MILLIKEN DAM : STRUCTURAL MONITORING OF A CONCRETE ARCH DAM

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Abstract

Milliken Dam is a concrete arch dam located near Napa, California. Constructed during 1923 – 1924 with a crest length of 720 feet and a maximum structural height of 120 feet the dam is owned by the City of Napa. The dam is an overpour crest configuration with no spillway. Lift joint separation and minor cracking accompanied by seepage developed in the lowermost section of the dam concrete during first fill (1924 - 1925). Structural monitoring using several methods has been conducted to measure the behavior of the arch as the reservoir cycles. Changes in the appearance of the downstream face during the 1950's led to installation of twelve Carlson resistance wire joint meters to monitor changes in cracked or separated lift joints. Joint meter readings indicated that most crack changes occurred during the last 20 ft (6.1 m) of reservoir fill. Regular dam crest surveys were also started in 1961, but the overpour crest configuration prevented surveying of the dam during spill. To enhance monitoring of the dam, a program to establish improved crest surveying methods and to replace the Carlson joint meters was implemented by the City in 1998. The history of structural monitoring, design and installation of enhanced measurement systems, and data collected with these systems is presented.

1. Introduction

During the three decades following 1900, California experienced an unparalleled period of dam construction. While the basics of dam design and construction have not changed significantly since the 1930's, our capabilities for monitoring these structures have developed dramatically. Milliken Dam has gone through several "eras" of observation and monitoring during its history. The progression of monitoring of this dam and results of the most recent monitoring will be presented.

2. Description of Dam and Appurtenant Works

Milliken Dam is located in northern California about 50 miles northeast of San Francisco in the Coast Range geologic province (See Figure 1. Location Map). The Coast Range province is a highly seismic area with numerous large active strike slip faults. The Green Valley Fault, a major active strike-slip fault first recognized in 1982, is about one mile (1.6 km) east of Milliken Dam. Owned by the City of Napa, Milliken Dam is located on Milliken Creek on the eastern flank of the Napa Valley. The Milliken Creek watershed receives virtually all of its 30-inch (0.8 m) annual rainfall in the winter months when storms sweep in from the northern Pacific Ocean. Milliken Dam impounds a 1980 acre-foot (2.44 million cu.m.) reservoir at maximum reservoir elevation of 923 feet (281.4 m). Water from Milliken Reservoir accounts for about 5% of the City's total supply and is used primarily for peak leveling during the high-demand summer months. Water released from Milliken Reservoir flows back into the creek and is intercepted at a side-channel intake about one mile downstream where it is treated for delivery to the City's distribution system. Most of the City's water comes from another City-owned reservoir, Lake Hennessy, and state water project deliveries via Barker Slough Pump Station located east of Fairfield. Each City water source has its own treatment plant.

Milliken Dam is a concrete dam with a constant radius curved center section and linear left and right gravity sections. The dam was cast in a total of seven sections separated by reinforced

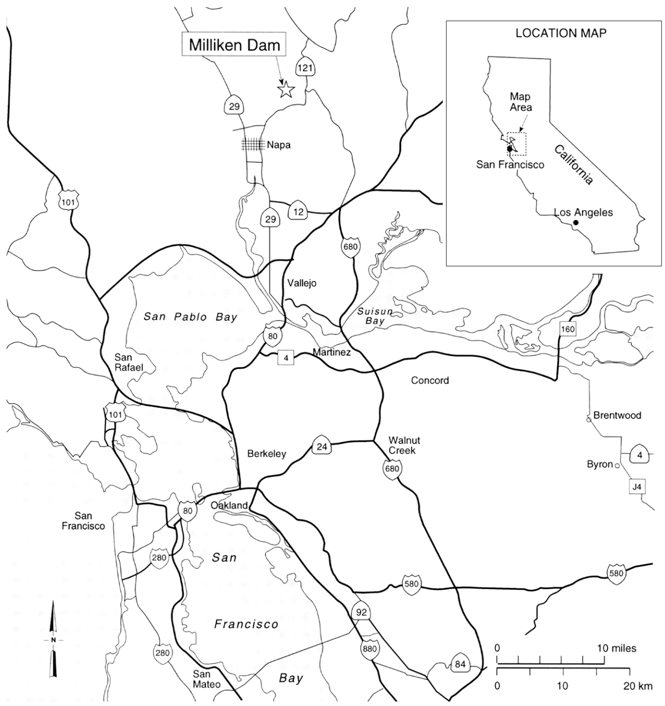

Figure 1. Location Map

vertical keyed contraction joints. The dam was constructed during 1923 –1924 for the City of Napa. The crest length is 720 feet (219.5 m) with centerline stationing extending from 0+00 to 7+20. The arch center section has a crest length of 440 feet (134.2). The left and right gravity sections are monolithic while the central arch section was cast in five panels. The maximum structural height of the dam is 120 feet (36.6 m). The upstream face of the dam is vertical and the downstream face slopes at 1:3. The dam is approximately 37 feet (11.2 m) wide at the base and tapers to 2.5 feet (0.8 m) wide 5 feet (1.5 m) below the crest elevation of 923 ft (281.4 m). There is a thickened section, 3.5 ft (1.1 m) wide along the entire length of the crest. Milliken Dam is a design referred to as an overpour crest. There is no separate spillway so the reservoir spills across the entire length of the crest. Along the crest is a series of integrally cast bench-like blocks called aeration piers that interrupt the nap of water spilling over the crest. The intake is a free-standing, 9-foot outside diameter (2.7 m) cylindrical tower located immediately upstream of the dam at the maximum section. The top elevation of the intake tower is 923 feet (281.4 m), the same elevation as the crest. The intake tower has seven 12-inch diameter ports at elevations ranging from 814 ft to 917 ft with internally mounted gate valves. The valves are operated manually from the top of the intake tower. A 24-inch cast iron outlet pipe extends from the base of the intake tower, through the dam, and terminates in a valve box at the downstream toe of the dam. The valve box contains an 18-inch downstream control gate valve for emergency releases and an 8-inch auxiliary gate valve for normal streamflow releases.

3. Dam Monitoring (1924 – 1955)

Monitoring of Milliken Dam during the first thirty years of operation consisted of regular visual observation and inspections. Milliken Dam was completed before the Division of Safety of Dams (DSOD) was created within the State of California Department Water Resources in 1930. Design drawings and specifications were submitted to the State for review even though there was no official dam safety organization at the time. Once the DSOD was formed, Milliken Dam became a jurisdictional dam (No. 7 in the state's roster) and monitoring of the dam in the form of annual visits was conducted by the DSOD.

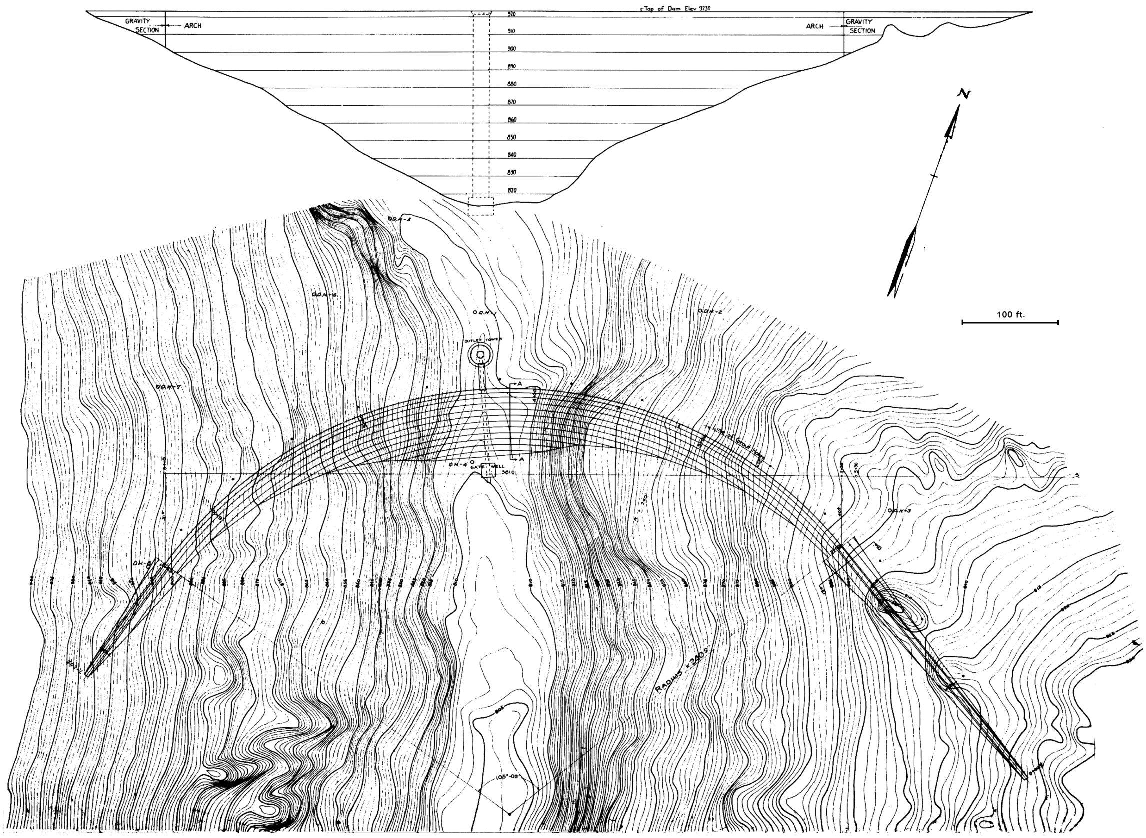

Figure 2. Plan and Profile of dam from original contract drawings.

During first fill in 1925, seepage along approximately six horizontal features identified as cracked or separated lift joints was observed on the downstream face of the dam. Seepage initially described by the DSOD as "very considerable leakage" declined to "minor" by 1931. Cracking in the lower block (inner gorge) section of the dam changed very slowly during the next 25 years according to DSOD inspection reports. Spalling of an approximately 10-foot-long, wedge-shaped block from the lower downstream face was observed by DSOD inspectors in 1954.

4. Crack Monitoring (1956)

The spalled block from the downstream face observed in 1954 suggested to the DSOD that the dam might be undergoing changes or deformation leading to stress concentration at the downstream face. A system of downstream face survey points was designed and installed in 1956. Four pairs of survey points were attached to the lower downstream face of the dam to measure possible differential movement across three selected lift-line cracks. The survey points consisted of brass rods with spherical ends set into the dam face about three feet apart along a vertical line. A reading instrument composed of a triangular steel frame with a horizontal micrometer attached to the top rail was fabricated to measure horizontal movements. After a few readings, it was concluded that the survey point system produced "valueless" readings because the survey points were being deformed by impact from falling debris when the reservoir spilled.

5. Joint Meter Installation (1959)

The City's experience with the downstream face survey points is typical of dam instrumentation and presents a lesson to be learned. Dams and their surroundings are, even in mild climates like northern California, fairly hostile environments for any kind of measuring or monitoring device.

The odds of successful monitoring and longevity of the instruments are very low unless the instruments can be adequately protected. Once it was concluded that manual observation of dam deformation was not workable, the search for another approach began. A professor at the University of California Berkeley provided the solution. Professor Carlson had developed a new type of electrical instrument that was capable of measuring very small deformations in concrete structures. The meter consisted of a spring-tensioned resistance wire attached to the two opposing ends of a nested cylinder body sealed with a bronze bellows. Changes in the length of the cylinder body resulted in changes in resistance of the tensioned wire. The meter was very sensitive, with a resolution of 0.001-inch.

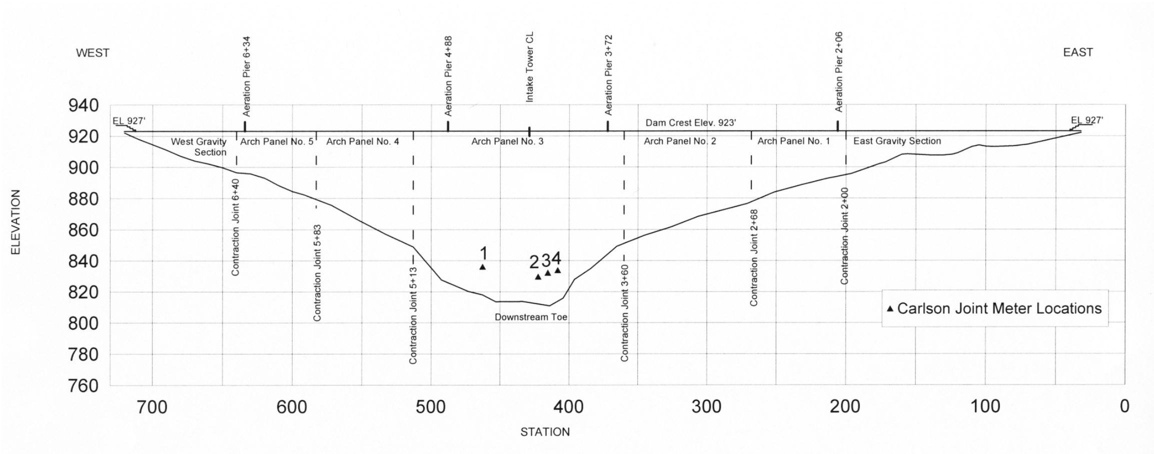

Figure 3. Developed Downstream Face Profile (viewed looking upstream). Meter locations No.1 and No. 4 have meter pairs at the upstream and downstream faces.

The monitoring system consisted of twelve Carlson joint meters installed in orthogonal pairs at six different horizontal crack locations, four on the downstream face and two on the upstream face. (See Figure 3, Developed Downstream Face Profile) Each meter pair was designed to measure vertical and upstream/downstream horizontal movement across the selected crack. The meters were installed in adits carved into the dam concrete so that the floor of the adit was a cracked (separated) lift line. The heavy gauge, multistrand cable attached to each meter was routed overhead to a shed on the right abutment above the dam containing the readout meter system. The Carlson meters functioned properly at first. Meter readings indicated crack changes were typically in the 0.01-inch range. The joint meters at Sta 4+66 (Elevation 835) showed larger movements than the other meters, with maximum meter readings in the 0.1-inch range. Also, the readings showed that most of the crack changes occurred during the uppermost 20 feet (6.1 m) of reservoir fill. After the first winter cycle, the upstream meters began to give readings indicating possible meter malfunction. The upstream meters were replaced the next year and the readings were continued. The meters and cabling system ultimately proved to be vulnerable to the elements. The replacement upstream meters showed signs of suspected water invasion after a few years. The downstream meter installations were repeatedly damaged by falling water and debris when the reservoir spilled. The upstream overhead cables were severed during high winds one winter shortly after installation. The cables were repaired, but the cables were not coded so it was never certain whether the meters were attached to the correct cable.

6. Dam Crest Surveying (1961)

Optical crest surveying is a common dam monitoring technique that can provide important information about the net deformation of a structure as the reservoir loading changes. A crest surveying protocol was established for Milliken Dam during the late 1950's. The survey system consisted of control points located on both abutments and three tacks set flush in the crest of the dam. Dam deformation was measured by manually observing offset from a fixed sight line established by a single reference point on the right abutment and three separate monuments on the left abutment upstream of the dam. Surveys collected in 1961 indicated the dam crest was deforming downstream on the order of one inch near the maximum height with the reservoir near spill. The dam surveys would prove to be difficult for several reasons: 1) the surveys were labor intensive, 2) the readings were highly influenced by human error (plumb bobs were used for sighting), 3) the dam could not be surveyed during spill because the crest survey points were under water.

7. Instrumentation Program (1998)

The City of Napa implemented a program to improve monitoring of Milliken Dam in 1998. URS worked closely with the City and the DSOD to establish an overall plan for consistent safety monitoring and identify specific short-term and long-term goals to achieve the monitoring program. Three primary goals were identified: 1) Conduct a comprehensive crack map of the dam, 2) Establish an improved surveying protocol, and 3) Reestablish monitoring of selected cracks.

7.1 Crack Mapping

Milliken Dam was inspected by URS in November 1998. The reservoir was at Elev. 885.6, approximately 38 feet below the crest of the dam. Following are conclusions based on a review of the DSOD's files and the URS crack pattern observations conducted during 1998: 1) Both Gravity Sections have through-going vertical cracks. The East Gravity Section has four cracks each spaced about 40 feet apart and the West Gravity Section has one through-going crack and one crest crack, 2) The horizontal crack and spalling patterns observed in the lower dam section during the 1950's have changed slightly based on a comparison of the existing conditions and DSOD inspection reports, 3) The vertical crest cracking patterns in Arch Panel No. 3 appear to continue to propagate based on comparisons of crack maps and photographs dating from 1930, 4) The vertical cracks near the maximum section are through-crest cracks and are roughly symmetrical about the intake tower centerline, 5) A series of horizontal cracks near Elev. 845 appears to have developed left of the maximum section since the 1959 crack mapping. Minor spalling appears to be developing along this pattern, 6) A new set of diagonal cracks was first noted in 1994. These cracks are apparently discontinuous, occurring as a group of laterally stepping features that are usually associated with seepage. These cracks dip steeply into the dam and possibly intersect the foundation upstream and left of the DS face or intersect the contraction joint, 7) Two of the contraction joints (CJ4 and CJ5) show signs of cracking at the dam crest. CJ4 is cracked through the key stem between the panels while CJ5 shows signs of cracking around the key area, but does not appear to be cracked through the key stem.

7.2 Survey Monuments

Two key requirements were identified for establishing a new survey network at Milliken Dam: 1) surveying must be conducted from the right abutment only with no need to access the crest of the dam during spill, 2) surveying must be possible at any time when the reservoir is spilling. When the reservoir spills, the entire crest is covered by flowing water that is normally up to 1.5 feet deep. Three elements were needed for implementation of the new survey system: 1) a new survey base station location, 2) new dam-mounted survey monuments, and 3) off-dam control monuments.

A new survey base station was established on a large concrete footing embedded in the hillside above the right abutment. The footing, approximately 4 ft (1.2 m) square with a flat top surface, was part of a foundation for large machinery during construction. A brass monument was set in the center of the footing and three stainless steel expansion anchors set flush with the surface to accept the tripod feet. This would enable the surveyor to set up, center his instrument, and maintain location even in adverse weather and darkness.

Crest guard rails limiting sight lines and flowing water over the crest during spill made designing and locating new crest survey points difficult. Since the four aeration piers located along the crest were all visible from the new base station location, a 25 mm yoke-mounted target prism was mounted on each pier. Additional survey points were required to measure crest deflections adequately. After considering several alternative designs, post-mounted targets were installed. Since the only access to the left abutment is across the crest, the post-mounted targets had to be removable. A three-section post design made from specially threaded 4-inch heavy-walled stainless steel well casing was fabricated. The posts consisted of a female threaded base section 2.5 feet long set flush with the dam concrete in a six-inch diameter cored hole. The main post section was fabricated with male threads at both ends. A special female-threaded blank top cap was fabricated to accept the target mounting yoke. Four of the post-mounted targets were installed on the crest of the dam in late 1998.

Three off-dam control monuments were also established. Two monuments consisting of 50 mm yoke-mounted target prisms were mounted on bedrock outcrops upstream of the dam on the left side of the reservoir. On the right abutment upstream of the survey base station, a flush-mounted pin was set in a concrete pier in the access road. Sight-line and rock slope conditions made this the only feasible choice.

7.3 Crack Meters

The two meter pair locations that had measured the largest apparent deformations in the 1960's were selected for installing new meters (See Figure 4, Crack Meter Installation Locations). After evaluating several alternative designs, a meter design based on vibrating wire technology was chosen. Vibrating wire meters offered significant installation and operational advantages over the original Carlson meters: 1) Not affected by wire length adjustments, 2) Large measurement range combined with high resolution, 3) Stable meter calibrations (very low drift), 4) All stainless steel construction, 5) Designed for submerged operation.

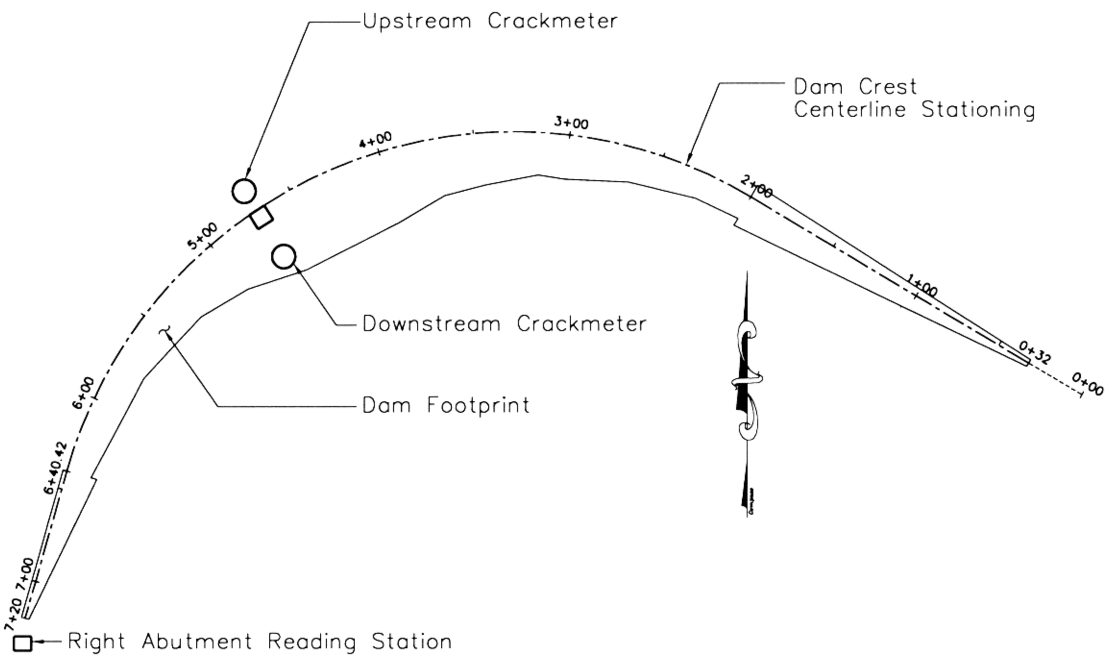

Figure 4. Crack Meter Installation Locations (1998)

The original adit cut into the dam for the Carlson meters was selected for the downstream meters. Most of the original installation at this location had been destroyed by falling water and debris.

To prepare the adit, the remaining filler concrete was chipped out and new holes were drilled for the threaded anchors used to attach the new meter assembly. A stainless steel mounting bracket assembly was fabricated and bolted into the adit to accept vertical and horizontal meters. A heavy-gauge stainless steel cover was then bolted to the dam concrete to cover the adit.

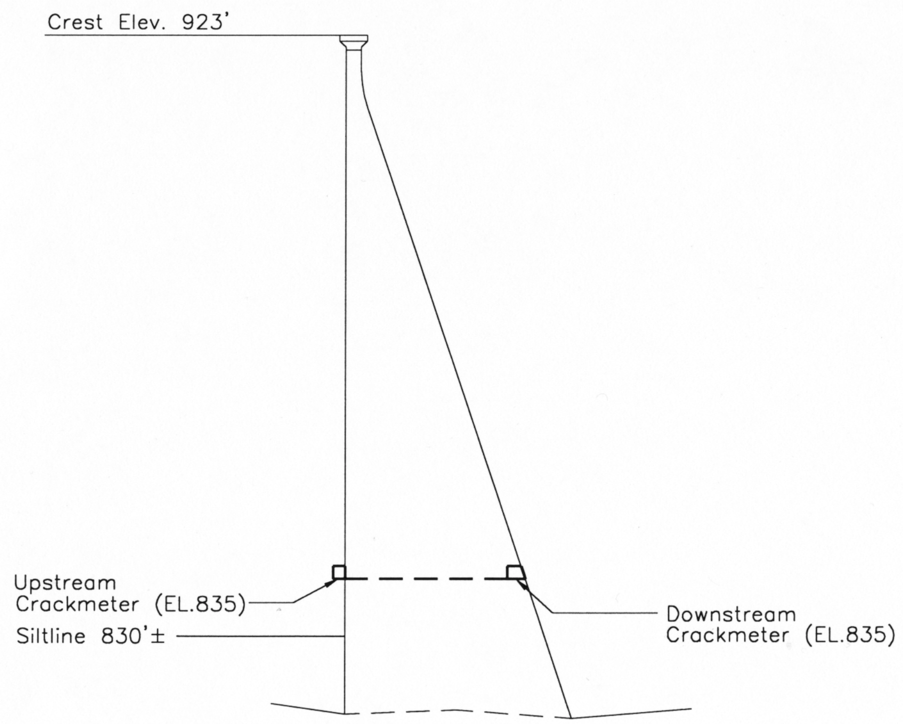

Figure 5. Profile of Milliken Dam showing new vibrating wire meter locations. The dashed line is the estimated location of the separated or cracked lift line.

Lowering the reservoir below the upstream meter elevation was not feasible, so the meter installation was planned using a diving team. The upstream meters were designed to be surface-mounted on the vertical upstream face of the dam since visibility was low. Working from a basic meter bracket design concept, Geokon developed a pre-assembled bracket on which the meters would be mounted and calibrated by the engineer at the surface. Using a special template, the divers installed eight stainless steel threaded anchors and then set the bracket assembly onto the anchors. After tightening the anchors, the two bracket halves were separated by removing the temporary straps.

8.0 Monitoring Results (1999 – 2001)

All of the crack meters were installed and operational by mid November 1999. The reservoir level at installation was 869.5 feet, the seasonal low for the 1999 – 2000 water year. Following meter installation, there was a period of warm, dry weather extending into February 2000. This provided an excellent opportunity to collect meter readings when the reservoir elevation was changing very slowly. Assessing the as-built temperature coefficient of meter installations is typically a very difficult and imprecise task. In this case, all of the elements for a reliable, statistically-based approach to temperature correction were present. Since the external loading on the dam (the reservoir) was changing very little, changes in the meter readings could be ascribed to dam concrete thermal effects and the temperature characteristic of the meter system. The upstream meters experienced small temperature swings while the downstream meters experienced larger daily changes caused by solar heating.

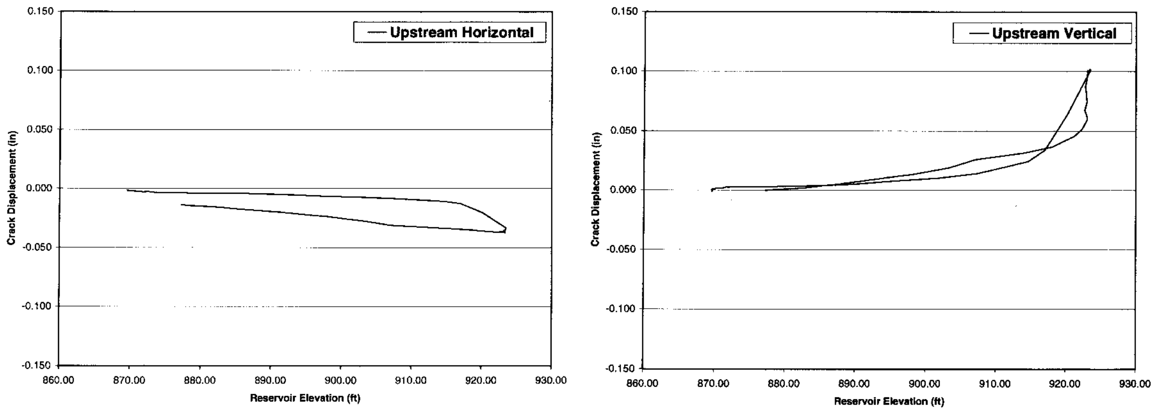

Figure 6. Upstream Vibrating Wire Crack Meter Readings. Horizontal displacements are on the left and vertical displacements on the right. Readings for the downstream horizontal meter are similar to the upstream meter readings.

Figure 6 shows the reduced temperature-corrected upstream meter data during the period of November 1999 to September 2000. The vertical meter readings indicate that the crack aperture increases about 0.1-inch (2.5 mm) at the upstream dam face when the reservoir changes from 869.5 ft to 923.1 ft. The upstream horizontal meter readings show the upper part of the dam moving downstream about 0.04-inch relative to the lower part of the dam. Most of the deformations occur during the last 20 feet of reservoir filling. This is a pattern observed in the previous meter readings as well as the current survey data. It is also interesting to note that, as the reservoir elevation declines, the meter readings do not follow the same path, giving the initial impression that the crack may not return to its original position at the beginning of the reading cycle. As the reservoir elevation declines, the meter readings appear to be returning to the previous initial readings. These patterns suggest that changes in the cracks for this reservoir cycle do not appear progressive.

The City of Napa purchased a new Topcon GTS-311 automatic total station instrument in conjunction with the dam survey grid project. New survey grid baselines were established in January 1999. Since then, the grid has been surveyed more than 25 times over a range of reservoir levels. The survey data (originally collected as northing and easting data) has been reduced to radial and tangential vectors relative to the dam to better assess deformations. Figure 7 (following page) shows the radial and tangential data plotted for survey monument No. 5, near the center of the dam. The upper curve is a plot of the reservoir elevation over the period monitored. Note that the reservoir declines gradually during the spring and summer when water is being released through the outlet works. Reservoir fill is typically very fast as the plot shows in early 2000. The middle plot in Figure 7 shows the radial component of the survey data collected over the same period, ie. the component of the data in the direction of the center of the arch. The net downstream deflection of the crest at the survey monument is approximately 1-inch, similar to the deflections measured using the original lead tack survey points set flush in the crest of the dam. The third curve is the calculated tangential component of the survey data. This is the component parallel to the arch at the survey monument location. The tangential component of the data can be seen to be relatively small compared to the radial component, typical of concrete dams.

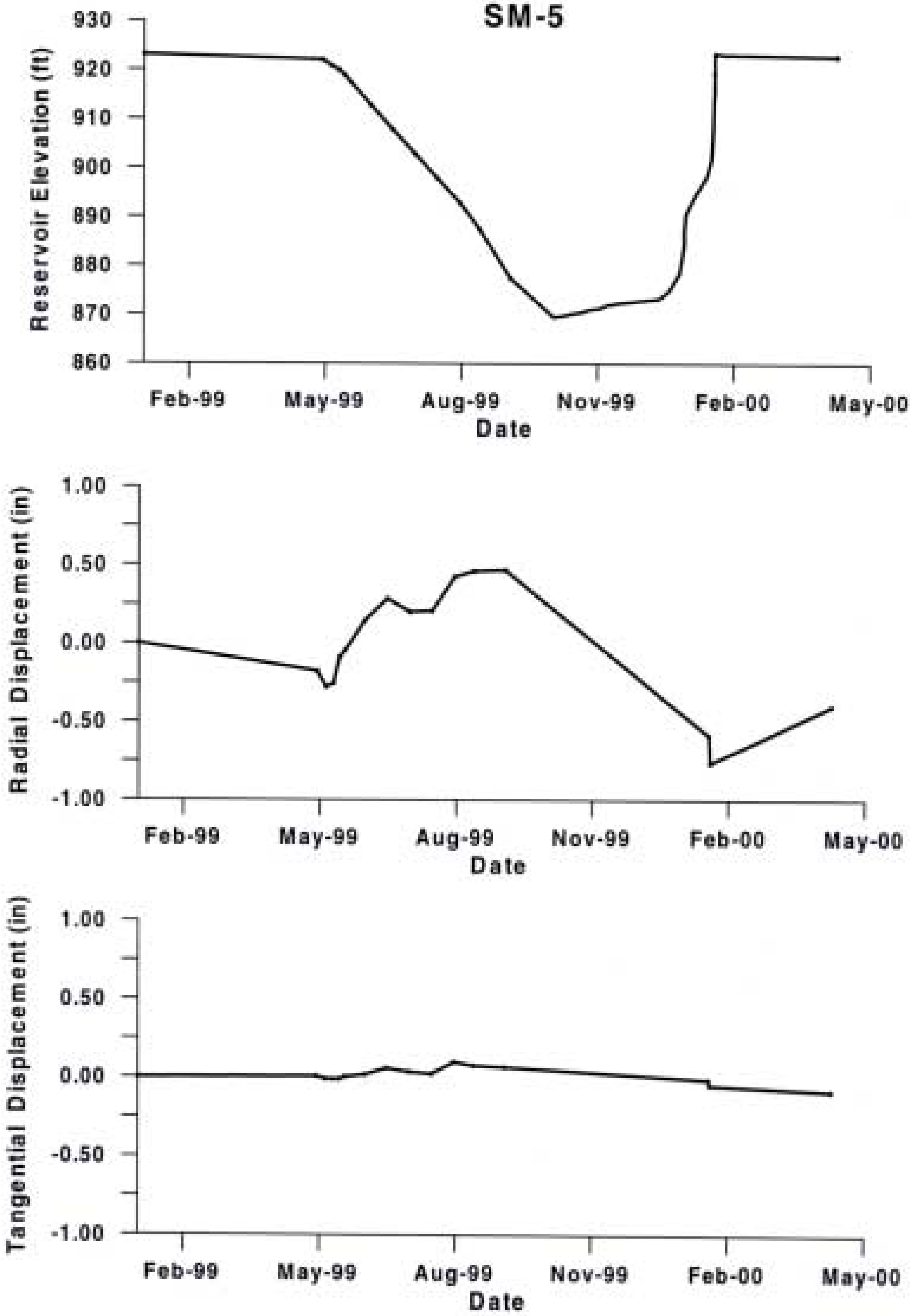

Figure 7. Survey Monument Reading Results at SM-5, near the maximum section of the dam.

9. Conclusion

Visual observation of Milliken Dam since the 1930's confirms that changes in its appearance have been very gradual. Recent crack mapping of the dam does show that the cracking pattern established years ago has developed or matured only slightly. While cracks in concrete dams are not unusual and all dams deform when loaded by the reservoir, it is the pattern of measured dam deformation that has been an issue at Milliken Dam. The pattern of onset of deformations near spill has been noticed by State inspection staff over the years and has been the source of questions regarding the performance of the dam. However, instrumentation and crest survey data has consistently provided evidence that deformations resulting from static loading conditions are likely not progressive and do not represent a concern for the safe operation of the dam. Advancements in our monitoring capabilities, while they have not changed our assessment of Milliken Dam, enable the City to once again keep close track of dam performance. Consistency in observation and measurement has proven in the long run to be the City of Napa's most powerful tool in the continuing effort to assess the operational safety of Milliken Dam.