SONIC PULSE VELOCITY TESTING TO ASSESS CONDITION OF A CONCRETE DAM

Edward D. Billington, AG&E-Schnabel, Greensboro, NC
Dennis A. Sack and Larry D. Olson, Olson Engineering Inc., Wheat Ridge, CO

Abstract

A velocity analysis was performed to assess the condition of a concrete arch dam in western North Carolina. Sonic pulse velocity (SPV) measurements were made at 28 locations along the dam by impacting the downstream face and recording arrival times on the upstream face. The sonic energy was generating using a remotely operated impact source specifically designed for the project that could be lowered from the dam crest. The compressional wave energy was recorded using a string of hydrophones on the upstream face of the dam. A tomographic analysis of the arrival time data was performed to generate cross sections at each station to show the velocity distribution through the dam. An underwater inspection of the upstream face provided the opportunity to correlate velocity anomalies with diver observations. The results of the velocity analysis will serve as a baseline for future assessments of the dam.

Introduction

Lake Logan Dam is located in Haywood County, North Carolina, on the West Fork Pigeon River, approximately 13.4 miles upstream from Canton, North Carolina. located in Haywood County, NC. The dam, constructed about 1931, is a concrete arch structure approximately 560 feet long with a maximum height of about 64 feet (Figure 1). The dam impounds approximately 2,068 acre-feet and has been assigned a high hazard classification by the North Carolina Department of Environment and Natural Resources (NCDENR). The impoundment serves as water supply for the Blue Ridge Paper Products paper mill in Canton, NC. There is also a fish hatchery downstream of the dam that draws fresh water from a set of intake pipes.

The dam arc is 130 degrees with a radius of 237.2 feet. The upper 14.25 feet of the dam has a crest thickness varying from 4 feet at the center to 6 feet at the abutments. The upstream face of the dam is vertical and the downstream face has a batter of 3.625 horizontal to 12 vertical. The dam is approximately 18 feet thick at the base. The construction drawings indicate that the dam was constructed in lifts and blocks with horizontal and vertical construction joints. These drawings also indicate 26 gage copper waterstops at horizontal and vertical construction joints.

Prior Repairs and Investigations

Concrete Repairs

A storm of record in August 1940 overtopped the dam and resulted in significant scour at the toe of the dam. Holes were eroded in the concrete in the dam face and in the concrete splash apron. The holes were patched with concrete. Around 1986, the lake water level was very low, allowing inspection of the upstream face. A number of open vertical and horizontal joints and some honeycombed areas were patched with epoxy mortar at that time. These open joints may have been related to some seepage on the downstream face.

Figure 1. Lake Logan Dam (view from left abutment)

Previous Ultrasonic Tests

Ultrasonic tests were performed on the Lake Logan Dam in 1974 and 1986 to determine the condition of the mass concrete of the dam (Law Engineering Testing Co., 1974 and 1986). These tests were reported to follow the ASTM Standard Test Method for Pulse Velocity Through Concrete, C-597-61. The tests were conducted at 28 stations along the dam. Ultrasonic pulse velocities were determined at interval of 2 to 5 feet by placing single transducers on either side of the dam and recording the acoustic signal transmitted through the dam. The underwater transducer was placed in a carriage and lowered down the upstream face. The transducer was positioned on the downstream face by lowering a person in a bosun's chair.

The ultrasonic tests in 1974 and 1986 were used to determine the compressional pulse velocity of each ray path. For each of the approximately 8 source locations on the downstream face, there were two receiver locations, giving a total of about 126 raypaths for analysis. In addition to recording the time delay, the attenuation of the signal was also considered. The majority of the compressional pulse velocities ranged from 12,000) to 15,000 feet per second (fps), indicating good quality concrete (see Table 1 below). Several velocities were measured below 12,000 fps and, in several other locations, no signal was detected.

While the results of the 1974 and 1986 tests indicated that the majority of the concrete was in good condition, several questions were left unanswered. Namely, the location and extent of the lower-velocity concrete areas were not well defined. These questions were addressed in the 1998 investigation.

November 1998 Sonic Pulse Velocity Testing

Sonic pulse velocity (SPV) testing was conducted by Applied Geosciences and Engineering Inc. (now AG&E-Schnabel, a Division of Schnabel Engineering Associates, Inc.) in October 1998 to evaluate the condition of the concrete at the Lake Logan Dam. Data acquisition and processing were provided by Olson Engineering Inc.

Purpose of Investigation

After the initial ultrasonic evaluation in 1974, the Lake Logan Dam owner decided to conduct velocity tests about every 10 years to assess the condition of the mass concrete in the dam. The correlation between concrete quality and velocity is well known; the higher the velocity, the better the concrete quality. The correlation table used in this analysis is provided below:

Table 1. Quality of Concrete and Pulse Velocity
(after Leslie and Cheeseman, 1949)

General Conditions	Pulse Velocity (ft/sec)
Excellent	Above 15,000
Good	12,000 - 15,000
Questionable	10,000 - 12,000
Poor	7,000 - 10,000
Very Poor	Below 7,000

The correlation shown in Table 1 is useful as a general guideline. However, the relationship between strength and velocity is site-dependent and varies with several factors, including age of concrete, quantity and orientation of reinforcing steel, and degree of saturation of concrete. A direct correlation between velocity and concrete quality for a specific site requires sampling and testing of the concrete.

Data Acquisition

The field testing was performed from October 5 through 9, 1998. Tests were delayed on Wednesday, October 7 due to heavy rain. Prior to the rain on October 7, the water level was approximately 6 feet below the top of the flashboards; following the rain, the lake level rose to about 1.2 feet below the top of the flashboards by Friday, October 9.

The SPV tests were conducted at 28 stations along the dam centerline, approximately the same locations that were tested during the previous investigation in 1985 (Law Engineering Testing Co., 1986). At each station, a sonic impact source was lowered vertically down the downstream face of the dam and used to generate sonic pulses at 3 feet intervals (Figure 2). The sonic source was a solenoid-operated impactor mounted on a rolling carriage suspended from a rope and rolled down the downstream face of the dam. The solenoid impactor allowed the transmission of high-amplitude signals that could be detected by the hydrophone string even at high source-to-receiver angles.

Figure 2. Photographs from October 1998 data acquisition. From left: Closeup of solenoid-actuated sonic impact source; lowering source from top of dam; recording data at station near left abutment. For most stations, the recording unit was in a boat.

The compressional and shear wave energy transmitted through the dam were recorded using a string of seven hydrophones held vertically against the upstream face of the dam (Figure 3). The hydrophone spacing was one meter (3.28 feet) for a total length of six meters (19.8 feet). The water depth was measured at each station to determine the number of vertical hydrophone locations necessary to get full coverage. In most cases, the hydrophone string was lowered vertically for additional tests to provide full coverage of the upstream face of the dam. The source locations were repeated for each hydrophone string location. The use of a multiple channel hydrophone string and repeated source locations provided up to 220 raypaths and velocity measurements per station A typical plot of raypath density is shown in Figure 3. The number of raypaths was less for the shallower areas nearer to the abutments.

Stationing for the tests was established by using the right end of the flashboard section as Station 1+00. This was the same stationing used for the 1985 tests. A fiberglass measuring tape was stretched from Station 1+00 along the upstream side of the flashboards. Paint marks were placed every 10 feet along the top of the flashboards as reference for the testing locations.

Problems encountered during the field work included difficulty in obtaining a sufficient signal at some locations due to buildup on the downstream dam face. In these instances, the impact source was moved slightly up or down the dam face, or slightly to either side, until a signal of sufficient amplitude was obtained. The intakes for the fish hatchery on the left side of the dam were open during the test, causing some background noise that reduced the confidence level of the first arrivals for records obtained close to the intakes.

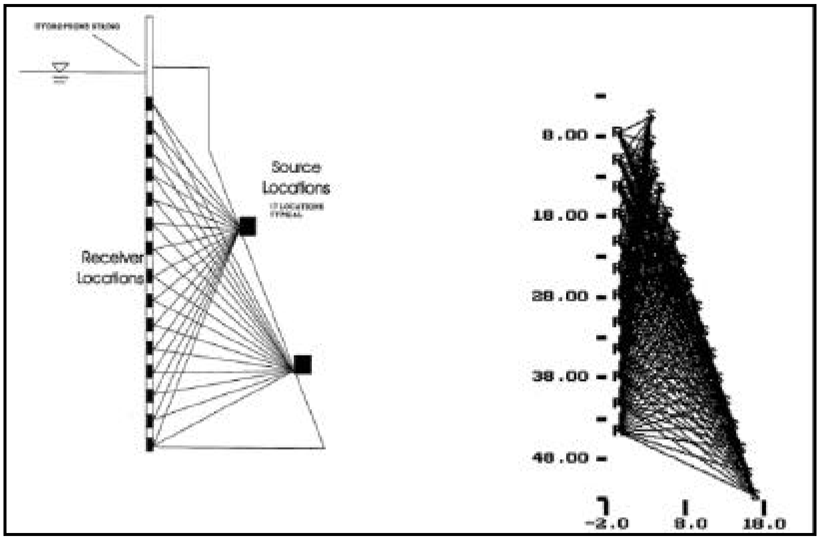

Figure 3. Schematic raypath geometry (on left) and raypath density plot for typical station.

Data Analysis

The data were recorded digitally for each measurement location. The first arrival of the compressional wave at each hydrophone was picked manually (Figure 4). In some cases, the first arrival of the shear wave energy was used where the data was too noisy to pick the first arrival of the compressional wave (Figure 5). Prior to running the tomograms, the shear wave arrival times were converted to the equivalent compressional arrival times using an empirically derived constant (Poisson's Ratio).

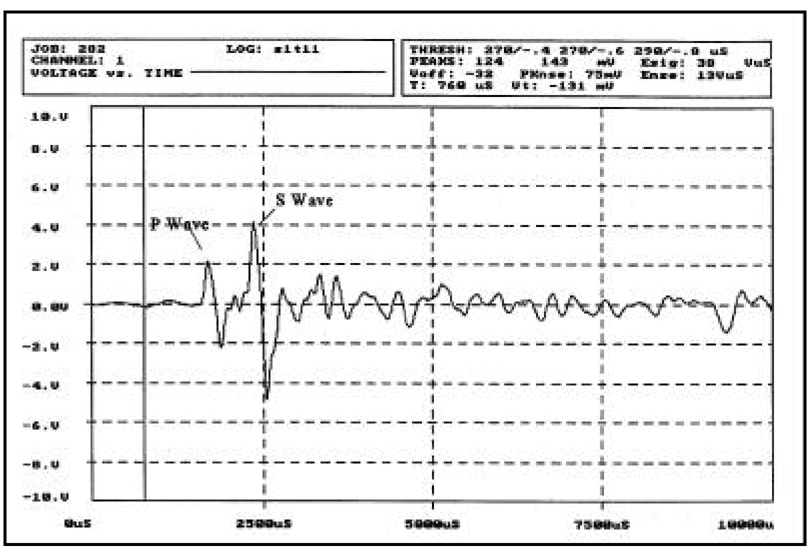

Figure 4. Example trace showing P-wave and S-wave arrivals through dam. Note high signal-to-noise ratio.

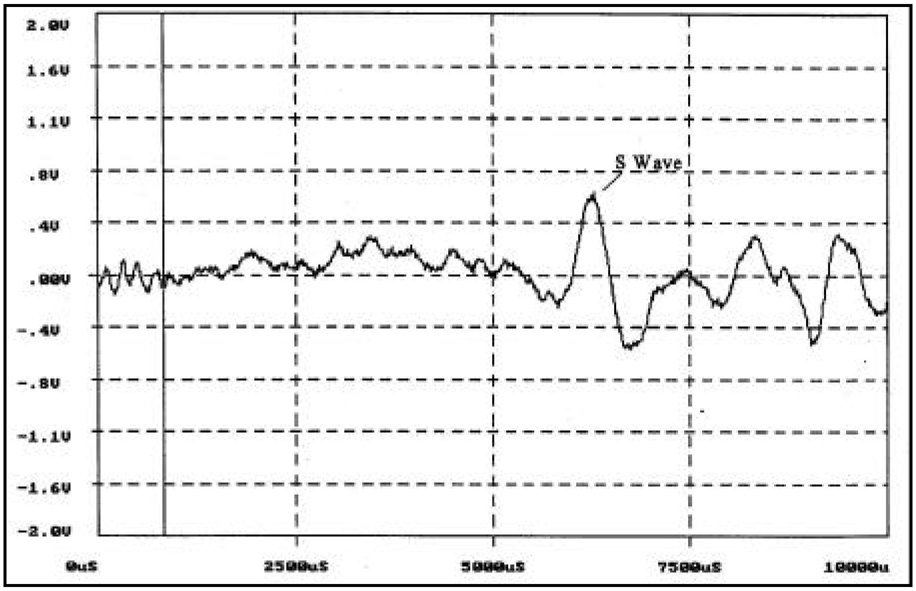

Figure 5. Example data trace showing low signal-to-noise ratio and no clear P-wave arrival. Note the strong S-wave arrival that was used in these instances.

The arrival times and dam geometry were used as input to a tomographic computer program (GeoTomLo) to generate 2-dimensional tomograms of velocity for each station. For most stations, 17 source locations and 13 to 14 receiver locations were used, with data collected between every source location and every receiver location. This provided about 220 raypaths per station. Near the abutments, the number of test points per station dropped due to the smaller vertical section of the dam that was available for testing.

The tomograms for each of the 28 stations are shown at the end of this paper. Each tomogram shows the source and receiver locations used to collect the data and the velocity distribution for each 2-dimensional slice though the dam. Red is used to indicate compressional wave velocities above 12,000 fps, indicative of good quality concrete. Yellow is used to indicate areas with measured velocities in the questionable range of 10,000 to 12,000 fps. Green is used to indicate velocities less than 10,000 fps, which can represent poor quality concrete, cracks, or partially open joints.

The color outside of the region bounded by the source and receiver locations on each tomogram has no relevance, as this is outside of the test area. In addition, areas with few or no raypaths will have less accuracy and lower confidence than areas with higher raypath density. In general, any low velocity zones at or very near to the edges of the test area are not reliable. Velocity values for the interior of the dam are of higher confidence.

Discussion of Results

The tomograms show the majority of the concrete to have a velocity between 12,000 and 15,000 fps, indicative of good quality concrete. Some of the low velocity zones are near the edges of the test area, specifically, at or near the upstream and downstream faces and near the bottom of the dam. These areas are of low confidence and may not represent actual velocities and conditions. Low velocity zones interior to the dam are of higher confidence and could represent lower quality concrete or open cracks and/or joints.

Higher confidence velocity anomalies are located at Stations 0+86, 1+23, 1+78, 1+96, 4+15, 4+34, and 4+47. These anomalies may represent partially open construction joints, cracking, or weaker areas in the concrete. Each anomaly is discussed below. The range in feet given for each anomaly is based on project elevation, relative to the top of the flashboards at project elevation 153.5 feet.

Station 0+86: This station is located above the center of the gate house, as shown on Figure 1. The tomogram for this station shows two low velocity anomalies. The anomaly from elevation 143.5 to 147.5 feet extends from the upstream side of the dam to the center of the dam. The anomaly from elevation 120.5 to 124 feet is in the interior of the dam directly above the gate house but is considered lower confidence due to the small number of raypaths through this area.

Station 1+23: The tomogram for this station shows an anomaly from elevation 143.5 to 147.5 feet between the center of the dam and the downstream face. The vertical orientation of this anomaly is suggestive of a vertical joint, crack, or weak zone. A low confidence anomaly is also noted from about elevation 130.5 to 135.5 feet near the upstream face.

Stations 1+78 and 1+96: A small, apparently horizontal anomaly at Station 1+78 at elevation 115.5 feet correlates with a larger anomaly at the same elevation at Station 1+96. In addition, the tomogram at Station 1+58 shows a velocity distribution that is very similar to that at Station 1+78, including a zone of lower velocity centered at elevation 115.5 feet. The alignment of these anomalies suggests a partially open, horizontal construction joint that is widest at Station 1+96 and becomes thinnest at Station 1+58. The lack of any efflorescence on the downstream face at this elevation indicates that if the anomaly is due to an open joint, it is not open through the dam.

Stations 4+15, 4+34, and 4+47: A relatively large anomaly is present at about the same elevation (114.5 to 119.5 feet) at Stations 4+15 and 4+34. The anomaly at Station 4+47 is slightly higher in elevation but is similar in size and shape, suggesting a possible relationship between these anomalies. Station 4+15 shows another higher confidence anomaly at elevation 128.5 to 133.5 feet near the upstream face.

Comparison to Observed Concrete Conditions

The condition of the concrete on the downstream face of the dam was observed on October 9, to note the location of efflorescence and spalling of the concrete (Figure 6). Most of the efflorescence appeared to be related to vertical and horizontal construction joints. Comparison of the concrete velocity anomalies with the approximate location of efflorescence does not show any obvious correlations, suggesting that the condition causing the efflorescence has not affected the strength of the concrete.

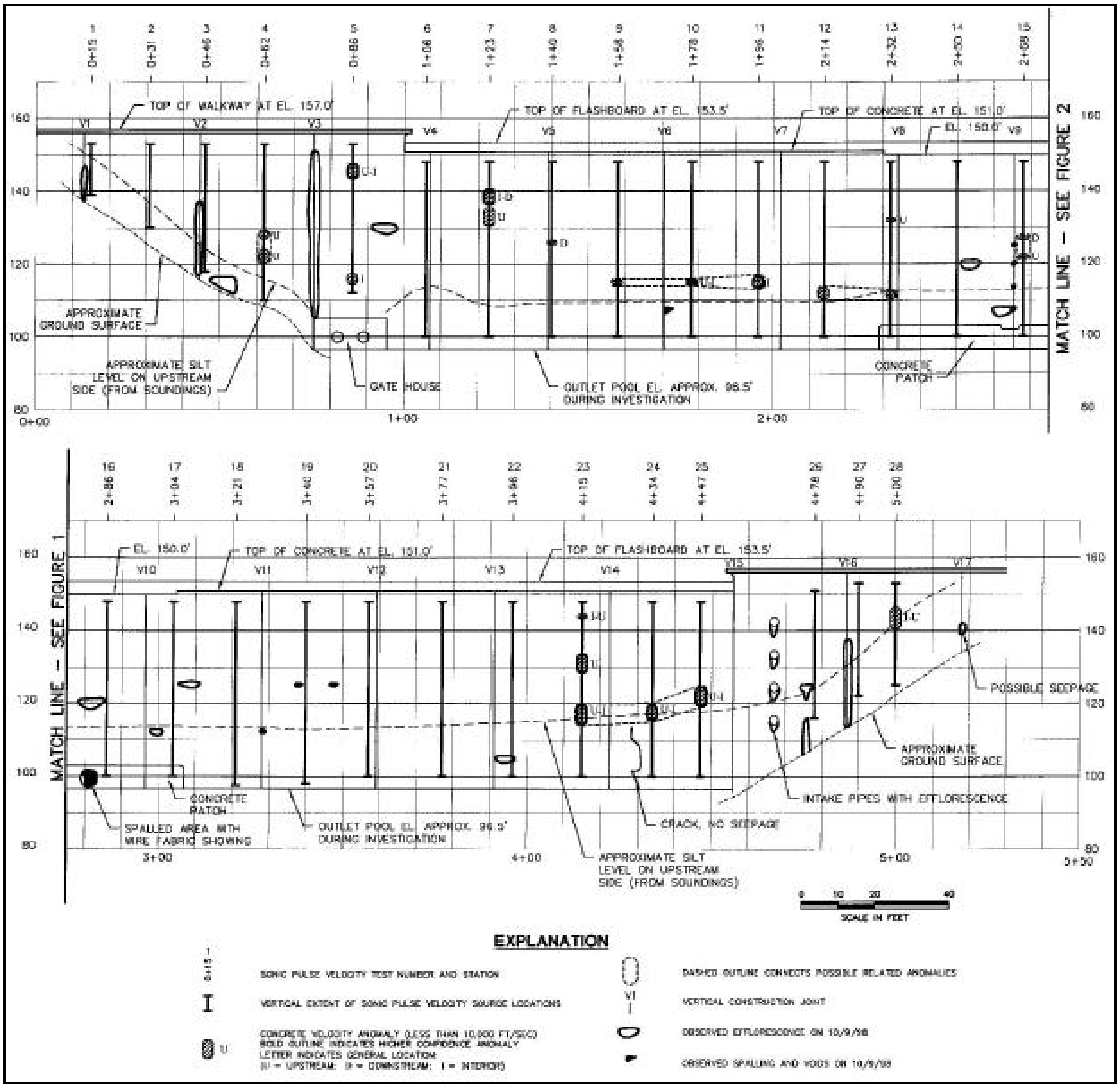

Figure 6. Schematic elevation of dam (looking upstream) showing location of 1998 sonic tests, anomalous velocity areas, and visual observations.

Comparison with 1986 Results

The 1998 velocity anomalies have been compared to the results of the ultra-sonic pulse velocity tests reported in 1986 (Law Engineering Testing Co., 1986). A direct comparison is not possible, since the 1986 tests measured one velocity per raypath and computed velocities for only 15 raypaths per test location, compared to over 220 velocity measurements per station during the 1998 tests. The 1986 data provided only an average velocity for each raypath through the dam, while the 1998 tomographic analysis provided a much higher resolution of the velocity distribution of the concrete. While some of the anomalies detected during the 1998 investigation may have existed in 1986, it would have been difficult to detect them using the 1985 test methods.

The 1986 testing report listed five anomalous areas. Four areas were based on tests reported as having noisy data; the 1998 data does not show any low velocities corresponding to these four locations. However, the 1986 report inferred the presence of a crack at Station 1+78, source elevation 123 to receiver elevation 117. This location is approximately the same as the 1998 anomaly noted at Stations 1+78 and 1+96, elevation 115.5, and considered to represent a partially open construction joint. Lower velocities were not noted at Station 1+96 in the 1986 report, suggesting that this possible open construction joint may have increased in horizontal extent since that time.

October 2000 Dive Inspection

A routine dive inspection was performed at Lake Logan Dam in fall of 2000 to assess the underwater conditions. The inspection was conducted by Underwater Construction Corporation with oversight by AG&E-Schnabel. This inspection afforded the opportunity to check the location of the 1998 velocity anomalies that had been noted at or near the upstream face.

No open joints and only one very small crack were noted during the dive inspection. In most cases, the location of the velocity anomalies corresponded to joints or cracks that appeared to have been filled with some type of epoxy mortar. These repairs probably are the ones that were conducted in 1986 when the water was low. This correlation suggests that the epoxy mortar has a lower velocity than the concrete or that the cracks and joints were only filled surficially, leaving some open areas within the dam. In either case, there is not any observable seepage associated with these anomalies, so the repairs appear to be intact and the apparent defects do not affect the integrity of the dam.

Conclusions

The 1998 sonic pulse testing and tomographic velocity analysis of Lake Logan Dam indicates that the majority of the concrete in the Lake Logan Dam has a velocity 12,000 feet per second or higher, indicative of good quality concrete. The 1998 analysis shows more low velocity areas than those seen in 1986; this is due, at least in part, to the higher resolution of the 1998 tests and may not indicate a decrease in concrete quality over time.

This analysis indicates the presence of areas with a velocity between 8000 and 10,000 feet per second. These anomalies are relatively small and limited in extent compared to the size of the dam. Some of these anomalies may be related to one another and may represent partially open construction joints, cracks, or weak zones in the concrete. The locations of the anomalies do not appear to be related to the locations of efflorescence and spalling observed on the downstream face on October 1998, suggesting that any open construction joints or cracks associated with these anomalies are not continuous through the dam. The October 2000 dive inspection indicated that many of the velocity anomalies that extend to or near the upstream face are associated with joints that have been filled with an epoxy mortar.

Intrusive investigations could be conducted to determine if any open joints, open cracks, or honeycombing is present within the dam. However, since recent dam safety inspections concurrent with the 1998 velocity tests indicate that the dam is safe, there is no need for intrusive investigations at this time. The upstream face should be monitored periodically by divers and/or visual inspections to assess the condition of the joint filler.

As concrete structures age, the quality of the concrete can degrade. The sonic pulse velocity method applied in this investigation could be used to investigate similar structures. This method would also be useful in determining the spatial extent of cracks that are observed on the face of mass concrete structures.

References

Leslie, J.R. and W.J. Cheeseman. An ultrasonic method for studying deterioration and cracking in concrete structures. Amer. Concrete Inst., Proceedings, Vol. 46, Sept. 1949, p. 17-36.

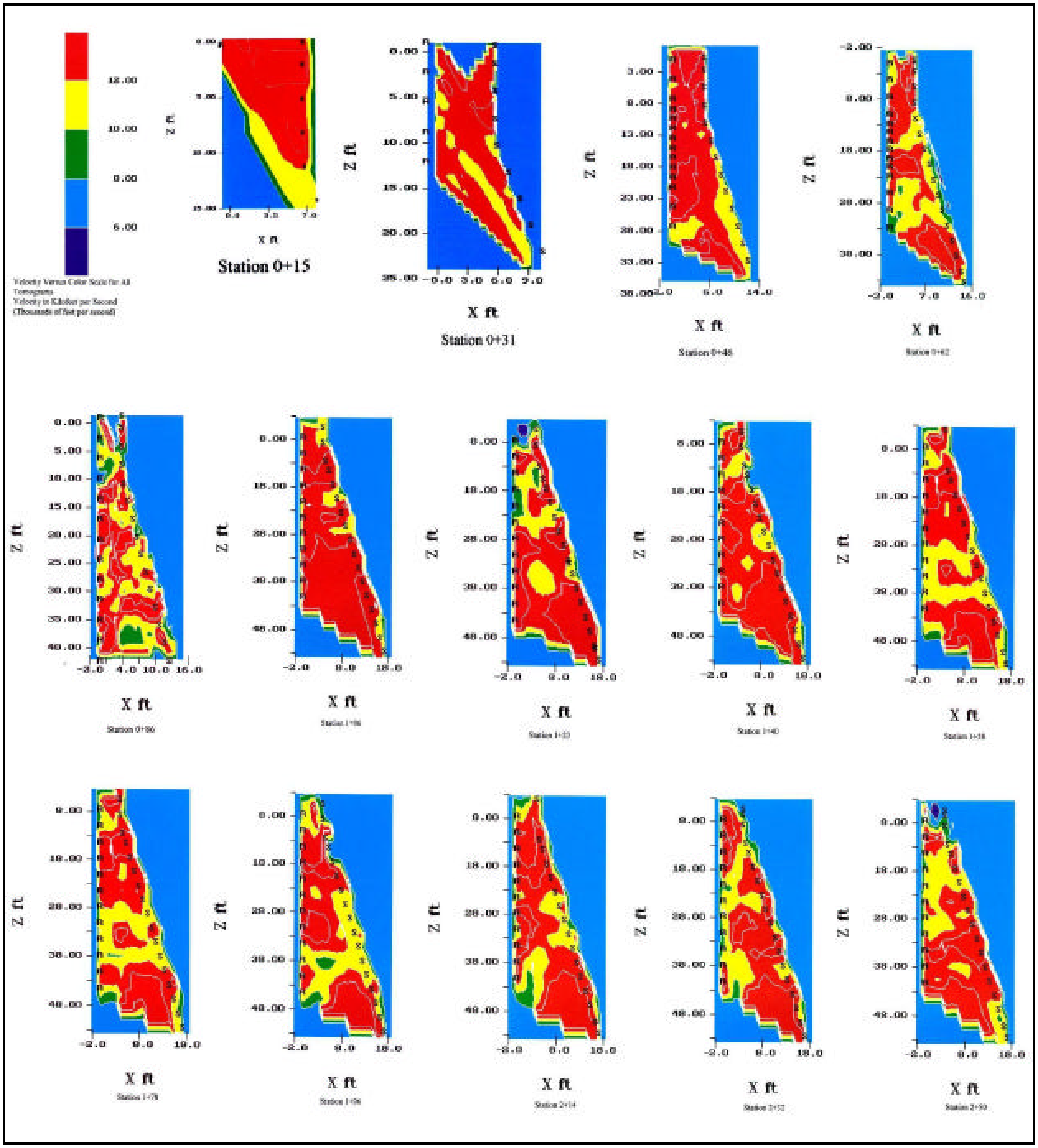

Figure 7. Tomograms for Stations 0+15 through 2+50

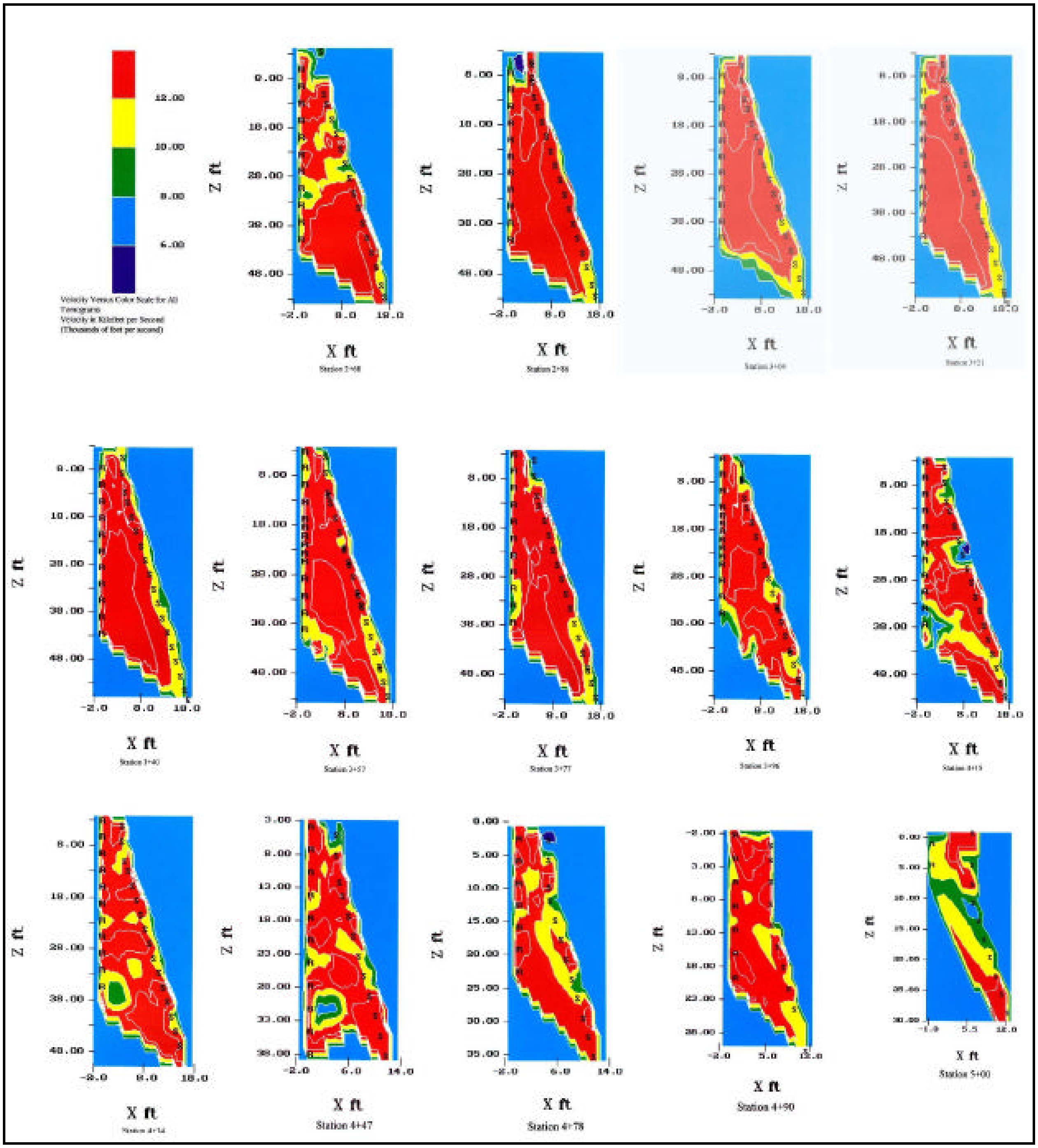

Figure 8. Tomograms for Stations 2+68 through 5+00