Falsework Collapse at US Highway 101 (Willits Bypass) Floodway Viaduct (Br. No. 10-0165) Contract 01-262004 01-Men-101-R69.4/R78.9

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Prepared by

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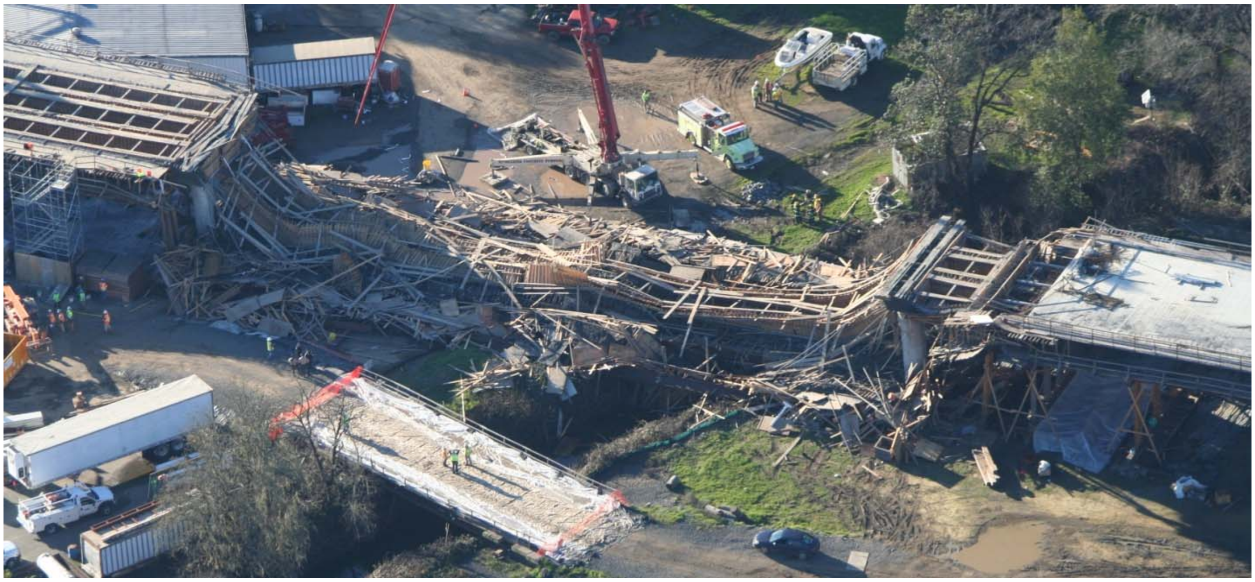

This report is intended to document the findings of Caltrans' investigation of the January 22, 2015 Floodway Viaduct falsework collapse near Willits, CA. It is intended for the use of Caltrans as part of its continuous improvement process. This investigation and report is not intended to assign fault in the legal context.

Disclaimer

This report represents the findings of the California Department of Transportation / Division of Engineering Services / Structure Construction investigation into the collapse of the falsework at the Floodway Viaduct (Br. No. 10-0165) Frame 1 that occurred January 22, 2015. As falsework is a complex temporary structure comprised of varying materials the analysis does not easily lend itself to determining one specific cause of collapse but this report attempts to provide a most probable cause. As many entities have reviewed the collapse itself and due to pending litigation from such events not all information and learned opinions are available for consideration in this report. As with any investigation, future information may cause findings within this report to be refuted or supported. This report is intended for the use of Caltrans as part of its continuous improvement process and no other usage is warranted. This report is not to be used without the express written consent of the California Department of Transportation.

I. Background

1. Introduction

This report is intended to document Structure Construction's investigation of the Floodway Viaduct falsework[1] collapse that occurred during the placement of soffit and stem concrete. This report includes the evaluation of the most probable collapse mechanism of the falsework, the response to the collapse and the evaluation of the effectiveness of current procedures with respect to this collapse. This report is generally laid out chronologically beginning with the falsework systems approval and erection, followed by investigative efforts and identification of contributing collapse mechanisms. Based on this investigation, recommendations regarding future actions needed to address falsework safety and operations are presented.

The California Department of Transportation (Caltrans) over the past 40 years has provided specifications and best industry practice for the safe construction of falsework through contract specifications and the *Falsework Manual*[2]. When falsework fails to perform in the prescribed manner for which it was designed, Caltrans investigates and attempts to determine the most probable cause for the failure or collapse and considers if changes to the specifications or manual are necessary to prevent similar falsework collapses in the future.

2. Project Information

The construction contract (01-262004), included constructing 15 bridges as part of the realignment of US Highway 101 in Mendocino County in and near Willits. This contract was awarded by the State of California to the contractor DeSilva Gates – Flatiron West, a Joint Venture. Flatiron West being primarily responsible for construction of the bridges.

The Floodway Viaduct (Br. No. 10-0165) is an eight frame thirty three span cast- in-place pre-stressed box girder bridge approximately 13 m (42.67 ft.) wide by 1829 m (6001 ft.) long. The substructure consists of two column bents on pile caps over driven piles. The super elevation varies from 2% to 5% as the bridge goes from a northerly direction at Abutment 1 to a westerly direction at Abutment 34 through a compound curve that has a variable radius from 700 m to 1,200 m (2,297 ft. to 3,937 ft.). The Project Title Sheet, Floodway Viaduct General Plan and Structure Plan No. 1 are included as Attachment 2.

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[1] The term *falsework* refers to the temporary supporting system between the ground and the bridge soffit (bottom surface) that provides a stable platform for cast-in-place concrete bridges until they are capable of supporting themselves.

[2] *Falsework Manual* issued by Structure Construction; State of California, Department of Transportation, Division of Engineering Services and is available at:
http://www.dot.ca.gov/hq/esc/construction/manuals/OSCCompleteManuals/FalseworkManual.pdf

3. Structure Construction's Response

On Thursday, January 22, 2015, around 2:45 p.m. it was reported to the Structure Construction[3] (SC) Headquarters office that a portion of the Frame 1 falsework for the Floodway Viaduct (Br. No. 10-0165) had collapsed during stem and soffit concrete placement. Structure Construction is under the Division of Engineering Services (DES).

The SC HQ Statewide Falsework Engineer, Ajay Sehgal, was given an assignment to report to the project site and assist with the investigation and develop a report documenting the collapse, possible causes, ultimately determining the most probable cause and determine if future specification, policy, or procedural changes are required to prevent a similar collapse in the future. Mr. Sehgal reported at the project site on Friday morning, January 23, 2015. The Contractor was to submit a demolition plan for removing hanging superstructure concrete and the debris created from collapsed falsework that same evening for Caltrans' review and acceptance. The Caltrans Structure Representative approved the Contractor's debris and demolition plan, after which the contractor commenced removal operations of the fallen concrete, reinforcing steel, form work, and falsework on January 24, 2015, after stabilizing the remaining falsework. Mr. Sehgal and project personnel spent over a week conducting the field investigation. The on-site investigation consisted of mapping the falsework elements position and observable condition. Where possible member damage was identified and categorized as being either due to debris from the collapse, exceeded stresses, or unknown.

To assist with mapping and recording the locations of the fallen and failed members, daily aerial photographs were taken of the site and field engineers from the project assisted in taking photos and mapping during removal of the collapsed falsework. Photogrammetry[4] also provided aerial photographs and technical support with the evaluation of photographs taken.

A team of SC Engineers was assigned to review the original falsework design for compliance as an initial check of SC procedures. After the field investigative effort, a separate team began analyzing the as-built falsework condition for compliance and potential collapse mechanisms. Several individuals within these teams were assigned additional analysis to determine probable forces needed to initiate the potential collapse mechanisms.

Additionally, Geotechnical Services performed a geotechnical review to address the potential of settlement at the falsework supports. Material Engineering and Testing Services (METS) performed load testing of the cable bracing and sand jack elements. These are discussed later in the report.

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[3] California Department of Transportation (Caltrans) / Division of Engineering Services / Structure Construction.
[4] Division of Engineering Services / Structure Design / Office of Photogrammetry and Preliminary Investigations

II. Floodway Viaduct Falsework Background

1. Approved Falsework System

The approved falsework design for this structure was composed mostly of the typical falsework systems used in California. It consisted of wood post, steel cap/sill, and steel stringer arrangement with most of the bents bearing on timber pad foundations, except for the falsework bents in the vicinity of the creeks traversing under the bridge and those supporting the diaphragm on the long side of the bridge hinge, which were supported on pile foundations. Internal transverse bracing typically consists of wood braces connected with 1" diameter bolts to the posts. For falsework bents supporting bridge hinges, prestress strand was used for internal transverse bracing.

Longitudinal stability was provided by combination of following elements:

a) Friction between stringer and the cap or C-clamps were used to attach stringers to the cap.
b) Cable bracing and timber blocking with 3/4" diameter coil rods as ties to connect falsework bent caps adjacent to bridge columns together.
c) Bracing at traffic openings and at falsework Bent 3-4, Dayton pipe braces (B-4 or B-5) or EFCO Super Stud were required per approved plan to be attached to deadman.[5]
d) Double cap restraint.

The cables were required to be pretensioned [6] to remove the slack for them to be effective in taking horizontal lateral load and limit the movement of the cap.

The falsework plans for Frame 1 are in Attachment 3. Figure 1 provides a plan and elevation view of the falsework for Span 3 and a portion of Span 4 of the Floodway Viaduct.

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[5] A heavy anchor, such as a concrete block or a log, usually buried underground and used for securing the end of a tie or guy. Per http://www.dictionaryofconstruction.com Common use in falsework is for it to be a concrete block.
[6] Per sheet 54 of 59 of approved falsework plans for 5/8″ diameter longitudinal cable for spans length up to 30 ft., preload specified is 500 lbs, and greater than 30 ft. and up to 60 ft. preload specified is 1,000 lbs.

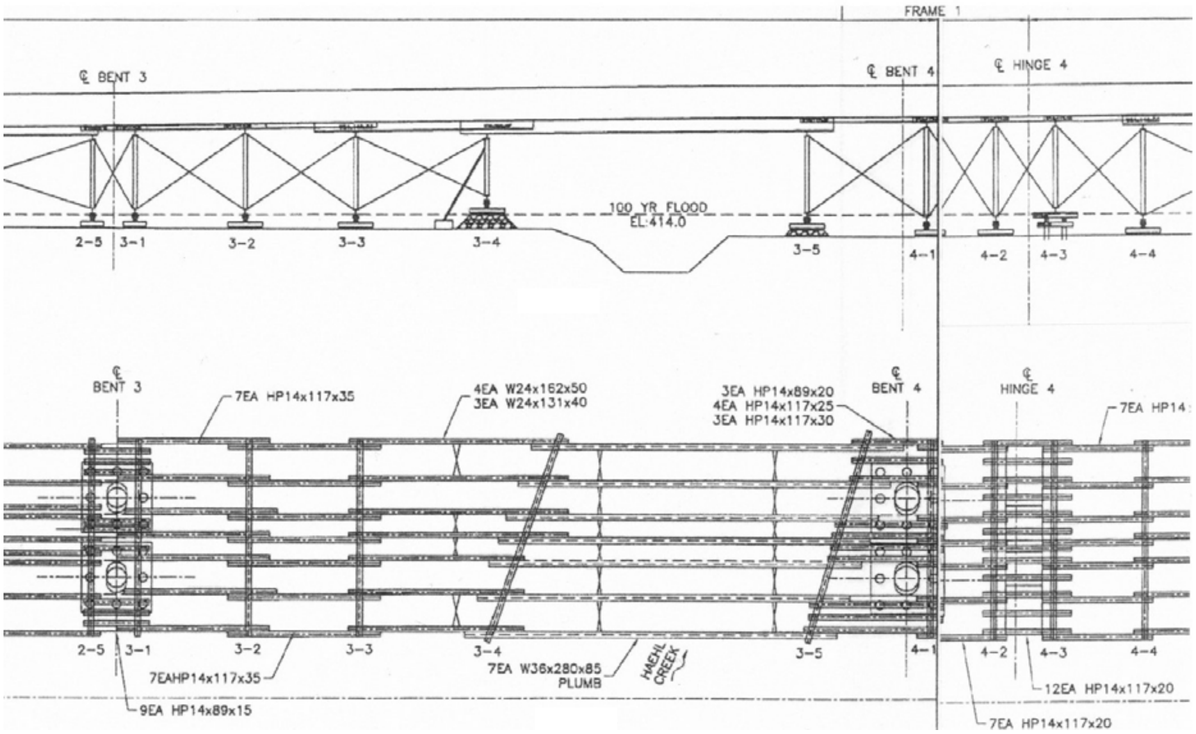

Figure 1: Falsework Span 3 to Hinge 4

Falsework Bents (3-4 and 3-5) adjacent to Haehl Creek were oriented nearly parallel to the creek (20° ± skew to the structure), approximately 20 ft. tall and supported the 73 ft. span across the creek and the adjacent spans that varied in length due to the skew (30 ft. – 45 ft. in Span 3-3 and 8 ft. – 27 ft. in Span 3-5). Bent 3-4 consisted of four doubled up 12 x 12 posts with pipe braces attached to post A & D at one end and deadman at the other end. Bent 3-5 consisted of three doubled up 12 x 12 posts and a single 12 x 12 post on the left[7], post A. The foundations for both of the bents adjacent to Haehl Creek were comprised of two rows of timber piles (20" butt x 12" tip diameter). Each row had 6 timber piles driven to exceed the 45 ton design bearing capacity per ENR[8] formula. The embedment depth was approximately 60 feet. The piles were capped with an HP14 x 89 that spanned between the piles in adjacent rows. An HP14 x 117 bottom sill was shown[9] to be placed on top of the pile cap. On top of the bottom sill was a 12" x 12" x 24" timber block placed perpendicular to the sill, on top of it was a 15" x 21" sand jack. On top of the sand jack were 2″ x 6″ buildups and a wedge pack[10]. An HP14 x 117 was shown[9] to be placed on top of the wedge pack. Double 12 x 12 posts were placed on top of the top sill and were capped with an HP14 x 117.

[7] References in this report to left and right are as you are looking up station or if you were standing on abutment 1 looking towards bent 2. Elements (stringers and posts) are labeled from left to right, e.g. stringer 1 is on the left and stringer 7 is on the right, post A is on the left and post D is on the right.
[8] ENR - Engineering News Record Formula
[9] Refers to what was shown on the approved falsework plans.
[10] Wedge packs were comprised of three pairs of wedges with their orientation alternating.

Tell-tales were attached to the falsework to indicate any vertical movement due to settlement of the support system which includes pad settlement and joint take up[11] between the members. Figure 2 provides a view of tell-tale placement along with the nomenclature used to describe the falsework members for both falsework on pads and piles.

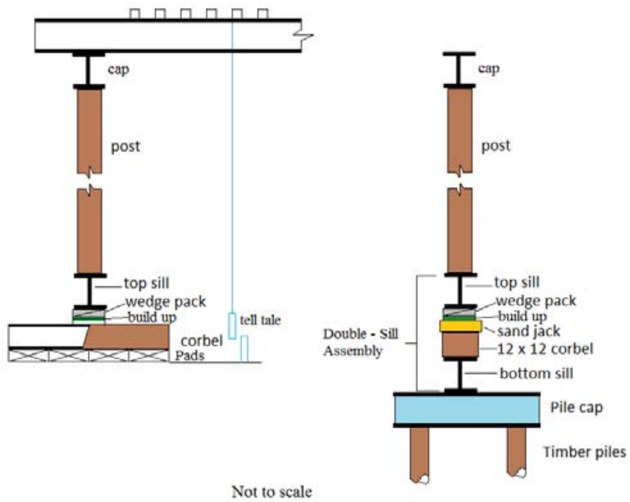

Figure 2: Falsework Nomenclature

Attachment 3 also contains selected sheets from the contractor's approved falsework drawings. The approved falsework drawings Revision 7 contained multiple notes but the following seem to be the most relevant to the collapse:

- Note on Sheet 1 of 59 stated "HP14 x 117 and W14 x 120 can be substituted for caps except where shown on X-sections."

- Sheet 31 of 59, Bent Cross Section 3-4, shows driven piles with an HP14 x 89 pile cap, HP14 x 117 bottom sill, 12 x 12 corbel, wedge pack, and sand jack supporting a top sill with two notes that read "MUST BE HP14 x 117 x 50" and "MUST BE HP14 x 117 x 45 BOTTOM CAP."

- Sheet 31a of 59, Bent Cross Section 3-5, shows driven piles with an HP14 x 89 pile cap, HP14 x 117 bottom sill, 12 x 12 corbel, wedge pack, and sand jack supporting a top sill with the note "MUST BE HP14 x 117 x 50" and "MUST BE HP14 x 117 x 45 BOTTOM CAP."

[11] Timber falsework members crush at the contact points when transferring load. In falsework members, it is estimated that joint take up will be in order of 1/16" – 1/8" per contact surface depending upon workmanship.

2. Falsework Submittal

Falsework for all eight frames were submitted as one submittal. The Contract Special Provisions stated that "falsework plan submittal shall consist of plans for a single bridge or portion thereof. For multi-frame bridges, each frame shall require a separate falsework plan submittal." The contract allowed 8 weeks total review time for the Floodway Viaduct Structure or portions thereof. Frame limits are shown on the attached project plans and falsework plans.

For Falsework Submittal Log see Appendix A: *Chronology of Falsework Review & Events during Falsework Construction.*

3. Falsework Revisions

There were a number of revisions to the falsework drawings that may have been influenced by the following factors:

- Regulatory Agency Permits determined work windows near the stream which affected the construction schedule. The work window permitted was from June 15th to October 15th.
- The settlement period of approach fill at Abutment 1 was eliminated allowing work to begin earlier on Frame 1.
- Regulatory Agency opposition to leaving piling in the stream channel during period outside of work window.
- Contractor evaluating the cost of pads versus pile foundation.
- Heavy vegetation along the stream was not removed until Spring 2014. This revealed to the contractor what they considered unstable bank conditions resulting in their use of pile foundations at falsework Bents 3-4 and 3-5.

In Revision 6, there were four falsework bents in Span 3 with the bents adjacent to Haehl Creek normal to the bridge centerline and labeled as Bents 3-3 and 3-4. Falsework Bent 3-4 was reasonably close (9′-9″) to the columns of bridge Bent 4. Revision 7 revised the falsework span lengths resulting in five falsework bents being in Span 3 and oriented the Bents 3-4 & 3-5 to be parallel with the creek making them skewed to the bridge centerline. Falsework Bent 3-5 was adjacent to bridge Bent 4; the distance between falsework Bent 3-5 and the centerline of bridge Bent 4 varied from 6'-9" (left) to 21'-9" (right).

4. Certification of Falsework

The project special provisions requires[12] that the contractor's engineer who signs the falsework drawings to certify in writing that the falsework is constructed in conformance with the approved drawings. The contractor's engineer who signs the drawings may designate a representative to perform this certification. This contract requirement was met when Flatiron West's Engineer of Record's representative performed an inspection of the falsework and certified in writing that the falsework was constructed in conformance with the approved drawings and the contract specifications. The inspection was performed on January 13, 2015, and the certification presented to Caltrans on January 21, 2015. This certification is Attachment #4.

This certification was also used to fulfill the requirements of California Code of Regulation, Title 8, Section 1717, *Falsework and Vertical Shoring,* which requires that the Engineer of Record or authorized representative shall perform an inspection of the falsework after construction of the falsework and prior to concrete placement. The person performing the inspection must certify in writing that the falsework system substantially conforms to the working drawings and that the material and workmanship are satisfactory.

5. Loading of Falsework Prior to the Collapse

The falsework collapse occurred during the placement of concrete for the soffit and stems of Frame 1. The limit of the Frame 1 falsework collapse included stringers from Span 2-5 in the south, all of the falsework in Bridge Span 3 and Span 4-1. The cap at Bent 4-2 moved about one foot with respect to the bottom towards Bent 4-3.

The falsework failure occurred around 2:15 p.m. The concrete placed prior to the collapse in Span 3 and Hinge 4 was as follows:

- A second placement crew began placing soffit concrete from bridge Bent 3 to Hinge 4 at about 7:30 a.m. while the first crew was still placing concrete in Span 2.
- All soffit concrete was placed in Spans 3 and 4.
- In Span 3, concrete was placed in the easterly exterior girder up to the construction joint between the deck and the girder, and similarly concrete was placed in the westerly exterior girder concrete up to the construction joint for most of its length, except it was half full near the vicinity of Bridge Bent 3.
- Bent 4 concrete placed up to the bottom of prestressing ducts.

[12] Section 10-1.88, *Concrete Structures*. The Contractor's engineer who signs the falsework drawings shall also certify in writing that the falsework is constructed in conformance with the approved drawings and the contract specifications prior to placing concrete. This certification shall include performing any testing necessary to verify the ability of the falsework members to sustain the stresses required by the falsework design. The engineer who signs the drawings may designate a representative to perform this certification.

- In Span 4, concrete was placed in the two exterior girders between bridge Bent 4 and bridge Hinge 4 up to the construction joint.
- At Hinge 4, the short hinge diaphragm concrete was placed up to the bottom of the prestressing duct.
- Returning to Span 3, concrete was placed in the remaining top half of the westerly exterior girder from bridge Bent 4 to near Bent 3 (north to south).
- The crew was near Bent 3 waiting for additional concrete when the collapse occurred.

For a graphic of concrete placed prior to the collapse refer to Attachment #5.

III. Falsework Collapse Investigation

1. Observations During Field Investigations

(Refer to photos in Attachment #1 & falsework collapsed debris plan in Attachment #6)

Collapsed falsework debris generally fell southerly for Falsework Bents 3-4 to 3-1 with sills close to the as-built location. Falsework Bents 3-5 and 4-1 fell northerly.

The following is a description of the debris field:

a. Falsework Bents:

- Bent 3-1
  The sill rotated in place, some of the posts were hit by the Bent 3-2 cap. Posts fell southerly. The cap from Bent 3-1 landed on top of the sill beam. The right end of the sill fell close to its as-built location, and the left end was away from the as-built location. (See photos #1, 2, 3, 4, and 5)

- Bent 3-2
  The sill didn't move, and the falsework bent toppled over. The cap fell near Bent 3-1. The cap from Bent 3-3 landed on top of the right edge of the sill at Bent 3-2. (See photos # 6 and 7)

- Bent 3-3
  The sill moved about 4 feet south from its as-built location.
  (See photos #8A, 8B, 9, 10A and 10B)

- Bent 3-4
  - Numerous broken sand jack frames were observed.

  - The top sill rotated (east end south, west end north) about the centerline of the bent. The top sill fell on top of the bottom sill crushing the build-up. (See photos #11, 12, and 13). The posts (4-double 12 x 12) were lying nearly perpendicular to the bent. Both Post A and D were attached to a pipe brace. The two pipe braces were permanently deformed as shown in photo #14 and 33.

- Bent 3-5
  - The top sill was found north of the as-built location about 13′ and 7′ from its as-built location along the right and left edges respectively. The cap was found north of the as-built location about 7 ft and 3ft from its as-built location along the right and left edges respectively. The posts fell both north and south. Three (double 12 x 12s at posts B, C, and D) on the right fell to the north away from the creek. One (post A) broken post with pipe brace still attached with bolt fell south, towards the creek (Photo #15 and 32). The bottom sill remained atop the pile caps, but was about 3′ south of its as-built location on the right edge.
  - The top sill exhibited damage to the flange and web. The top flanges on the south side were bent downwards. The top of the web also exhibited bending towards the south at 3 of the 12 points where measurements were taken. Measurements were taken about every 4 feet. (See attachment #7)
  - 15 of the 17 sand jacks were retrieved. Thirteen were structurally intact. (See Photos #16, 17, 18, and 19)
  - Post A (single 12 x 12 timber) landed south of its location with pipe brace attached. (See Photo #15).
  - Post B (two 12 x 12 timbers) was damaged (splintered) at the top. The damage was similar for both members of this post. (See Photos #20 and 21).
  - Post C (two 12 x 12 timbers), one of the two members making up the post was damaged. (See Photos # 22 and 23).
  - Post D (two 12 x 12 timbers) was undamaged. (See Photos #24A, 24B and 25)
  - Two C-clamps were found in the debris.

- Bent 4-1
  The sill rotated in place, and the post fell to the north resting against Bent 4-2. The cap came to rest midway down on top of the leaning 4-1 posts. No indentation was found on the 4-2 post, therefore it indicates that the cap was dislodged during the post moving north. (Photos #34 and 35).

- Bent 4-2
  The top moved north about 1 foot due to impact of the posts from Bent 4-1 falling

onto the braces. The stringers in Span 4-1 lost their support at Bent 4-1. The pad appeared to be settled into the soil but upon further review it was determined that during construction the removal of vegetation set the pad below the surrounding ground surface. (Photo #34 & 35).

b. Falsework Spans:

- Span 3-4
  Six stringers (W36 x 280) landed upright on the bottom sills of Bents 3-4 and 3-5. The seventh (right side) stringer was on the ground and leaning towards the east. (Photos # 11, 13, and 26).
- Span 3-5
  - The tie rods between Bents 3-5 and 4-1 appeared to have been broken by falling debris. Six broken tie rods pieces were found in the debris. (See Photos #27, 28, and 29).

c. Longitudinal Cables:

- The connections of the longitudinal cable connecting the right side of Cap 3-3 and Top Sill 3-4 slipped. Two of the wire rope clamps were missing. The remaining clamp was on the wire rope but the loop had been lost (See Photo 30). The cable (connecting the left edges of Cap 3-3 to Top Sill 3-4) was found broken close to Top Sill 3-4 (See Photo #31).
- Cable connecting the right sides of Cap 4-1 to the Top Sill 3-5 appeared to be birdcaged[13].
- All other cables connecting caps and sills were intact.

d. Bridge Columns:

- Bent 4 - Both of the pinned columns rotated toward Span 3 (southward) by about 3 degrees.
- Bent 3 - No rotation of the pinned columns was observed.

2. <u>Observations During Post Collapse Review of Falsework Drawings</u>

The falsework system constructed generally conformed to the approved falsework plans, but it has been determined that several key elements were changed or missing. These omitted or changed items had detrimental influence on the stability of the falsework in Span 3 of the

[13] A colloquialism descriptive of the appearance of a wire rope forced into compression. The other strands form a cage and, at times, displace the core. A "birdcage" is caused by sudden release of tension and the resulting rebound of rope. These strands and wires will not be returned to their original positions.

Floodway Viaduct (bridge). Attachment 8 shows this information superimposed on the falsework drawings and are discussed below:

1. The top cap and bottom sills for Bents 3-4 & 3-5 were specified to be HP14 x 117 but were constructed using W14 x 120 members. The top sill was specified as "must be HP14 x 117 x 50' but a W14 x 120 was used instead. (Revision 7 Sheet 31 and 31a of 59).
2. Elements for the "DOUBLE CAP RESTRAINT DETAIL" were not installed on the double sills of Bents 3-4 and 3-5. (Revision 7 Sheet 31 and 31a of 59.) (The Double Cap Restraint Detail can be found in Revision 6 Sheet 57 of 59.) These elements of the double cap restraint were not found in the debris or upon examination of the photos taken prior to pour at Bents 3-4 and 3-5. The double cap restraints as designed were found to be structurally deficient to transfer the load from the top sill to the bottom sill, but as stated earlier they were not installed.
3. At Bent 3-4 two of the four pipe braces were installed. (Revision 6 Sheet 49 of 59.) (Details of these braces are on Revision 6 sheet 51 of 59.) These pipe braces were Dayton B-4 connected to a deadman. (Photo #36)
4. At Bent 3-5, a pipe brace was added to post "A" and attached to the left column of Bent 4. This brace was not shown on the approved falsework drawings. (See photos #36, 37, and 38)
5. Four- ¾" coil rods between the falsework at Cap 3-5 and Cap 4-1 were installed on an incline. However, out of 4 tie rods only six pieces of broken tie rods were found. 4"x4" blocking was installed at an incline between falsework Cap 3-5 and the Bent 4 column. The standard detail (FD-1) shows the coil rods and 4"x4" timber blocking being horizontal between the bent caps and column. (See photo #39)
6. Stringers in Span 3-4 were 7-W36x280x85. The approved plans showed them as being symmetrical about the centerline of the span. The stringers were not placed symmetrically about the centerline of the span and near the right column of Bent 4 were placed with 10' tails into Span 3-5. The third stringer from the left edge of deck side also had the longer tail towards the left column of Bent 4.
7. A 12 x 12 supplemental stringer beam was added between the two bridge girders on the right (between the 5th and 6th stringer) near Bridge Bent 4, right column. The supplemental stringer was attached to the right column of Bridge Bent 4. The detail shown on sheet 13 of 59 of the approved falsework plans was used with modification. Per the Contractor's Superintendent and the Caltrans Structure Representative's interview statements a 12 x 12 stringer was placed longitudinally rather than a 2 x 4. (See Attachment #9)

3. Other Information Collected During the Investigation

a. Tell-tale Readings

In general vertical displacements at the falsework bents varied from 1/4" to 1/2" based on the discussion with field engineers monitoring the tell-tales. These displacements are documented in the Assistant Resident Engineers Daily Report for January 22, 2015.

b. Stringers to Cap Attachment

Stringers (W36 x 280) in Span 3-4 sat on top of the cap and were plumbed using hardwood wedges across the full width of the cap. C-clamps were used during construction (erection) and not as part of the longitudinal stability of the completed constructed system.

Stringers in Span 3-5 (HP14 or W14 beams) were connected to the blocks at Bent 3-5 with wood post to cap beam connection (FD-35 on sheet 56 of 59) both to the cap and the stringers as shown in Figure 3.

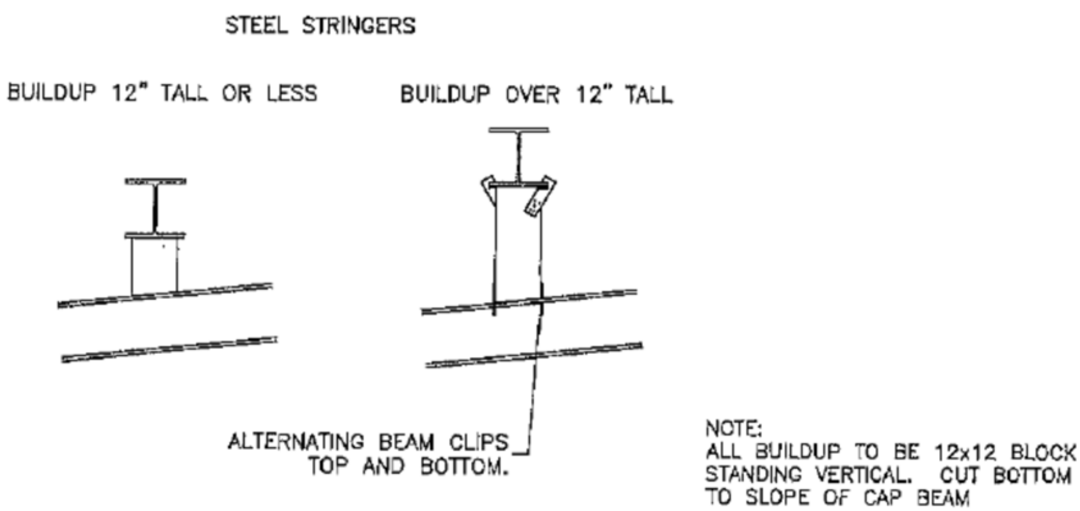

Figure 3: Build-up Connection Details (FD-35)

c. Cap to Post Connectors

The cap to post connectors (Wood Post to Cap Beam Connection FD-13) (Figure 4) seem to have been adequately installed. They showed varied types of damage. Some were still attached to the wood posts but were twisted, while others exhibited damage as though they had been sheared across the narrowest part of the plate (Photos #44 to 49).

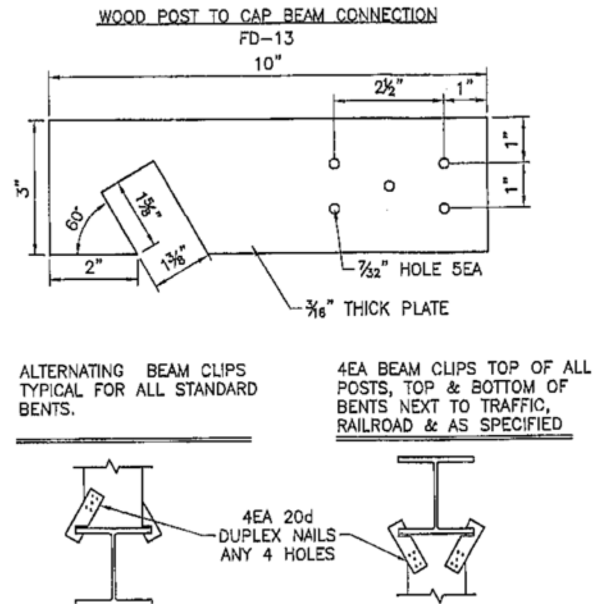

Figure 4: Wood Post to Cap Beam Connection Details (FD-13)

IV. Discussion of Potential Collapse Mechanisms

The following is a discussion of the components of the falsework or the events that may have either lead to the collapse or provides information on the potential collapse mechanism.

1. Concrete Placement at the Time of Collapse

Concrete was not actively being placed at the time of the collapse due to a short delay between concrete truck deliveries. The last concrete placed was also away from what is believed to be the location where the failure began. This indicates the possibility of a stress increase over time at the location of the collapse.

2. Eyewitness Account

The Assistant Structure Representative reported that at approximately 2:00 P.M. (14:00) the falsework appeared secured when telltales were inspected. At 14:20, falsework started to collapse near bridge Bent 4, and continued to collapse to Bent 3. The remaining Caltrans inspectors and Flatiron crew ran to Abutment 1 to get off the temporary structure.

From this account it is surmised that the collapse started in falsework span 3-5 closest to bridge Bent 4 and proceeded progressively from southward to falsework span 3-1. This is supported by the crew's action of "running" to Abutment 1. The collapse can be classed as catastrophic since the temporary support structure (falsework) and permanent work were laying on the ground and required removal before any further work could be undertaken at this location.

3. **Soil Bearing Pressures and Settlement**

The Log of Test Borings (LOTB) included in the contract plans for the Floodway Viaduct show clay with sand / clay / clayey sand strata in borings nearest to Span 3. The LOTB for those borings nearest Bent 4 are B-22 and B-66 and are on contract plan sheets 812 – 814 (Attachment # 10). The area was flooded on December 11, 2014, and remained so for a day before the water receded back into Haehl Creek (See Photos #40A & 40B).

Tell-tales indicate settlement which includes joint take-up and settlement of the pads. The joint take up will account for almost all of the small settlement readings taken visually and recorded by the Caltrans field engineer in his diary; therefore the soil settlement component should be negligible. This is collaborated by the statement from the Caltrans Structure Representative, who stated that he did not see any indication that the pad at Bent 4-2 sank into the soil. There are several areas where the gap between the pad and soil is visible as seen in photos 41 and 42. During placement of the pads, ground vegetation was removed, giving the appearance that they were placed below the surrounding ground surface.

Caltrans Division of Engineering Services / Geotechnical Services performed a site review of the falsework foundations at Bents 3-5, 4-1 and 4-2 and provided a report with the following geotechnical observations:

- <u>Bent 3-5</u>
  Geotechnical Services (GS) estimated that timber piles for Bent 3-5 had nominal pile capacities of 180 kips or greater based on the assumed pile set-up factor of 2.38. The report further concluded that Falsework Bent 3-5 did not indicate any pile movement or displacement.

  Geotechnical Services confirmed that timber piles were structurally adequate to support the falsework load without noticeable pile movement or displacement. This verified field record/observation that pile were driven to at least 45 tons (90 kips) bearing using the ENR formula and anticipated settlement were in agreement with tell-tale readings taken by field personnel at Falsework Bent 3-5 of the falsework.

- <u>Bent 4-1</u>
  Geotechnical Services reviewed the falsework pad at Bent 4-1, which was on top of 16″ of fill placed over the Bridge Column 4 foundations. Their report determined that pad foundations and the bridge foundation were adequate and that anticipated settlement was in agreement with telltale readings taken by field personnel at falsework Bent 4-1.

- <u>Bent 4-2</u>
  Based on Boring B-66 and a concrete load of 829 psf, GS estimated theoretical elastic settlement of the foundation soils at Bent 4-2 to have between 0.2 to 0.4 inches at the time of failure. Based on April 2, 2015 site visit, GS found no indications of viable movement of the Bent 4-2 falsework foundation. Based upon a soil bearing pressure of 2,200 psf, a safety factor of 2.5 or greater was estimated at the time of failure.

This report determined that falsework foundations were adequate at Bents 3-5, 4-1 and 4-2 and that anticipated settlement were in agreement with tell-tale readings taken by field personnel at these bents.

4. Sand Jacks

Initial observations of the broken sand jacks indicate that the sand jacks crushed as a result of the falling falsework members impacting them.

At Bent 3-5, 15 sand jacks were retrieved of the 17 installed. Thirteen were intact structurally. Two were found damaged. One of the two damaged was broken but the two straps were intact without any structural failure. (See Photos # 16, 17, 18, 19). The Caltrans Material Engineering and Testing Services (METS) Structural Materials Representative looked at broken straps from the sand jack and concluded that it was due to impact.

The sand jacks were not covered to protect them from the elements. Therefore, they were subjected to potential rain water intrusion during the December 2014 storm. When the area was flooded during this time period, the sand jacks were above the level of the water.

The sand jacks used on the project substantially complied with the preapproved wood sand jack of the *Falsework Manual* Memo C-18 except that the banding was 25 gauge banding but the preapproved sand jack required 20 gage banding. For this report, sand jacks from the project were tested by Caltrans / Division of Engineering Services/Materials Engineering and Testing Services (METS). This testing consisted of:

- A vertical load applied to the centerline of the sand jack while measuring vertical displacement of the plunger[14] and load.
- An eccentrically placed vertical load, while measuring vertical displacement of the plunger at each end of the sand jack.

The test results indicate that the wood sand jacks were structurally adequate to support a concentric load equal to the load (34 kips) they were subjected to prior to the collapse. Maximum load applied during testing was 34 kips.

During the investigation a possible mechanism was an unbalanced loading condition (eccentricity), therefore it was decided to test whether sand within the sand jack would move under an eccentric load. The sand jack was tested with an eccentric load to evaluate this case. An additional question as to how the sand would behave if it was moist. This was considered due to the December rain storm flooding. Wind driven rain may have collected on top of the sand jack and seeped under the plunger. Flooding didn't reach the level of the sand jack nor did the contractor's falsework inspector or SC inspector report any wind driven water issue around the sand jacks.

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[14] The plunger is a plywood bearing plate on top of the sand within the sand jack on which build-up and wedges are installed to transfer the load from the sill beam.

Testing with eccentric loading at 7″ was done to evaluate the effect of eccentricity on the dry and moist sand jacks. During the testing with 7″ eccentric loading and moist sand, it was noticed that the plunger was rotating with gradual loading. At a load of 31 kips, sand started to leak. This indicates that 7″ eccentric loading with moist sand can cause premature failure of sand jacks. Prior to leakage, the plunger was rotating as the eccentric load increased in 10 kips increments.

During testing with concentric loading with moist sand, it was noticed that at a load of 34 kips, maximum plunger displacement was in the order of 0.4″ indicating that sand jack is vulnerable to water intrusion because the sand jack became functionally unsatisfactory as it did not meet serviceability criteria which limits vertically displacement to ½" maximum at concentric 68 kips loading.

Based on the limited testing:

- The sand jack filled with dry sand is functionally and structurally adequate when loaded concentrically. Functionally adequate because the plunger did not displace excessively vertically and structurally adequate because the frame maintained its integrity under load.
- The sand jack with moist sand is functionally unsatisfactory when loaded concentrically due to its excessive vertical displacement.
- The sand jack with moist sand was structurally inadequate when loaded eccentrically.

5. Longitudinal Resistance

a. Cable Bracing & Pipe Braces

The longitudinal cable (connecting Bent 3-4 top sill with Bent 3-3 cap) slipped from the wire rope clip connection on the right side of the Bent 3-3 cap. This could be indicative of improperly installed wire rope clips. (See Photo 30)

The cable (connecting Bent 3-4 top sill with Bent 3-3 cap) failed on the left side of the falsework in Span 3-3. It indicates a wire rope tensile failure.

The cable connecting the cap of Bent 4-1 to the top sill of Bent 3-5 was found with bird caging,[15] indicating that the cable had most probably taken a shock load.

Three samples of cable from the project were tested by METS. In addition, two samples of unused cable were tested. The tests resulted in the following average peak load for:

[15] Bird caging as used here is the twisting of wire rope in an isolated area of the rope in the opposite direction of the rope lay. Bird caging of wire rope is considered to be permanent damage that may occur as a result of shock loads and other causes.

- Unused cable 31,118 Lbs. (15.6 tons)
- Used cable 35,046 Lbs (17.5 tons)

These test results are less than the ultimate cable capacity used by the contractor (20.6 tons) in their design calculations. The lower values do not appear to have materially contributed to the collapse.

The cables were pretensioned to take out the slack for them to be effective in taking the horizontal lateral load. The pretension for falsework at Span 3-3 was required to be 500 lbs. on the right side (30′ span) and 1,000 lbs on left side (45′ span). For the falsework at Span 3-5 cables on both sides (right and left) were pretensioned to 500 lbs. The longitudinal resisting system was discontinuous with no longitudinal cables in Span 3-4 over the creek. This configuration resulted in unbalanced pretension forces pulling the Bent 3-4 cap and sill to the south and pulling Bent 3-5 to the north. This force was adequately resisted by the planned Dayton braces at Bent 3-4 but only at the cap. Note though that only two of the four braces shown were installed. No Dayton (pipe) braces were shown on the plans at Bent 3-5of the falsework, though one Dayton-type brace was installed on the left side. The right side of the top cap of Bent 3-5 had no Dayton brace.

The bottom sills at Bent 3-4 did not have a positive restraint and thus the force is resisted by friction. Similar to Bent 3-4, Bent 3-5 did not have positive restraints at the sills for this longitudinal cable load. This could be a contributing factor in unseating the falsework build-up at Bent 3-5.

b. Timber Blocking Against Bridge Bent 4, Right Column

During the post collapse analysis of the falsework it was determined that the 4”x4” blocking on the right side of Falsework Bent 3-5 that spanned from the bent to the right column of Bridge Bent 4 was not adequate to resist the assumed horizontal load.

c. Tie Rods

Installation of tie rods at an inclination caused eccentric loading at the end of the tie rod connections thereby reducing its capacity and effectiveness to reduce lateral movement of the caps.

d. Double Sills and Double Cap Restraint

The approved falsework plans (Revision 7) showed the bottom sill connected to the exterior pile caps only. This connection consisted of angle iron with C-clamp, two at each end, 4 total.

The height of the stacked build-up between the top and bottom sills at Bents 3-4 and 3-5 did not meet the maximum 2:1 height to width criteria required per the Falsework

Manual[16] section 5-1.07, *Multiple & Built up Cap Systems*. This criteria has empirically shown to provide stability. However, Section 5-1.07 does allow the 2:1 criteria to be exceeded if the falsework cap/sill assembly is externally stabilized. The requirement for the external stabilization is that it must withstand the greater of the horizontal wind or construction load or a minimum 2% of the falsework dead load force applied to the top of the upper most cap/sill beam and must transfer this force and moment from top sill to the bottom sill.

The approved falsework plans called for a "DOUBLE CAP RESTRAINT DETAIL" (Figure 5) at the sills of the falsework at Bents 3-4 and 3-5 that would have provided some external stability. This detail was not installed.

If not properly detailed and constructed stacked structural shapes (double sills or caps) from past experience have been found to be susceptible to displacement from forces occurring during loading of falsework. Double sills rely heavily on being constructed with proper alignment between the members and application of the vertical load through the center of the support. Double cap restraints assist with keeping the top sill beam from moving out of alignment during initial construction and grading of the falsework when jacking operations are performed.

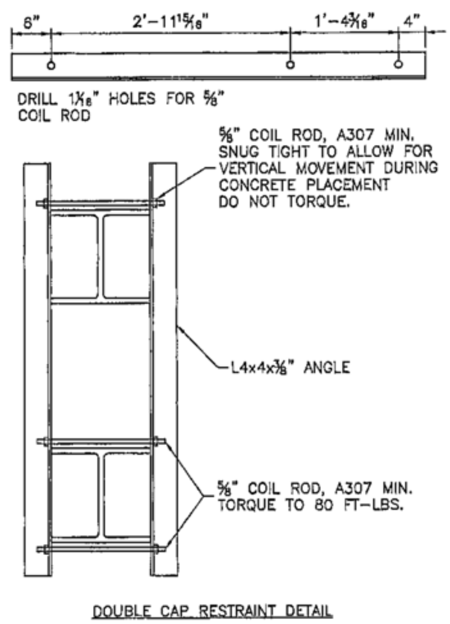

Figure 5: Double Cap Restraint Detail

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[16] The *Falsework Manual* is not intended to be a contract document but does represent the Department's opinion as to what constitutes "best general practice" for the design and construction of falsework.

The longitudinal cable bracings for this falsework was attached to the top sill. This creates a discrete force that must be considered for a double cap restraint to transfer this lateral load from the top sill to the bottom sill. The approved falsework drawings did not have a detail showing where the longitudinal cables should be attached when double sills are used. During the post collapse analysis it was determined that the "double cap restraint detail" is deficient in resisting the assumed 2% horizontal load. The 4 x 4 angles were overstressed in bending and the 5/8″ diameter coil rods were overstressed in tension.

The omission of the restraints is significant, whether it is intended to keep the two sill beams plumb (aligned) or transfer lateral load from the top sill to the bottom sill or both. The approved falsework plans (Sheet 31 and 31a of 59) showed that the top sill "must be HP14 x 117," so the W14 x 120 was not an allowable substitution per the notes[17] on Sheet 1 of 59 of the falsework drawings. The plans specifically called for the bottom sill beam to be HP14 x 117 but a substitution of a W14x120 was allowed per note on Sheet 1 of 59. Prior DES sponsored university research[18] demonstrated that beams with thinner webs have a tendency for the webs to bend when the flanges were loaded. The web thickness of the W14 x 120 used is 26% thinner than the HP14 x 117 that was detailed on the plans.

Section properties of the structural shapes mentioned above:

Designation	A in^2	d in	t_w in	b_f in	t_f in	I in^4	S in^3
HP14x117	34.4	14.21	0.805	14.885	0.805	1220	172
W14x120	35.3	14.48	0.590	14.670	0.940	1380	190
Where A- Area, d – depth of beam, t_w – web thickness, b_f – flange width, t_f – flange thickness, I – moment of inertia, and S – section modulus.							

The top sill of Bent 3-5 exhibited damage to the flanges and web that indicates an eccentric load had been applied to this member. These indicators include measurements of the distance between the flanges being less than expected even with mill tolerances considered. The web of the sill was also deformed. The measurements and observations of the top sill are in Attachment #7; the sill was reportedly undamaged when erected.

6. Falsework Bent 3-5

a. Loading on Bent Cap

The loads on the cap came from the stringers (W36) in Span 3-4 and the stringers (HP14) in Span 3-5. To account for the difference in beam depth, the stringers from Span 3-5 are

[17] HP14 x 117 and W14 x 120 can be substituted for caps except where shown on x-sections.
[18] University of Nevada, Reno. Report No. CEER 05-11 Recommendation for the Design of Beams and Posts in Bridge falsework. Reno, NV. January 2006.
http://www.dot.ca.gov/hq/esc/earthquake_engineering/Research_Reports/vendor/un_reno/2005-11/FinalReport-Contract%20No-59A0445-CCEER-05-11.pdf

set atop timber blocking. The bridge is relatively flat but it does slope uphill to the north in the longitudinal direction. The caps of Bent 3-5 were set level longitudinally and followed the bridge cross slope in the transverse direction.

The stringers from Span 3-4 followed the general upslope of the bridge and would rest upon the southern edge of the flange of the Bent 3-5 cap as the loading of these stringers increased the deflection of the beam and resulting curvature would increase loading towards the flange edge. This may have resulted in eccentric loading which would cause lateral bending of the cap beam and induce bending moments into the posts.

The timber blocking (12 x 12's set on end, as posts with bridge clips) under the stringers from Span 3-5. Detail FD-35 (shown in Figure 3) included a note that required to cut the bottom of the 12 x 12 standing block to the slope of the cap beam transversely but it does not specify cutting along the longitudinal slope. Due to the slope of the stringer sitting atop the blocking, the load may be toward the downslope edge.

Analysis of the loading shows that there may be an eccentric loading on the cap if not accounted for in the longitudinal bracing or blocking. This eccentric loading can be transferred to the post due to some fixity in the joint. In falsework design the joints between post and cap/sill beams are considered pinned although there is some fixity due to heavy timber (12 x 12) foot print.

b. Loading on Posts and Double Sills

Assuming some joint fixity due to member size and bridge clip connections, eccentric loading on the cap was passed on to the post and then to Bent3-5, to the double sills. The loading increased gradually as concrete placement progressed. The double sills were unable to resist this eccentric loading. Friction was the only resisting force present to provide horizontal resistance at each contact point within the double sill assembly. Refer to Appendix D: *Bent 3-5 Equilibrium under Eccentric Loading Discussion.*

c. Posts

All damage to the posts appears to be due to impact from falling stringers. Post loads were within the allowable design capacity. At the time of collapse they were subjected to a lesser load.

7. Supplemental Timber Stringer near Right Column, Bent 4

To reduce joist span at the right column of Bridge Bent 4, the contractor modified a detail from the approved falsework plans by using 12 x 12 timber members and wedging them in the tail of the W36 stringers from Span 3-4. The blocking/cribbing shown in Figure 6 was reportedly used. This blocking/cribbing was used as a support for the supplemental stringer built by transverse 12 x 12 timber beams bearing on the 12 x 12 blocking. The detail on Sheet 13 of the approved falsework plans (Attachment #3) lacks the following construction details:

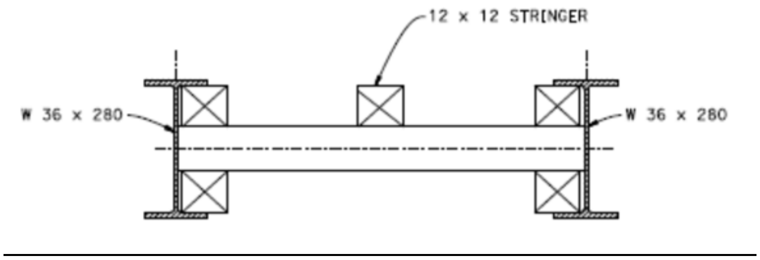

Figure 6: Actual Detail Implemented near Bent Caps

- Member sizes greater than shown were used and no connection details provided. Connection of the 12 x 12 stringer to the column and the blocking/cribbing shown in Figure 6 adjacent to the right column of Bent 4 does not conform to the detail on sheet 13 because the 2 x 4 is changed to a 12 x 12 and a connection to the column is made that is not detailed.
- The length of W36 girder tails from Span 3-4 was not shown on the plans and was not clearly identified to be loaded.
- The blocking was not fully supported as 12 x 12 post dimension is greater than the flange width projecting from the W36 web with fillets and blocking reportedly was not notched to abut against the web.
- This cribbing could become unstable because it was not fully supported over its width. If the 12x12 beam rotated due to load, it may have initiated the unseating of the 12x12 blocking

The details shown on the plan lacked sufficient detail and was different in scope when it was used in Span 3-5. The *Falsework Manual* in general discourages continuous span stringers.

The effect of long tails on 3-4 stringers and the loading of the same should not have had a significant impact on the stability of Bent 3-5.

8. Bridge Columns

- Bent 4:
  Both pinned columns rotated toward Bridge Span 3 (southward) because when the falsework fell the soffit and girder concrete along with the reinforcing steel which was tied to the column reinforcement pulled the column on its downward descent.
- Bent 3:
  No rotation of the columns was observed because concrete was set in Span 2 and Span 2 falsework was intact.

9. Administrative Observations Pertinent to the Collapse

- The contract states that a falsework plan consists of plans for a single bridge or portion thereof. For multi-frame bridges, each frame shall require a separate falsework plan submittal. The Floodway Viaduct is an eight frame structure that would have required eight submittals. The contractor submitted one falsework plan that included the falsework for all eight frames. The contractor made numerous revisions to the falsework plan which may have resulted in an incomplete design; these revisions were not highlighted on the plan sheets which may have led to an incomplete review of some of the details, particularly those revisions causing a changed orientation of the falsework bents at Haehl Creek in Revision 7.
- A day before the concrete placement, a supplemental timber stringer near the right column of Bent 4 was added without approval. The contractor's contention is that this was a slight modifications to a detail used to support the ends of joists near columns. The detail in question does not have dimensions but the size of the lumber members appears to be small on the plans and definitely not something the size of a 12x12 timber.

  Although investigation determined that the insertion of this member likely did not contribute to the collapse, by changing the detail without authorization, raises concerns internally as to the effectiveness of the falsework plans as submitted and the contractor's quality control of their work.
- The contract states that the Contractor's engineer who signs the falsework drawings shall also certify in writing that the falsework is constructed in conformance with the approved drawings and the contract specifications prior to placing concrete. The engineer who signs the drawings may designate a representative to perform this certification. The Floodway Viaduct certification was provided by a representative of the Contractor's engineer who signed the drawings. The deficiencies listed under "Observation during Post Collapse Review of Falsework drawings" and Attachment 8 (List of As-built Deficiencies) indicates that the certification by the Engineer of Record's representative failed to ensure that the falsework was constructed in conformance to the approved plans.

10. Seismic Considerations

USGS reported seismic activity 30 miles away at 14:25 at the time of or after the incident. Due to the low intensity of this seismic activity its impact on the stability of falsework is negligible.

11. Equipment Hitting Falsework

No incident was reported indicating that any construction equipment hit the falsework.

12. Suspicious Activity

No suspicious activity was reported immediately prior to the collapse.

V. Most Probable Collapse Mechanism

Based on the eye witness accounts that indicate failure first occurred around Bridge Bent 4 and the fact that multiple deficiencies as discussed above were present at Falsework Bent 3-5, the most probable cause of failure is the instability at the base of Falsework Bent 3-5. Instability is a condition not readily identifiable when multiple factors are involved.

Contributing factors resulting in loss of stability are as follows:

1. At Falsework Bent 3-5, double cap restraint details were not installed.
2. Un-equal span loading, and loading from the stringers not centered on the Bent 3-5 cap.
3. Unbalanced longitudinal pretension (preload) force in cables.
4. Between Bents 3-5 and 4-1 there existed insufficient longitudinal lateral stiffness on the right side of the falsework near right column, Bridge Bent 4.
5. Potential out of plumb bent due to workmanship (construction tolerances).
6. Potential misaligned double sill beams.

The exact cause of collapse is unknown but based upon the debris pattern, eye witness accounts, deformation of top sill and analysis of the approved falsework compared to actual falsework built and in light of the above observations and findings, it is concluded that the most probable failure mechanism were as follows:

1. Eccentric loading of Falsework Bent 3-5 cap.
2. Forces due to eccentric loads exceeded the resisting friction force.

VI. Internal Review and Analysis

A team of engineers with varied experience with Structure Construction was asked to review the submitted falsework plans for the Floodway Viaduct (Br. No. 10-0165) after the collapse. Their analysis revealed that the longitudinal blocking was not adequate to resist or carry the horizontal design load longitudinally at Bent 3-5.

Additional engineers were added to the post review team (forensic team) to discuss possible causes for the failure. This team also performed additional analysis to determine the loads and stresses on the various members as an aid in determining a probable cause.

VII. Conclusions

1. The falsework was not installed as shown on the approved falsework drawings.
2. Certification by the contractor's Engineer of Record's designated representative may have been ineffective.
3. The collapse was rapid with no prior indicators of an incipient loss of stability of falsework Bent 3-5. Once Bent 3-5 collapsed, it created instability in Falsework Bents 4-1 and 3-5. Subsequently, progressive failure of falsework bents in a sequential fashion from Bent 3-5 to Bent 3-1 took place.

VIII. Recommendations

1. Evaluate revising Standard Specifications 48-2.01C (2), *Shop Drawings,* regarding delegation of certification of the falsework and timing of certification.
2. Evaluate the need for horizontal forces to be positively restrained.
3. Evaluate the need to provide internal training for the review on the best practices in design, construction and inspection of the falsework.

IX Attachments

Included for reference are:

- Appendix A: Chronology of Falsework Review & Events during Falsework Construction
- Appendix B: Sand Jack Testing Report
- Appendix C: Geotechnical Review Memo
- Appendix D: Bent 3-5 Equilibrium under Eccentric Loading Discussion
- Attachment # 1: Photos
- Attachment # 2: Project Title sheet General Plan & Structure Plan No. 1
- Attachment # 3: Contractor's Falsework General Plan and Elevation
- Attachment # 4: Engineer's Representative Certification
- Attachment #5: Concrete Placed Prior to Collapse Diagram
- Attachment # 6: Falsework Collapsed Debris Plan
- Attachment # 7: Bent 3-5: Deformed Top Sill Measurements
- Attachment # 8: As-built Deficiencies
- Attachment #9: Supplemental Stringer Detail at Bent 4
- Attachment #10: Project Log of Test Boring