Collapse Scene Investigation (CSI) Carmel River Bridge Failure

Catherine M.C. Avila, P.E., D.WRE, MSCE, MBA

Member of ISSMGE, President, Avila and Associates Consulting Engineers, Inc.,

(San Francisco, CA, USA)
E-mail: cavila@avilaassociates.com

The Collapse of the 1995 Highway 1 Bridge in 1995 caused a 400 km detour to get around the collapsed bridge. The clues from design and maintenance reports will be followed including channel bed degradation and local scour estimates to determine the cause of the bridge failure and potential missed opportunities to fix the bridge before it collapsed. The economic consequences of the bridge failure including lost opportunity cost will be summarized.

Key Words : *Carmel River, Bridge Scour Failure, Detour Cost, Temporary Bridges*

1. Following the Clues

(1) Setting the Scene

The project site is located just outside of the City of Carmel located in Monterey County in Central California as shown in Figure 1.

Figure 1: Location Map within California

As shown in Figure 2, there have been three state highway bridges at the site and a pedestrian bridge is proposed.

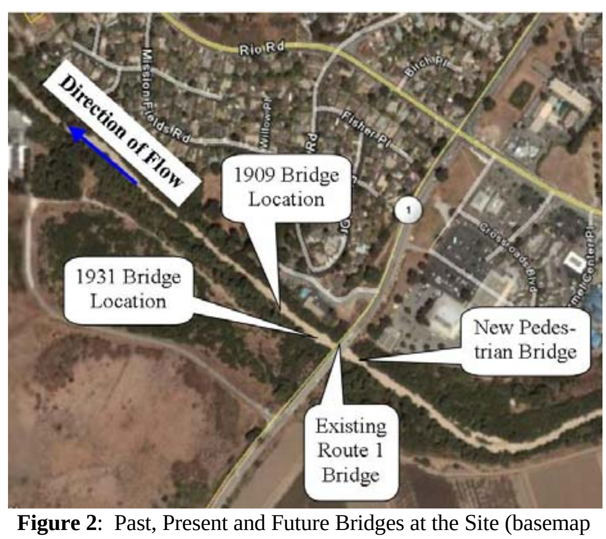

Figure 2: Past, Present and Future Bridges at the Site (basemap from googleearth.com).

The earliest bridge with records available was constructed in 1909. This 1909 timber bridge was replaced in 1934 with a bridge upstream because the timber piles and deck were rotting and the bridge was settling. The 1934 bridge was replaced in 1995 with a reinforced concrete box girder bridge upstream when three spans of the 1934 bridge washed into the river on March 10, 1995. A pedestrian bridge is currently proposed upstream of the 1995 Route 1 Bridge as part of a pedestrian and bicycle corridor planned by the Transportation Agency of Monterey County (TAMC).

The Carmel River is a central California coastal stream that drains a 23.7 sq meters watershed to the Pacific Ocean (Figure 3). The river has two dams on its mainstem: the 25.9 m high San Clemente Dam located at Rivermile (RM) 18.6 and the 42.1 m high Los Padres Dam located at RM 23.5.

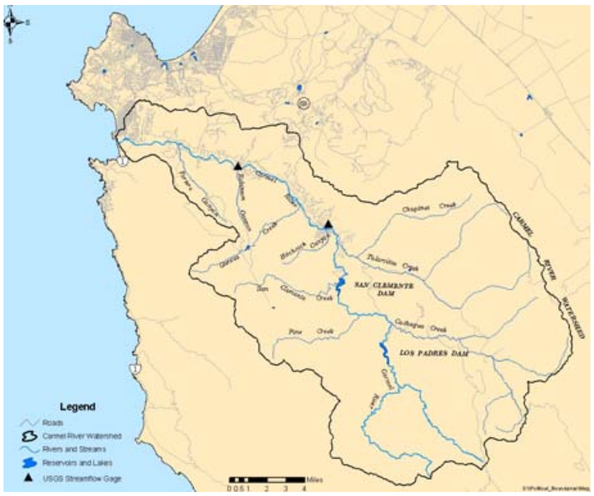

Figure 3. Carmel River Basin (from Monterey Peninsula Water Management District).

The gage upstream of the bridge (Carmel River near Carmel, Gage #11143250) has been in place since 1964. The highest recorded discharge was 453 cubic meters per second (cms) on March 10, 1995 when the bridge failed as shown in Figure 4.

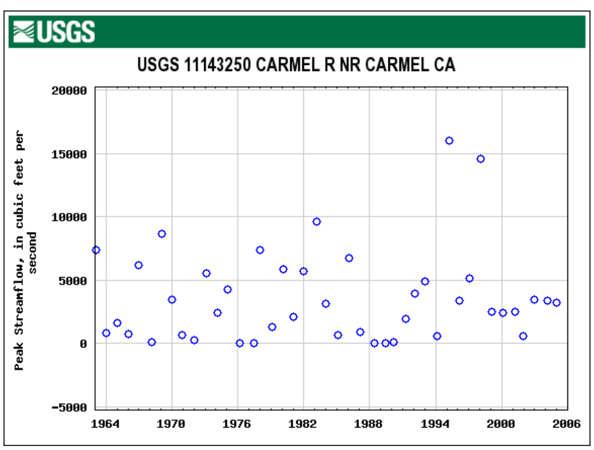

Figure 4: Discharges at the Carmel River Gage near Carmel (note discharges in cubic feet per second)

The FEMA study estimated the 50-year discharge to be 651 cms and 100-year discharge to be 824 cms (FEMA, 1991). The March 10, 1995 discharge of 453 cms equates to approximately a 30-year discharge assuming the above hydrology is valid. The proposed pedestrian and bicycle bridge over the Carmel River provides an excellent opportunity to see if the forensic clues that led to the March 10, 1995 Carmel River bridge failure can be used to enhance the longevity and survivability of the new bridge under a variety of flood events.

(2) Clue #1: 1934 Bridge Design

The 1934 Carmel River Bridge was constructed approximately 43 m upstream of a timber through truss and trestle spans constructed in 1909. The bridge had four 20.1 m timber through trusses on "mass concrete" on timber piles in the main channel and eleven 6.7 m timber trestle spans on timber piles. The old bridge was 155.4 m long and 5.5 m wide and had a soffit elevation of 7.4 m. Note all elevations are in National Geodetic Vertical Datum of 1929 which is the datum of the as-built plans for the 1934 bridge.

The 1909 bridge was replaced because the piles under the trestle and other parts of the bridge were badly rotted out making the bridge structurally unsafe. The north pier had settled .3 m or more and the trusses had been blocked up (to prevent more settlement). The waterway under the trestle portion had been seriously encroached upon by a network of bracing placed there not long before. (State of California, 1931).

The 1934 bridge was designed for a 75-year discharge of 496 cms – only slightly larger than the 453 cms that destroyed the bridge. At the time of the bridge design, there were no dams on the Carmel River, and the "high-water" was estimated to be at elevation 6.1 m. The soffit elevation was recommended at 6.7 m while another portion of the report notes that the "elevation of high-water taken from contour map on data by Mr. Mitchell, 22.0" (State of California, 1931).

The bridge which was designed was made longer (158.5 m instead of the proposed 146.3 m) than the preliminary recommendations. In addition, a vertical curve with a maximum soffit elevation of 7.9 m and minimum soffit elevation of 7.6 m was added provided as shown in Figure 5.

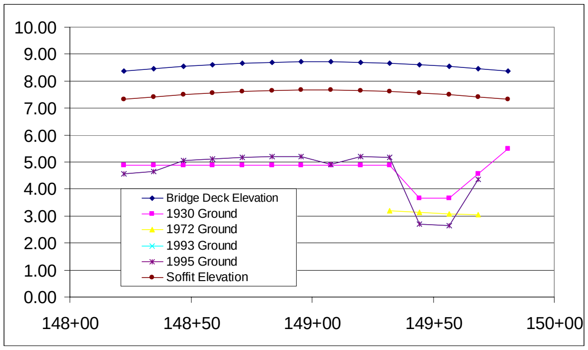

Figure 5: Ground Elevations and Profile of the 1934 Bridge (meters)

The 1934 bridge was designed assuming no cutting down (degradation) and probable silting up, given its proximity to the ocean. Interestingly, the proposed materials for the bridge were gravel transported by rail from Monterey as well as sand from the streambed. The report noted an open commercial sand pit 183 m upstream of the bridge. This may have contributed to the degradation noted below.

(3) Clue #2: Maintenance Records

The maintenance records for the 1934 bridge (Caltrans, August 1995) indicate significant drift caught on the piers between 1955 and 1986. In 1972, the encroachment of a cultivated field encroaching into the waterway between Abutment 1 and Pier 10 was detailed. This encroachment prompted the inspector to decrease the waterway adequacy of the bridge, and may have contributed to the amount of water flowing under the bridge instead of out into the historic floodplain. In 1958, structural damage of Piers 11 and 12 was detailed, and the upstream pile of Pier 6 was also knocked out of plumb. Later in 1977, the 5th pile in the bent is noted as being cracked and Pier 12 was the first pier to fail in 1955. The 1991 report notes that the bridge was placed in the maintenance program for pile encasement of Piers 10, 11 and 12 (the bridge predated the Caltrans Scour Countermeasure program which started in 1997).

(4) Clue #3: Cross Sections

A cross section was taken on March 2, 1995, just 8 days before the bridge failed. According to the cross section information (see Figure 5), the river degraded approximately 1-meter between 1931 and 1995. The degradation decreased the pile embedment from it original 5 m at Pier 12 and 5.4 m at Pier 11 to 4 m at Pier 12 and 4.4 m at Pier 11. The original estimated pile penetration was 5.5 m according to the 1931 Preliminary Investigations Report (State of California, 1931), which is greater than the actual penetration achieved in construction.

(5) Scene Reconstruction: Hydraulic Model

A hydraulic model (HEC-RAS) set up by Balance Hydrologics, Inc. was utilized to estimate the hydraulics at the bridge as it was in 1995. Although the model utilizes the 2007 topography, if the record discharge of 453 cms is contained in the channel, it provides an estimate of the water surface elevation and velocity for the old Highway 1 Bridge as shown in Figure 6.

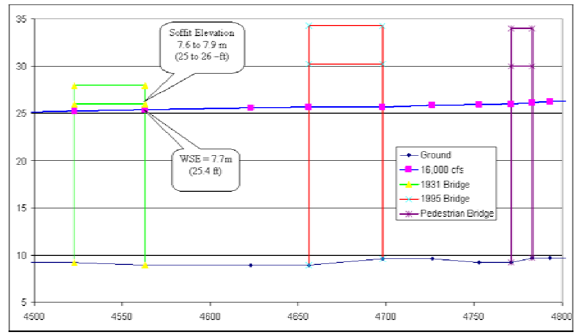

Figure 6: Output from HEC-RAS Hydraulic Model

(6) Clue #4: Debris and Pressure Flow

Debris pummeling the bridge was caught on amateur video late Friday afternoon just hours before the bridge collapsed by a local resident who commented that it "felt like an earthquake." The documented debris included debris rafts and large trees, which were over 30.5 m long with 1.8 m diameter root-balls. The water was at or near the soffit of the bridge with significant debris catching on the piers. Debris lodged on a pier can increase local scour at the pier by increasing the pier width and deflecting a component of flow downward. HEC-18 recommends estimating the scour depth by assuming the pier width is larger than the actual pier width and notes the problem is determining the increase in pier width to use in the pier scour equation. According to HEC-18, limited studies of pressure flow scour indicate that pier scour can increase 200 to 300% for a bridge under pressure flow (Richardson et. al., 2001).

With relatively small piers (0.46 m), the pier scour is 1.1 m. This leaves 3 to 3.3 m of pile embedment. If the pier width is assumed to double due to debris, the pile embedment is decreased to 1.8 to 2.1 m. Likewise, if the pier scour depth is doubled or tripled, the pile embedment is dramatically decreased.

According to the video (MPWMD, 2008), Pier 12 was the first pier to fail with 0.3 to 0.5 m of settlement showing as the bridge began to collapse.. Later video shows the complete loss of Span 12 and the tipping of Span 11 into the water. By morning, Spans 10-12 had disappeared into the river with just a downstream gas line spanning the 36.6 m opening.

(7) Follow the Clues . . .

The four factors leading to the bridge failure presented above include: Clue #1: 1934 study underestimating the discharge and potential degradation; Clue #2: Waterway encroachment and structural damage concentrating the flows and possibly weakening the bridge; Clue #3: Channel bed degradation decreasing the pile embedment; and Clue #4: Debris and pressure flow putting stress on the bridge. To sum up, the combination of relatively small pile embedment, pressure flow scour, debris and impact loading from large trees floating down the river likely caused the bridge failure.

2. Temporary and Permanent Bridges

In order to open the route to traffic as quickly as possible, a Bailey bridge which was stored at the Caltrans Maintenance yard at the San Francisco Oakland Bay Bridge was trucked down from Oakland to Carmel. The turnaround was fast: the 1934 bridge failed late Friday March 10th. The Bailey bridge was "designed" and loaded on trucks on Saturday, March 11th. The new bridge erection started on Sunday and was completed Thursday, March 16th (see Figure 7).

Figure 7: Looking downstream at Bailey Bridge Launching in March, 1995 (photo by Steve Ng, Caltrans)

The new bridge was designed while the Bailey bridge was under construction. The recommendations were 0.9 m of freeboard over the estimated water surface elevation during the 1995 storms with 30.5 m spans. Work started on the permanent bridge on April 1, 1995. It was opened to traffic on May 5, 1995 and was completed by September 1995 (the training walls were installed after traffic), as shown in Figure 8. The bridge cost almost $3.5 million U.S. dollars (Caltrans, September 1995).

Figure 8: New Highway 1 Bridge with Pier Wall Construction under way (photo by Author, 1995)

Since the bridge was constructed, significant analysis and improvements to the channel have been made. The County of Monterey is currently completing a "restudy" of the FEMA floodplain. This analysis shows a decrease in the water surface elevation due to the removal of some levees and improvement to the downstream lagoon. These improvements are lowering the anticipated water surface elevation as the channel uses more of its historic floodplain. The proposed pedestrian bridge was designed with 0.9 m of freeboard above the revised 50-year discharge to allow debris to pass under the bridge. 30.5 m long spans that line up with the downstream Route 1 Bridge were also recommended.

3. Economic Consequences

There is significant economic cost associated with channel bed degradation and lateral channel migration. This includes not only the cost of repairing or replacing the bridge, but also the lost opportunity cost associated with significant detours and/or traffic delays.

Due to the bridge wash-out, the trip from Carmel Highlands to Carmel was increased from 15 minutes to 6.5 hours due to the 400 kilometer detour (San Jose Mercury News, 1995). Some researchers have attempted to estimate the lost opportunity cost associated with detours. A 1986 study in Texas estimated the value of time to be $8.00 per vehicle-hour for drivers, $10.40 per vehicle-hour for passenger vehicles (assume 1.3 persons per vehicle) and $19.00 per vehicle-hour for trucks (McFarlan and Chui, 1986). These costs are approximately 20% higher when updated to 1996 dollars (Caltrans, 1996), or $9.60/veh-hr for drivers, $12.48/veh-hr for passenger vehicles, and $22.80/veh-hr for trucks.

Therefore, the cost to an individual driver (in 1995 U.S. dollars) to drive from Carmel Highlands to Carmel was increased from $2.40 to $62.40 when the bridge collapsed. Examining the cost of alternative transportation can validate this cost. During the 6 days between the bridge collapse and the temporary bridge erection, the only alternative to the 6.5 hour detour was a helicopter trip from one side of the river to the other taking less than 5 minutes. The $50 helicopter trip each way approximates the $60 detour "cost."

Had there not been 6 days of temporary bridge erection, there would have been an Average Daily Traffic (ADT) of 12,000 cars with 3% being trucks. At the costs described earlier, this equates to a lost opportunity cost of $5.7 million for cars and $320,000 for trucks or a total opportunity cost to the public of over $6 million. The temporary Bailey bridge restricted the traffic to one-way, causing an estimated 15-minute delay. Furthermore, to get the new bridge opened as soon possible, a $20,000 per day incentive was provided to the contractor. The bridge was completed 17 days ahead of schedule, netting the contractor a $340,000 bonus. The estimated lost opportunity cost for the 15 minute delay was $650,000 for the cars and trucks--which was twice the contractor bonus--proving that economic incentives work (Avila, 1998).

4. Conclusion

Following the clues showed that the bridge failed due to several factors: inadequate pile embedment exacerbated by channel bed degradation, a storm which brought water high enough to cause pressure flow, and significant debris pummeling the bridge. These clues provide a useful framework for evaluating existing and future bridges that face similar conditions and challenges. They also illustrate the value of bridge engineers understanding and interpreting maintenance and inspection reports during routine engineering assessments of existing bridges. In the case of the 1995 Carmel River bridge failure, a temporary bridge was quickly erected to bring the 6.5 hour detour down to approximately 15 minutes. The replacement bridge was designed and constructed ahead of schedule netting the contractor a bonus which was less than the delay "cost" to the traveling public.

5. ACKNOWLEDGMENTS

Special thanks to the following: Steve Ng, Caltrans Structure Hydraulics for bridge pictures, Lyn Wickham and Lance Gorman, and Caltrans District 5 for bridge information.

6. REFERENCES

1) Avila, Catherine Crossett, "Managing Impacts of Gravel Mining on Bridges in California (Overmining causes Undermining)" submitted in partial fulfillment of a Master of Science Degree, University of Calif. at Davis, 1998.
2) California Department of Transportation (Caltrans), Division of Structures, Bridge Maintenance Records and As-Built Plans for the Highway 1 Bridge over the Carmel River (Br #44 0013), August, 1995.
3) California Department of Transportation, "Report of Completion – Bridges for 44 0265" dated September, 1995.
4) California Department of Transportation (Caltrans), Division of Structures, 1996, "Construction Statistics".
5) Federal Emergency Management Agency, Flood Insurance Study. Monterey County, California Revised September 27, 1991.
6) http://www.mpwmd.dst.ca.us/programs/river/erosion_potential/erosion_potential.htm, 2008.
7) McFarland, William F. and Chui, Margaret K., 1986, "The Value of Travel Time: New Estimates Developed Using a Speed-Choice Model" prepared for the Texas State Department of Highways and Public Transportation.
8) Richardson, E.V., S.R. Davis, 2001, "Evaluating Scour at Bridges," Hydraulic Engineering Circular 18 Fourth Edition, FHWA NHI-01-001, Washington, D.C.
9) San Jose Mercury News, March 14, 1995.
10) State of California, Department of Public Works, Division of Highways "Preliminary Investigations Report for the proposed bridge over the Carmel River V-MON-56-H" dated February 11, 1931.

.