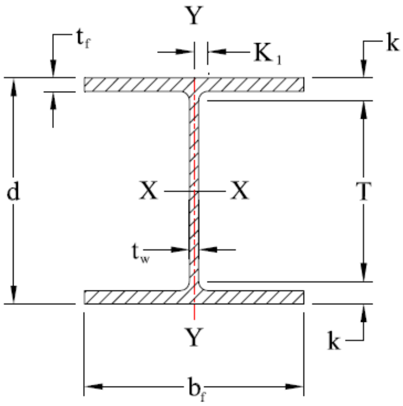
Steel Beam Yield Strength: $F_y := (50) \cdot ksi$
Beam Nominal Depth: NOMINAL_DEPTH := (8)
Beam weight per foot: WEIGHT_PER_FOOT := (21)

Beam Data - Fri Sep 15 09:13:04 2006

******* Post Information *******

Post Data for: Nominal_depth = 8 in

$Wt\_per\_foot = 21\,ft^{-1}\,lb$ $F_y = 50\,ksi$



POST DETAILS

$r_x = 3.49\,in$ radius of gyration with respect to X-X Axis (in.)

$I_y = 9.77\,in^4$ Moment of Inertia (Weak Axis (in^4))

$S_y = 3.71\,in^3$ Section Modulus (Weak Axis (in^3))

$Wt\_per\_foot = 21\,ft^{-1} \cdot lb$ Wt. per foot of length (lb/ft)

$d_n = 8$ Nominal Depth of member

$Area = 6.16\,in^2$ Area (in^2)

$d = 8.28\,in$ Actual Depth of Member (in.)

$t_w = 0.25\,in$ Thickness of Web (in.)

$b_f = 5.27\,in$ Width of Flange (in.)

$t_f = 0.4\,in$ Thickness of Flange (in.)

$k = 0.81\,in$ Distance to toe of fillet (in.)

$I_x = 75.3\,in^4$ Moment of Inertia (Stg. Axis (in^4))

$S_x = 18.2\,in^3$ Section Modulus (Stg. Axis (in^3))

$Z_x = 20.4\,in^3$ Plastic Modulus (Strong Axis (in^3))

$Z_y = 5.69\,in^3$ Plastic Modulus (Weak Axis (In^3))

$A_f = 2.11\,in^2$ Area Flange (in^2)

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Project #: 405160-00005

Subject: Box Culvert Guardrail - Task AE Calculations

Sponsor: Washington DOT Pooled Fund

***** Steel & Concrete Material properties *****

$F_{ysteel} := 50ksi$ Yield Strength of Steel Material (ksi)

$F_{yrebar} := 60ksi$ Yield Strength of rebar (ksi)

$F_u := 65ksi$ Rupture Strength of Steel Material (ksi)

$f'_c := 4000psi$ Compressive Strength of Concrete)psi)

****** Anchor Bolt Properties *******

$F_{ubolts} := 125ksi$ High Strength Super HAS Rod Material, ASTM A193, Grade B7 Material (ksi)

$Dia_{bolt} := \frac{7}{8} in$ Dia. of anchor bolts (in.) $Area_{bolt} := \pi \, Dia_{bolt}^2 \cdot 0.25$ $Area_{bolt} = 0.6 \, in^2$

$\phi_{bolt} := 1.0$ Strength Reduction Factor For Bolts

$E_s := 29 \cdot 10^6 \cdot psi$ Modulus of Elasticity (in.) $N_t := 2$ 2 bolts on the tension face

$A_s := \frac{\pi \cdot Dia_{bolt}^2}{4} \cdot N_t$ Area of tension bolts $A_s = 1.203 \, in^2$

$E_c := 57000 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi$ $E_c = 3604996.533 \, psi$ $n := \frac{E_s}{E_c}$ $n = 8.04$

***** Weld Properties *****

$F_{EXX} := 70ksi$ Weld Material Strength (ksi)

$t_{weld} := \frac{1}{4} in$ Weld Size (in.)

$\phi_{weld} := 1.0$ Reduction Factor for Weld

Texas Transportation Institute

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Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

****** **Baseplate Properties** ******

$D := 14in$ Baseplate Length (in.)

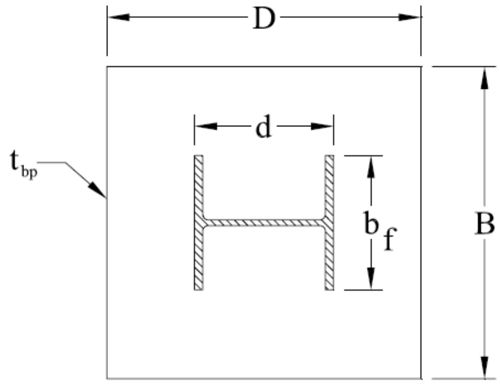
$B := 14in$ Baseplate width (in.)

$t_p := 1.000in$ Baseplate thickness (in.)

$d = 8.28\ in$ Depth of Post (in.)

$b_f = 5.27\ in$ Width of Post (in.)

$Hole_{edgedist} := 1.5in$ Distance to plate edge to hole center (in.)



BASEPLATE DETAILS

***** **Hilti Anchor Properties** *****

1.) As per page 112, 2002 Hilti Product Technical Guide,
HIT RE 500 Epoxy System, Average values for 4000 psi concrete:

$$Tension := \begin{pmatrix} 22670 \\ 63495 \\ 64730 \end{pmatrix} lbf \qquad Shear := \begin{pmatrix} 16365 \\ 48455 \\ 79020 \end{pmatrix} lbf$$

$$Depth_{embed} := \begin{pmatrix} 4 \\ 7.875 \\ 10.5 \end{pmatrix} in$$

Actual Embedment Depth (inches)
, see Hilti guide

$h_{ef} := 10.5000in$

Use Hilti Hight Strength Super HAS, 7/8" Dia. Rod:

$$HIT_{ultimatetensile} := linterp(Depth_{embed}, Tension, h_{ef})$$

$$HIT_{ultimateshear} := linterp(Depth_{embed}, Shear, h_{ef})$$

Interpolate for Embedment Depth, h_{ef}

$HIT_{ultimatetensile} = 64.73\ kips$ Ultimate Bond Strength (see pg 112 Hilti 2002 Tech. Guide)

$HIT_{ultimateshear} = 79.02\ kips$ Ulitmate shear strength of anchor (see pg 112)

Temperature := 110 °F   Max Temperature for Temperature Reduction

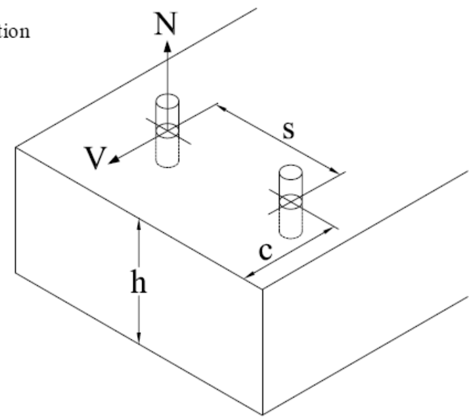
Check Load Adjustment Factors for Anchor Spacings & Clearance:

From page 119, Hilti 2002 Technical Guide

$S_{act} := 11.0in$ Actual anchor spacing (inches)

$C_{act} := 12in$ edge distance (inches) from concrete edge to Centerline of bolts

$h_{nom} := 7.875in$ Standard embedment depth (inches), see page 110



ANCHOR DETAILS

$S_{min} := 0.5 \cdot h_{ef}$ $S_{min} = 5.25$ in

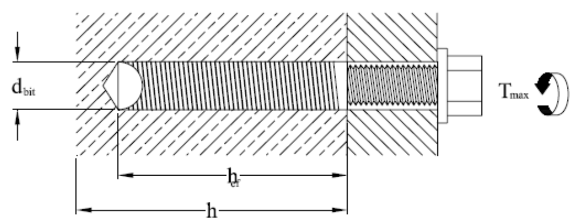
$S_{cr} := 1.5 \cdot h_{ef}$ $S_{cr} = 15.75$ in

$C_{min} := 0.5 \cdot h_{ef}$ $C_{min} = 5.25$ in

$C_{cr} := 1.5 \cdot h_{ef}$ $C_{cr} = 15.75$ in

$h := t_{deck}$ Thickness of slab, (in)

$h = 14$ in



ANCHOR GEOMETRY

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

$S_{act} = 11\ in$

$h_{ef} = 10.5\ in$

$S_{cr} = 15.75\ in$

**** Calculate Hilti Reduction Factors Spacing Tension & Shear ******

$$f_A := \begin{cases} f_A \leftarrow 0.3 \cdot \left(\frac{S_{act}}{h_{ef}}\right) + 0.55 & \text{if } S_{cr} \geq S_{act} \geq S_{min} \\ f_A \leftarrow 1.0 & \text{if } S_{act} \geq S_{cr} \\ f_A \leftarrow 0 & \text{if } S_{act} < S_{min} \end{cases}$$

$f_A = 0.864$

***** Calculate Reduction Factors for Edge Distance Tension, "f_{RN}" *******

$$f_{RN} := \begin{cases} f_{RN} \leftarrow 0.3 \cdot \left(\frac{C_{act}}{h_{ef}}\right) + 0.55 & \text{if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RN} \leftarrow 1.0 & \text{if } C_{act} \geq C_{cr} \\ f_{RN} \leftarrow 0 & \text{if } C_{act} < C_{min} \end{cases}$$

$f_{RN} = 0.89$

5.) Calculate Reduction Factors for Edge Distance Shear, "f_{RVperp}"

$$f_{RVperp} := \begin{cases} f_{RVperp} \leftarrow 0.7 \cdot \left(\frac{C_{act}}{h_{ef}}\right) - 0.05 & \text{if } C_{cr} \geq C_{act} \geq C_{min} \\ f_{RVperp} \leftarrow 1.0 & \text{if } C_{act} \geq C_{cr} \\ f_{RVperp} \leftarrow 0 & \text{if } C_{act} < C_{min} \end{cases}$$

$f_{RVperp} = 0.75$

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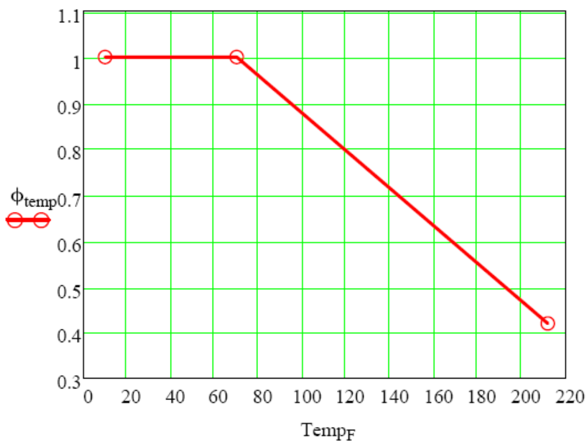
Sponsor: **Washington DOT Pooled Fund**

6.) Calculate total combined Reduction Factors for tension & shear:

$f_{RVperp} = 0.75$ $f_A = 0.86$ $f_{RN} = 0.89$

$\phi_{temp} := \begin{pmatrix} 1.0 \\ 1.0 \\ 0.42 \end{pmatrix}$ $Temp := \begin{pmatrix} 10 \\ 70 \\ 212 \end{pmatrix} °F$ $F := Temp$ $Temp = \begin{pmatrix} 260.93 \\ 294.26 \\ 373.15 \end{pmatrix} K$ $Temp = \begin{pmatrix} 260.93 \\ 294.26 \\ 373.15 \end{pmatrix} K$

$$Temp_F := \frac{\left[(Temp - 273.15K)\cdot\frac{9}{5}\right] + 32K}{K}$$ Temperature conversion



$\phi_{tempreduce} := \text{linterp}(Temp, \phi_{temp}, Temperature)$

$\phi_{tempreduce} = 0.84$

$\phi_{tension} := \overrightarrow{(f_A \cdot f_{RN} \cdot \phi_{tempreduce})}$ $\phi_{shear} := \overrightarrow{(f_A \cdot f_{RVperp})}$

$\phi_{tension} = 0.65$ $\phi_{shear} = 0.65$

$\phi R_{tension} := \phi_{tension} \cdot HIT_{ultimatetensile}$ $\phi R_{shear} := \phi_{shear} \cdot HIT_{ultimateshear}$

$\phi R_{tension} = 41.79 \text{ kips}$ $\phi R_{shear} = 51.22 \text{ kips}$ Hilti Factored Anchor Strengths for $h_{ef} = 10.50 \text{ in}$

Texas Transportation Institute

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Subject: **Box Culvert Guardrail - Task AE Calculations**

Sponsor: **Washington DOT Pooled Fund**

7. Calculate the Plastice Strength of the Post:

$F_y = 50\,\text{ksi}$ Yield Strength of Steel

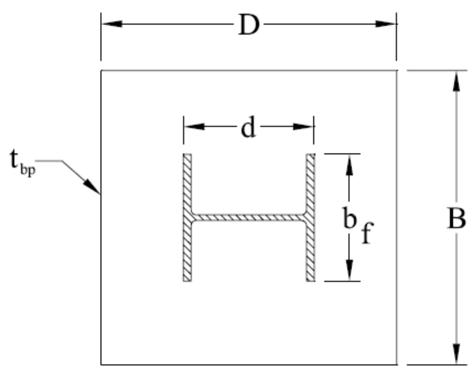
$Z_x = 20.4\,\text{in}^3$ Plastic Section Modulus of Post

$M_{xplastic} := F_y \cdot Z_x$

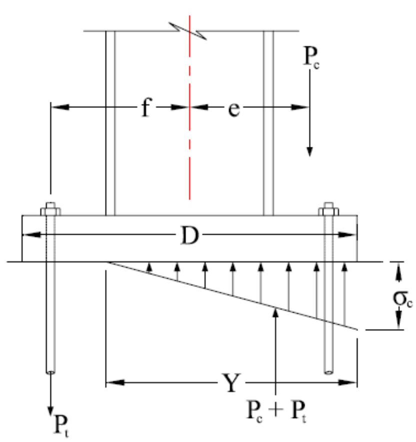
$M_{xplastic} = 85\,\text{kip}\cdot\text{ft}$ Plastic Moment

$M_{load} = 65\,\text{kip}\cdot\text{ft}$ Moment from Post Load

8.) Check Baseplate details & calculate anchor bolt forces:



BASEPLATE DETAILS



Given Basic Uplift Procedure as shown in Blodgett, "Design of Welded Structures" pages 3-3-8 through 10. and sketch w/ nomenclature showing Baseplate Geometry and distribution of force.

Find: Maximum Stress (σ_c), "Y", and force in the bolts (P_t) for applied force as shown.

This basic uplift procedure as shown in Blodget's "Design of Welded Structures" pages 3-3-8 through 10. It solves three equations for three unknowns for any combination of vertical & applied moment to the column. You have to combine the vertical load and moment to a single vertical load at some eccentricity "e". (Input Items in Yellow):

4 Bolts are used in he deign with 2 bolts located on the tension face

$P_c := .10\cdot\text{kips}$ Vertical Load on Column (kips)

Select Design Moment from Above:

$M_1 := M_{load}$ Applied Moment (k-ft.)

$e := \dfrac{M_1}{P_c}$

$e = 7800\,\text{in}$ eccentricity (in.)

$D = 14\,in$ BP Length (in.) $B = 14\,in$ BP Width (in.) $f'_c = 4000\,psi$

$d = 8.28\,in$ Post Depth (in.) $D = 14\,in$ BP Length (in.) $N_t = 2$ # Tension Bolts

$b_f = 5.27\,in$ Post Flange Width (in.)

$f := \frac{d}{2} - Hole_{edgedist}$ Distance from Col. Centerline to tension bolts.

From static, there are Three Equations & Three Unknowns, P_t, "Y", & s_c:

Use Mathcad's Solve Block to find solutions. Solve Block requires "Initial guesses and uses these guesses to converge on solutions for the three unknowns, s_c, Y, P_t:

Initial Guesses for unknowns: $\sigma_c := 1000 \cdot psi$ $Y := .3 \cdot ft$ $P_t := 10 \cdot kip$

Given

$$\frac{1}{2} \cdot Y \cdot \sigma_c \cdot B - P_t - P_c = 0$$ **Equation 1**

$$P_t \cdot f + (P_c + P_t) \cdot \left(\frac{D}{2} - \frac{Y}{3}\right) - P_c \cdot e = 0$$ **Equation 2**

$$\sigma_c = \frac{P_t \cdot Y}{A_s \cdot n \cdot \left(\frac{D}{2} - Y + f\right)}$$ **Equation 3**

$$\begin{pmatrix} Y \\ \sigma_c \\ P_t \end{pmatrix} := Find(Y, \sigma_c, P_t)$$

$Y = 3.0253\,in$

$\sigma_c = 4269\,psi$ Compressive stress @ the Edge of the Baseplate on Compression side.

$P_t = 90\,kips$ Tension Force in (N_t) Anchor Bolts

$P_{Bolt} := \frac{P_t}{N_t}$ $P_{Bolt} = 45.15\,kips$ Tension per Bolt (kips)

... o.k. close to Factored Hilti Ultimate for $h_{ef} = 10.5\,in$ $\phi R_{tension} = 41.79\,kips$

Texas Transportation Institute

Project #: **405160-00005**

Subject: **Box Culvert Guardrail - Task AE Calculations**

9.) Check Baseplate bending/thickness using forces & stress above separately.

Calculate moment in baseplate on bearing side:

$Y = 3.03\,in \qquad d_{edge} := \frac{D}{2} - \frac{b_f}{2} \qquad d_{edge} = 4.37\,in$

$$M_{plate1} := \frac{\sigma_c \cdot Y}{2} \cdot \left[\left(d_{edge} + \frac{t_f}{2} \right) - \frac{Y}{3} \right]$$

$$M_{plate1} = 22.96\,\frac{kip \cdot in}{in}$$

Calculate moment in baseplate on Tension Bolt Side:

$P_{Bolt} = 45.15\,kips$

$Hole_{edgedist} = 1.5\,in$

$d_{edge} = 4.37\,in$ Distance from Baseplate Edge to Post Edge

$$Bolt_{dist} := d_{edge} - Hole_{edgedist} + \frac{t_f}{2}$$

$Bolt_{dist} = 3.07\,in$ Distance from center of bolt to centerline of post flange

$$M_{plate2} := \frac{P_{Bolt} \cdot Bolt_{dist}}{Bolt_{dist} \cdot 2} \qquad M_{plate2} = 22.57\,\frac{kip \cdot in}{in}$$

$$M_{plate} := \begin{cases} M_{plate1} & \text{if } M_{plate1} > M_{plate2} \\ M_{plate2} & \text{otherwise} \end{cases}$$

Select worst case bending moment in plate bearing or anchor bolt tension

$M_{plate} = 22.96\,\frac{kip \cdot in}{in}$ Design moment in the baseplate for thickness calculations

Substract 1/8" since procedure is little conservative

Therefore:

$$t_{prequired} := \sqrt{\frac{4 \cdot M_{plate}}{F_y}} \qquad t_{prequired} = 1.36\,in \qquad t_{plate} := \left(t_{prequired} - 0.125\,in\right)$$

$$t_{bp} := Round\left(t_{plate}, 0.125\,in\right) \qquad t_{bp} = 1.25\,in$$

Final Baseplate Design Thickness (in.)

Project #: **405160-00005**

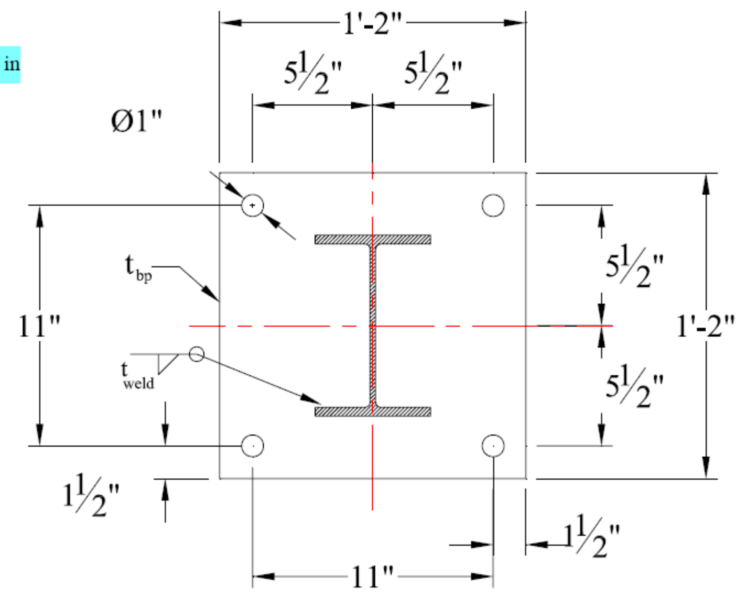
Subject: **Box Culvert Guardrail - Task AE Calculations**

RCOMMENDED BASEPLATE DETAILS

$t_{bp} = 1.25\ in$

$F_y = 50\ ksi$

$t_{weld} = 0.25\ in$



W8x21
BASEPLATE DETAILS

Anchor Bolts: 7/8" Dia. A193 Threaded Rods, 14 inches Long, embedded 10.0 inches minimum

Anchorage System: Hilti RE 500 Anchoring System

APPENDIX E. PHOTOGRAPHS OF TESTING

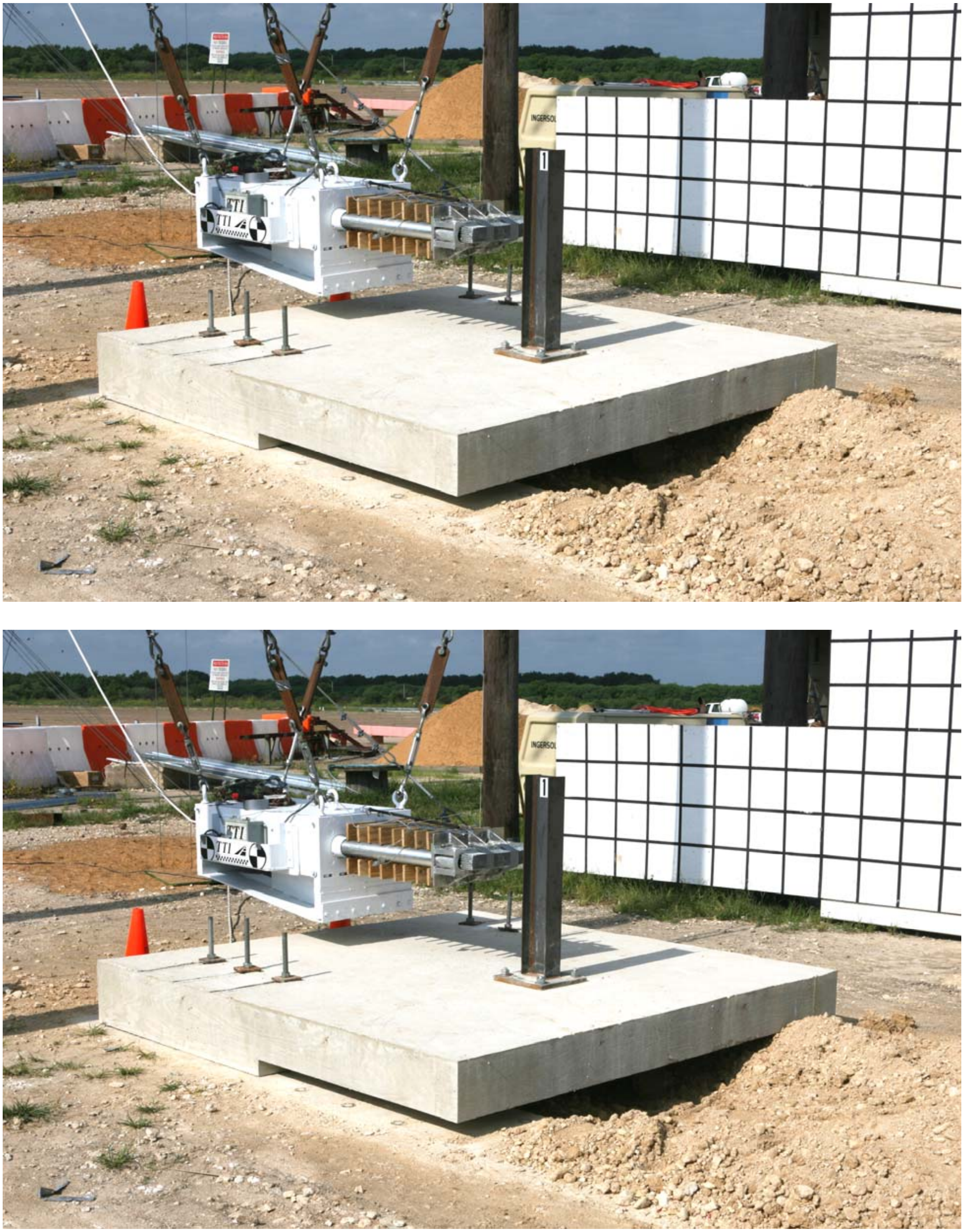


Figure E1. W6x9 post and deck sample before test P1.

Figure E2. W6x9 post after test P1.

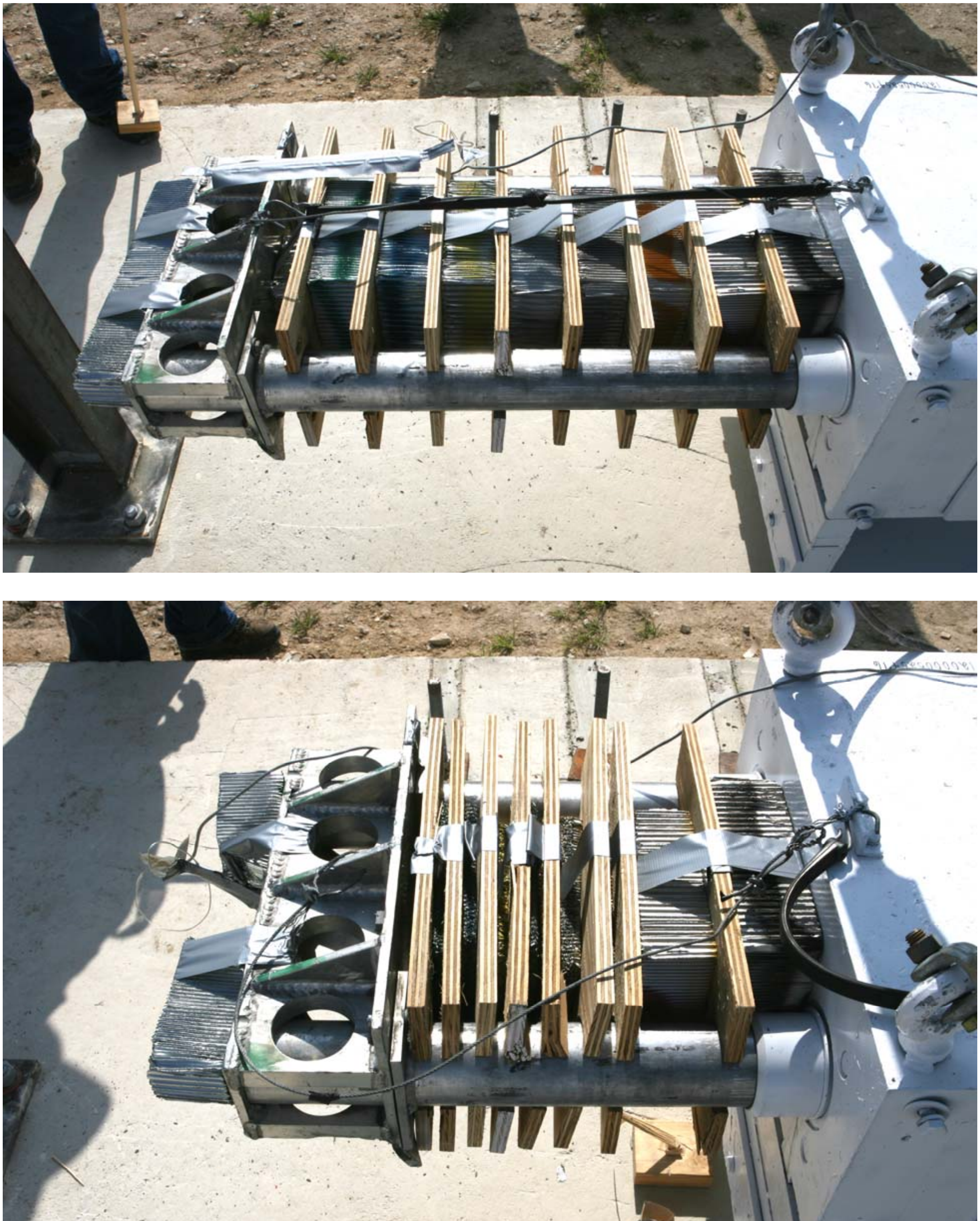
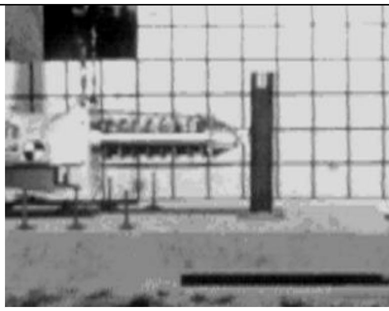
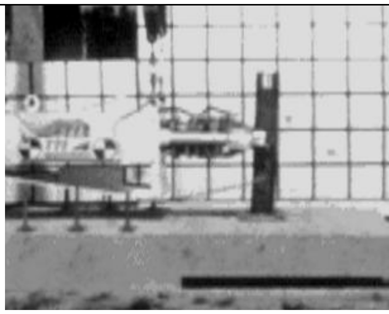


Figure E3. Pendulum bogie nose before and after test P1.

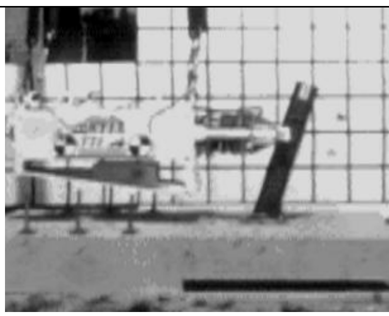
Table E1. Summary of results for pendulum test 405160-5-P1.



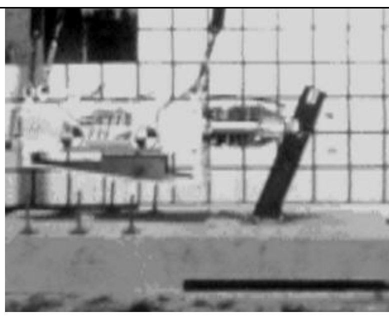
0.000 s



0.049 s



0.098 s



0.147 s

General Information
Test Agency .... Texas Transportation Institute
Test No. 405160-5-P1
Date 07-16-2007

Test Article
Type .... Guardrail Post
Name .... Guardrail Post on Box Culvert
Installation Height (m) .... 37 inches
Material of Key Element W6x9

Soil Type .... Simulated Box Culvert Deck

Test Vehicle
Type .... Bogie
Designation .... Pendulum
Test Inertia Mass .... 839 kg

Impact Conditions
Speed .... 35.0 km/h
Angle .... 90 deg

Occupant Risk Values
Impact Velocity
Longitudinal direction .... 8.9 m/s
Ridedown Accelerations
Longitudinal direction .... -3.9 g's

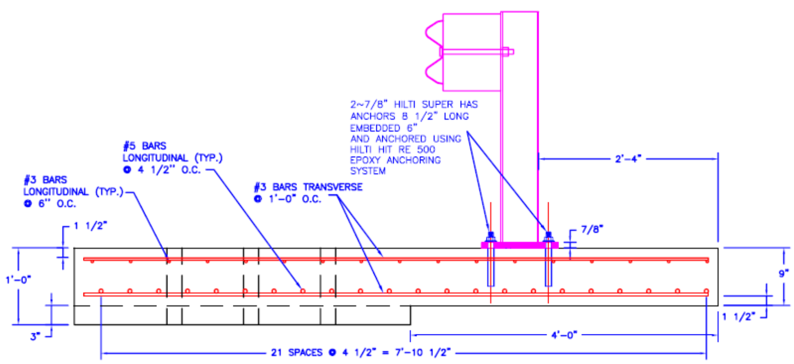


Figure D4. W6x9 post and deck sample before test P2.

Figure E5. W6x9 post after test P2.

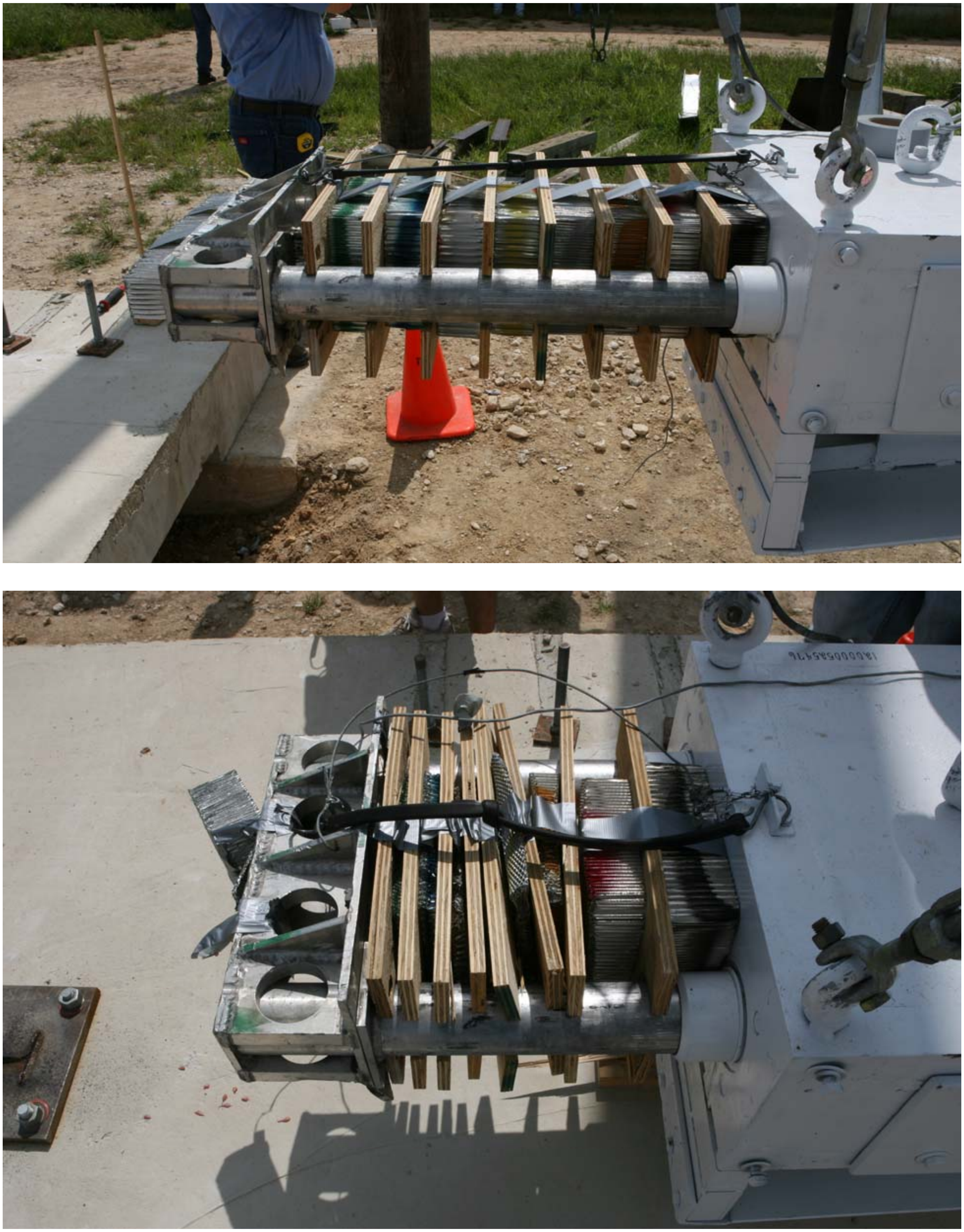
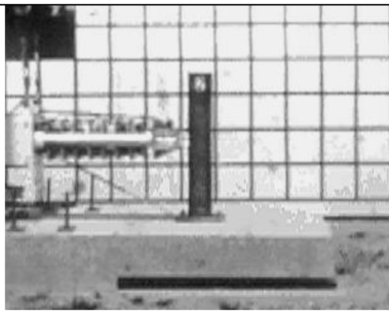
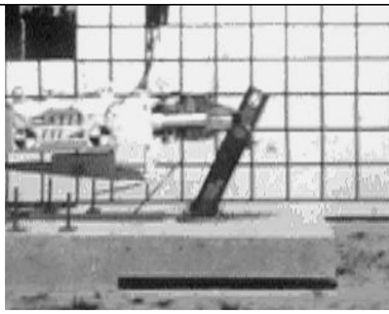


Figure E6. Pendulum bogie nose before and after test P2.

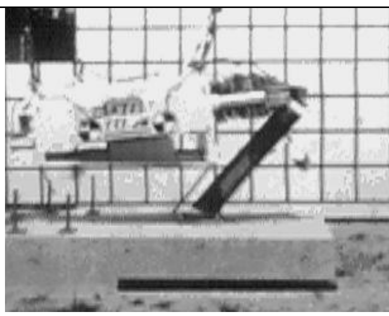
Table E2. Summary of results for pendulum test 405160-5-P2.



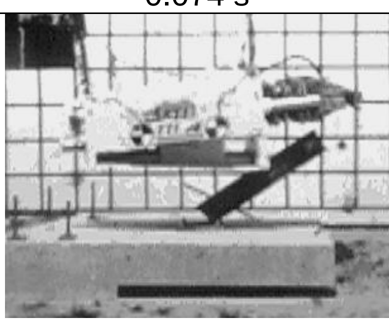
0.000 s



0.037 s



0.074 s



0.123 s

General Information
Test Agency............................Texas Transportation Institute
Test No. 405160-5-P2
Date 07-16-2007

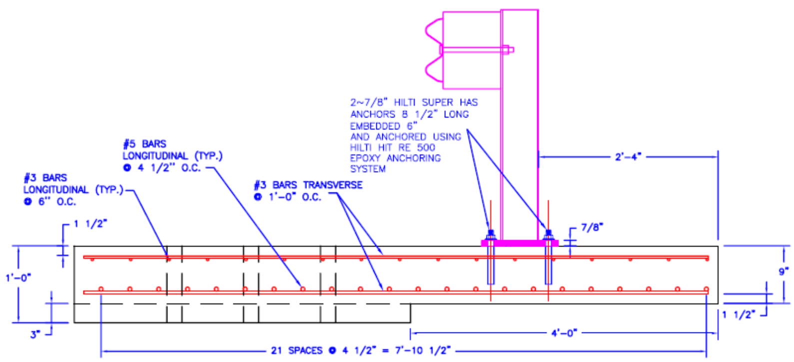
Test Article
Type.. Guardrail Post
Name ....Guardrail Post on Box Culvert
Installation Height (m)...37 inches
Material of Key Element W6x9

Soil Type....................................Simulated Box Culvert Deck

Test Vehicle
Type... Bogie
Designation.. Pendulum
Test Inertia Mass ....839 kg

Impact Conditions
Speed ....35.0 km/h
Angle .... 90 deg

Occupant Risk Values
Impact Velocity
Longitudinal direction..6.3 m/s
Ridedown Accelerations
Longitudinal direction..-0.6 g's



APPENDIX F. ACCELERATION AND FORCE TRACES

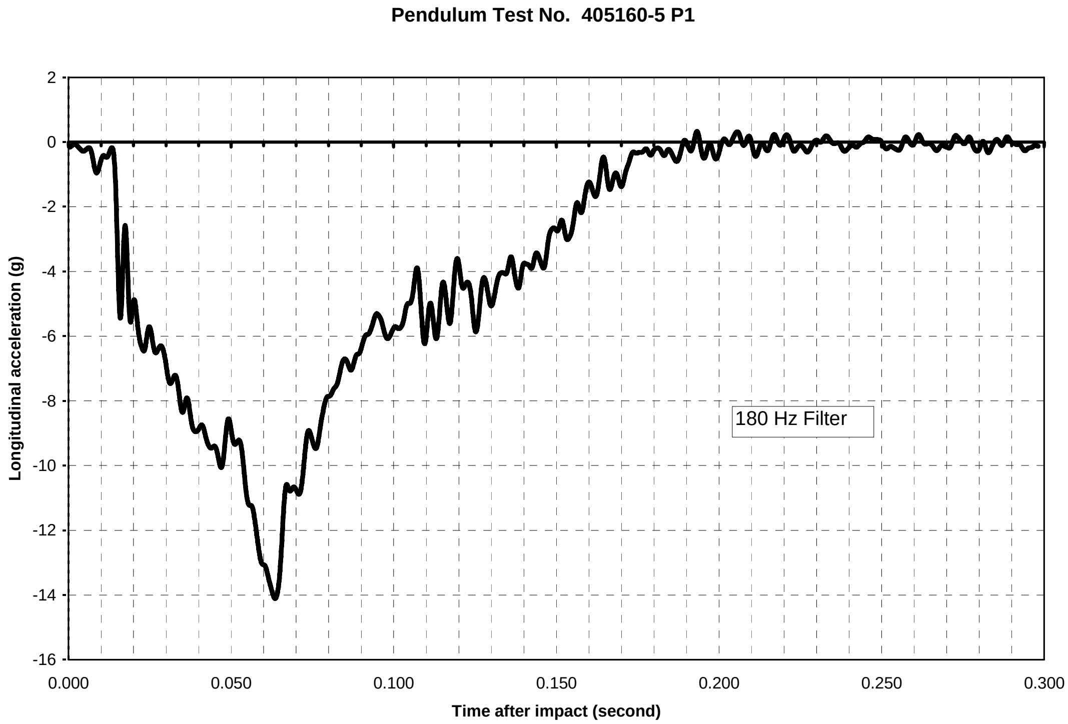


Figure F1. Accelerometer trace for test 405160-5 P1.

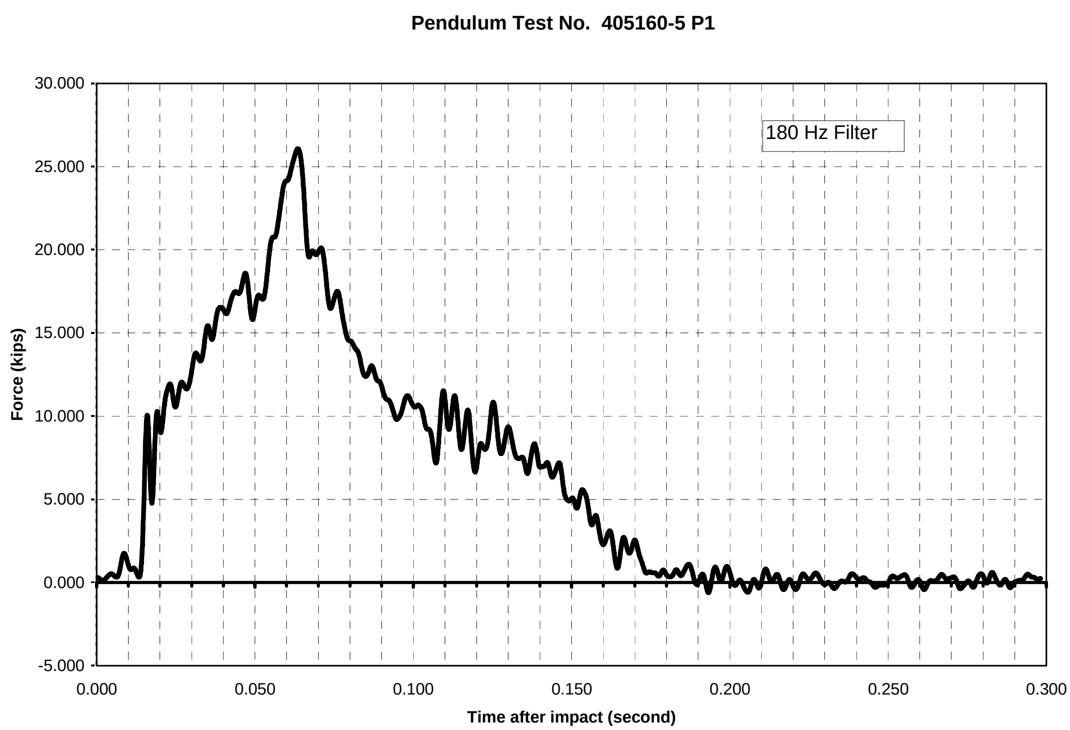


Figure F2. Force trace for test 4005160-5 P1.

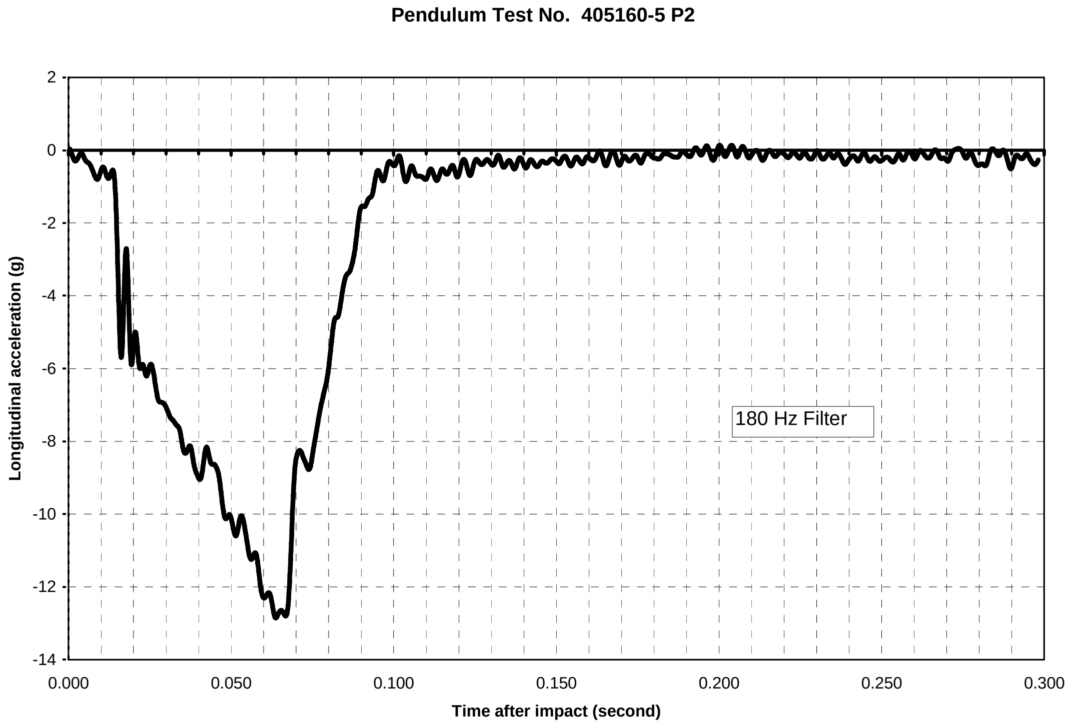


Figure F3. Accelerometer trace for test 405160-5 P2.

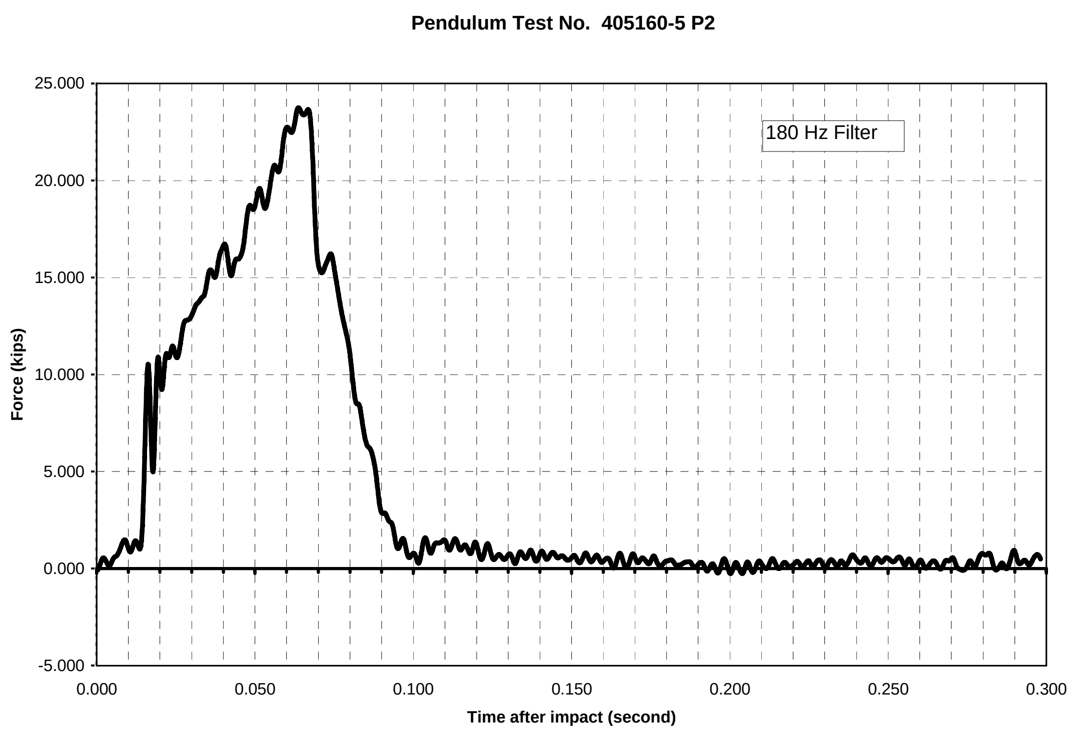


Figure F4. Force trace for test 4005160-5 P2.

APPENDIX G. VIDEOS

TEST 405160-5-P1 VIDEO

405160-P1 -- real time

405160-P1 -- high-speed

TEST 405160-5-P2 VIDEO

405160-P2 -- real time

405160-P2 -- high-speed