Appraising the Quality and Performance of Concrete by Pulse Velocity Measurements

R. W. SPENCER, Manager of Engineering Department; and
B. R. LAVERTY, Senior Civil Engineer;
Southern California Edison Company, Los Angeles

● THE SOUTHERN California Edison Company has utilized the technique of soniscope testing at numerous concrete structures to evaluate the condition and performance of existing concretes and to determine the strength properties and quality of new concretes.

The soniscope program includes the taking of periodic measurements at concrete dams, the experimental testing of concrete samples for proposed new structures, and tests of new concrete in miscellaneous structures.

The Edison Company is pleased to share its findings with members of the Highway Research Board and hopes that the results of its soniscope investigations, which have been conducted on structures other than roads and bridges, will be of value in supplementing the collection of data and ideas presented before this symposium.

PURPOSE AND HISTORY

In 1953, the Company initiated its program of annual soniscope testing of concrete in dams at the Big Creek-San Joaquin Hydroelectric Development in central California. This testing was in part an outgrowth of studies begun in 1942 by the Portland Cement Association in cooperation with the Edison Company and others to observe the long-time performance of concrete using 27 different cement types from various parts of the United States.

The first soniscope tests were made at the Florence Lake Dam, a multiple arch structure located in the Sierra Nevada Mountains at an elevation of over 7,000 ft. At this elevation the severity of exposure to freeze-thaw cycles is such that concrete is subject to deterioration if permitted to be in intermittent contact with water during the winter season. Deterioration that developed in the concrete on the upstream face of the dam was arrested by the application of an asbestile coating, and it was the practice for a number of years to take cores from the dam periodically for testing. In this manner it has been possible to maintain an up-to-date evaluation of the dam's performance. The time and expense of the coring were considered excessive, and following the establishment of P. C. A. soniscope test measurement points at the dam, it was believed that continued soniscoping by the Company would be effective in maintaining an up-to-date evaluation of the performance of the concrete with minimum coring. Since the use of the soniscope was begun at Florence Lake Dam, no cores have been taken for testing; and in the future only rarely will cores be taken to confirm the data gathered by soniscoping. In conjunction with the P. C. A. studies pulse velocity measurements are still made on groups of test bars and on walkway test slabs made from concretes utilizing various types of cement.

The initial program has now been expanded to include the periodic testing at all the dams at the Big Creek Development. The soniscope has been used to determine representative pulse velocities in these structures and to establish trends, if any, in these pulse velocities over a period of several years' duration. Consequently, the Company has gathered considerable field data and now welcomes the opportunity to join other soniscope users in an effort to analyze more closely the significance of its findings.

The first phase of this soniscope program has been the investigation of the condition of representative concrete in each structure. The second phase has been that of determining long-time trends in pulse velocities, which are considered probably the most important data provided to date by the soniscope. The third phase of investigation is the determination of the more specific relationships of measured pulse velocities to various concrete properties, when certain data such as design mixes, the use of admixtures, types of aggregate and types of cement are known. This latter phase is certainly still in its initial stages, and only the most preliminary information obtained regarding these more complex relationships will be indicated.

In addition to testing various massive concrete structures, the instrument has been used for the qualitative analysis of concretes in building structures and in large diameter concrete pipes; and to a limited extent it has been used in experimental tests of other materials, including wood and steel.

APPRAISING THE PRESENT CONDITION OF EXISTING STRUCTURES

Among the concrete structures that have been tested are those older structures wherein deterioration or concrete of questionable quality could have existed to an undetermined degree. The soniscope technique has been found useful to determine the extent of deterioration, if any, and to verify the adequacy of otherwise questionable concrete.

Pulse Velocity Measurements at the Big Creek-San Joaquin Hydroelectric Development

At the Big Creek Development the soniscope program has been of tangible value; for the tests have shown that the concretes in the eleven major dams are satisfactory, with pulse velocity measurements in the concretes varying from 11, 600 to over 15, 000 ft/sec. Of particular interest are the relatively high pulse velocities at some of the older dams that were constructed between 1913 and 1927. A number of the structures, having comparatively low concrete design strengths, have pulse velocities that compare remarkably well with new structural concretes at other more recently constructed structures. An example of this is at Shaver Dam, a gravity dam built in 1927, where mass concrete with a mix of 1:3. 2:7. 5 (by vol) exhibited average pulse velocities from 14, 550 to 15, 100 ft/sec. On the other hand, the Florence Lake Dam arch dam buttresses, having a richer mix of 1:2. 2:4. 7 (by vol), showed lower pulse velocities averaging 12, 750 ft/sec. Nevertheless, as shown in Figure 2, pulse velocity measurements at all locations have been found to be adequate; and this has materially reduced the need for other physical tests to confirm the existence of satisfactory concrete. The soniscope crew is shown working at Bear Dam, one of the small arch dams in Figure 5.

The concretes in the several dams have been designed to provide various strengths. For this reason it is helpful to classify the structures in groups based on the concrete design strength requirements--massive concrete in the gravity dams, intermediate concrete in the arch dams, and structural concrete in the appurtenant structures—when analyzing the results of the soniscope tests that have been conducted.

Massive concrete structures tested include three gravity dams: Shaver Dam, Dam 7 and Dam 3. Soniscope measurements at Shaver Dam show excellent pulse velocities for concrete regardless of its type as discussed above, and the Dam 7 pulse velocities in mass concrete are adequate, averaging about 13, 000 ft/sec. The measurements made at Dam 3 are low (11, 790 ft/sec and below) because of deterioration resulting from the dam's age, the severity of the local exposure conditions, and the nature of the pit-run mixes incorporated in the concrete. Dams 1 and 2 at Huntington Lake, companions to Dam 3, were steel-plate faced in 1955 to arrest further deterioration of the concrete on their upstream faces.

The soniscope pulse velocities for the structures having intermediate strength concrete cover a wide range of variation. Excellent performance is shown by Dam 4, an arch dam, where pulse velocities averaging 14, 790 ft/sec exceed those found in some structural concretes. The average pulse velocity values at Mono Dam, Bear Dam and at the Dam 1 overflow spillway (13, 790; 14, 130; and 14, 410 ft/sec, respectively) are considered satisfactory and are believed typical for 2, 000 to 3, 000 psi concrete in this region. Somewhat below the anticipated pulse velocities for intermediate concrete are the measurements made in Dam 5 and 6 and the Florence Lake Dam buttresses, which were in order: 12, 560; 12, 670; and 12, 750 ft/sec. However, the uniformity of

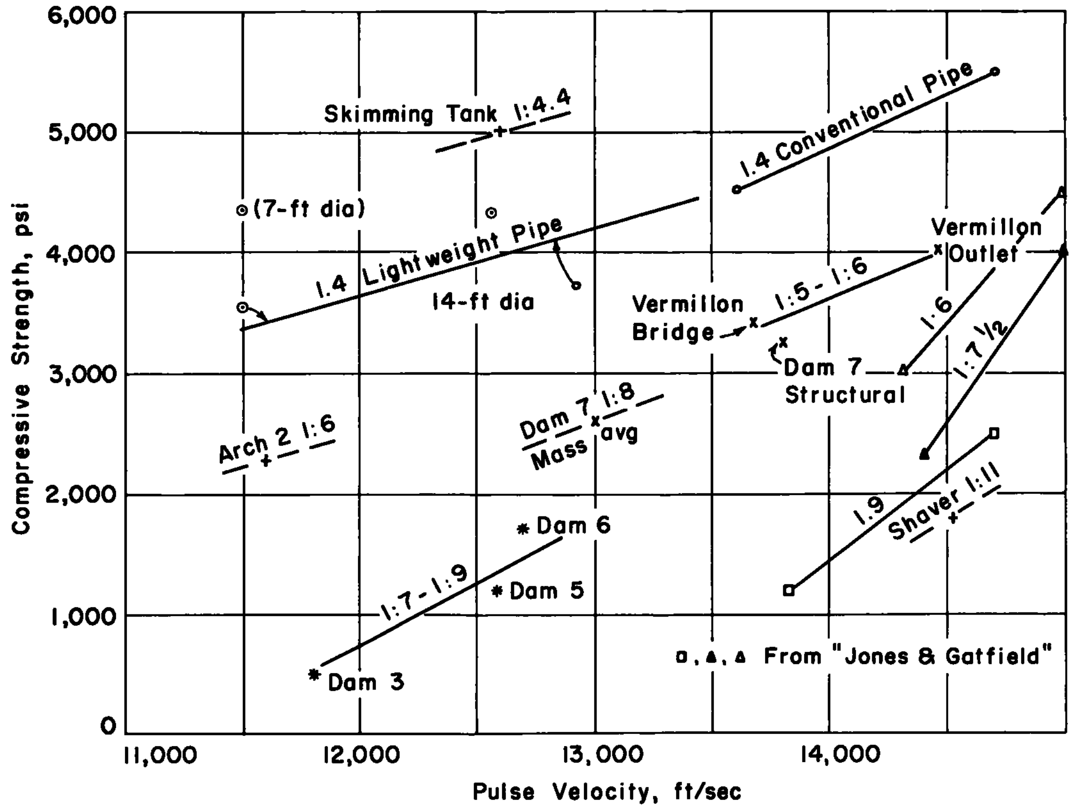

Figure 1. Relation between pulse velocity and compressive strength for various concrete mixes.

the yearly measurements has minimized the need for questioning of the above concretes' satisfactory performance.

The structural concretes in the outlet works and in the service spillway bridge at Vermilion Dam, in the training walls at Dam 7, and in the walkways at Florence Lake Dam were found to have satisfactory pulse velocities as indicated in Figure 2. However, they are in some instances lower than the pulse velocities that have been recorded by others for structural concrete. Pulse velocities exceeding 15,000 ft/sec have been infrequently found, as a rule.

Local aggregates were used in the concrete mixes for all the Big Creek dams. These aggregates may be classified as hornblende, biotite granites. They are characterized by their density, durability and lack of reactivity and they have usually been produced by quarrying or by processing of tunnel muck.

Figure 2 shows representative pulse velocities observed over periods of four to six years at each of the above-mentioned Big Creek dams.

Correlation of Laboratory Tests with Pulse Velocity Measurements

While no simple relationship has been established between the ultrasonic pulse velocity, modulus of elasticity, and ultimate compressive strength of a concrete specimen, the continuing accumulation of data does give insight into general relationships. The following test data are cited from Portland Cement Association investigations at Florence Lake Dam where soniscope measurements were conducted at 20 points on a section 1.65 ft in thickness on Arch No. 2 at an area where 4-in. diameter concrete cores were removed for testing to determine both Young's modulus of elasticity and the ultimate compressive strength of the concrete:

Core No.	Compressive Strength (psi)	Young's Modulus of Elasticity (psi)	Soniscope Pulse Velocity (ft/sec)
2-1 (1943)	2480		
2-1 (1945)	2540	1, 770, 000	
2-1 (1947)	2248	1, 980, 000	
2-1 (1949)	2230 (approx.)	1, 270, 000	
2-1 (1951)	2040	-	
Average:	2308	1, 670, 000	11, 600 (avg. of 20 tests)

In this instance the existence of the comparatively low average modulus of elasticity determined by laboratory compression tests of cores was substantiated by the corresponding low average sonic pulse velocity. The average compressive strength of the cores taken from this structure, while not exceptionally high, did illustrate that a concrete may show only moderate elastic properties from both physical and sonic tests yet have satisfactory strength.

Further data to assist in the correlation of pulse velocity measurements with other physical tests are given in Table 1 which contains pulse velocities, concrete compressive strengths, and other physical characteristics of the Big Creek Development structures where soniscope tests have been conducted. Included also are other data which are believed to effect the pulse velocity measurements of a concrete.

Reference is made to Figure 1 which shows observed relationships of pulse velocity to compressive strength for concretes of varying mix proportions. If compressive strength be considered a criteria for measuring quality, the plot becomes useful for gauging the quality of an aged concrete by means of pulse velocity tests when the approximate mix proportions are known. Applications of these relationships must be

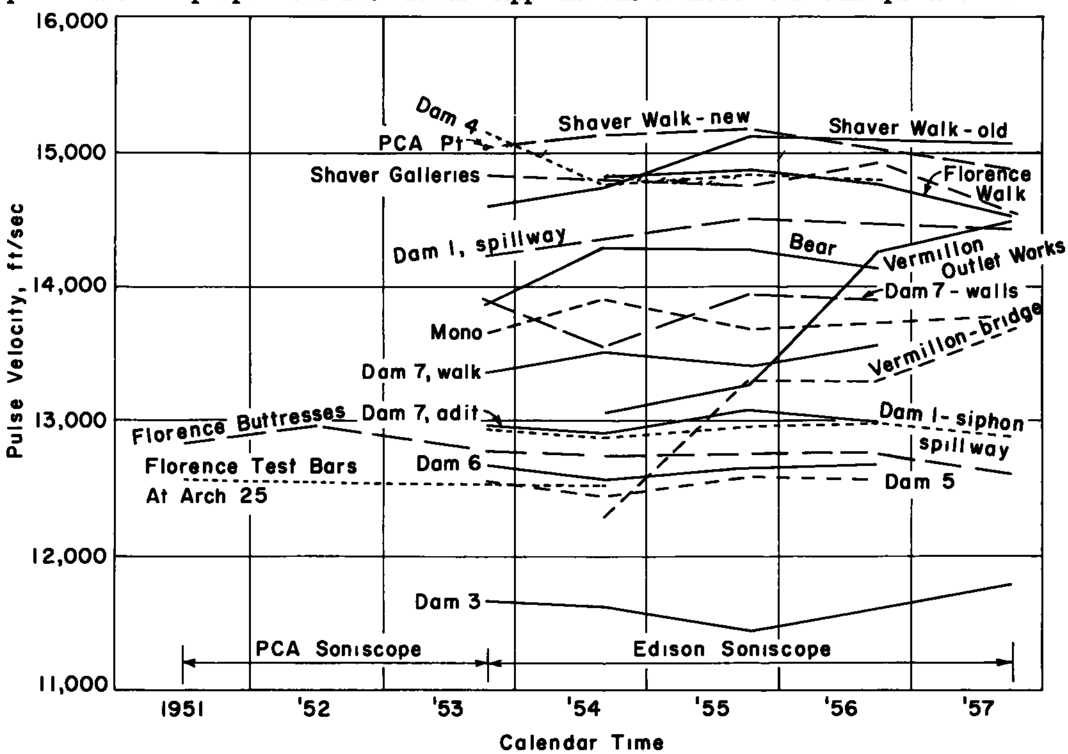

Figure 2. Comparison of pulse velocity vs time; soniscope testing of concrete—Big Creek Project Dams.

TABLE 1

PULSE VELOCITIES AND PHYSICAL CHARACTERISTICS AT BIG CREEK DAMS

Structure	Typical Mix Proportions	Admixture	Recent Pulse Velocity ft/sec	Tested Compressive Strength psi
Dam 7				
Mass Concrete	1:1¾:6¼ by wt[2]	Darex[1]	13,500	2600 - 28 day
Mass Concrete	1:1.84:7 60 by wt[3]	Pozzolan	12,500	
Structural Concrete	1:1¾:3½ by wt	Darex[1]	13,830	3300 - 28 day
Dam 6				
Crest	1:2¼:4½ by vol	-	12,670	1680 - 28 day
Shaver Dam				
Mass Concrete	1:3.2:7.5 by vol	-	14,550	1800 - 28 day
Florence Lake Dam				
Buttresses	1:2.2:4.7 by vol	-	12,750	
Arch 21	1:1.9:4.1 by vol	-	13,440	2860 - 1951 cores
Arch 2	1:1.9:4.1 by vol	-	11,600	2308 - 1943-51 cores
Vermilion Dam				
Outlet Works	1:2:3 by wt	Darex[1]	14,480	4040 - 28 day
Spillway Bridge	1:2.7:3.7 by wt	Darex[1]	13,690	3390 - 28 day
Mono Dam	-	-	13,790	
Bear Dam	-	-	14,130	
Dam 1				
Overflow Spillway	1:6 by vol	-	14,410	est. 2500 - 28 day
Dam 2				
Mass Concrete	1:8 by vol	-	-	700 - 28 day
Dam 3	1:9 and 1:7½ by vol	-	11,790	515 - 28 day
Dam 4	1:7 by vol	-	14,790	1230 - 28 day
Dam 5	1:9 by vol	-	12,560	1225 - 28 day

Structure	Dam Type	Height ft	Crest Length ft	Date Built	Elev. at Crest	Aggregate Source[4]
Dam 7	Gravity	250	891	1950	1413	
Mass Concrete						Local Quarry
Mass Concrete						Local Quarry
Structural Concrete						Local Quarry
Dam 6	Arch	155	495	1923	2250	
Crest						
Shaver Dam	Gravity	198	2169	1927	5371	
Mass Concrete						Local Quarry
Florence Lake Dam	Multiple Arch	154	3156	1926	7329	
Buttresses						Tunnel Muck
Arch 21						Tunnel Muck
Arch 2						Tunnel Muck
Vermilion Dam	Earth fill	165	4248	1954	7650	
Outlet Works						Alluvial Deposits
Spillway Bridge						Alluvial Deposits
Mono Dam	Arch	64	184	1927	7360	Tunnel Muck
Bear Dam	Arch	55	276	1927	7356	Tunnel Muck
Dam 1	Gravity	170	1335	1917	6954	Alluvial Deposits
Dam 2	Gravity	120	1862	1917	6954	Alluvial Deposits
Dam 3	Gravity	152	666	1917	6954	Alluvial Deposits
Dam 4	Arch	81	287	1913	4814	Tunnel Muck
Dam 5	Arch	60	224	1921	2950	Tunnel Muck

[1] Mixes containing Darex are designed for 5 percent entrained air content.
[2] Mix used for mass concrete within 8 ft of face of dam.
[3] Mix used for mass concrete over 8 ft from face of dam
[4] All aggregates are hornblende, biotite granites.

applied cautiously for the compressive strength data tabulated above were in numerous instances determined from test cylinders taken from concrete batches not placed in the immediate vicinity of the pulse velocity measurement points. Nevertheless, this manner of presenting the data is useful, and it is intended to gather further field and laboratory test data to clarify the relationships indicated above.

It is seen in Figure 1 that for a given pulse velocity, richer mixes will have a higher compressive strength than lean mixes, and that for a given mix and pulse velocity, the compressive strength of the concrete will vary with the compressive strength of the coarse aggregate.

Once sufficient testing has been done to establish the above relationships for a particular range of aggregates and mixes, it will be possible more closely to evaluate the probable compressive strength of concrete in an existing structure by use of soniscope measurements. Through this type of appraisal the Company hopes in the future to develop a useful tool to assist in accurately judging the competence of its structures.

Pulse Velocity Tests in Miscellaneous Structures

An example of the soniscope's usefulness on a "one test series" basis to appraise the condition of concrete was illustrated by tests recently conducted at a Los Angeles

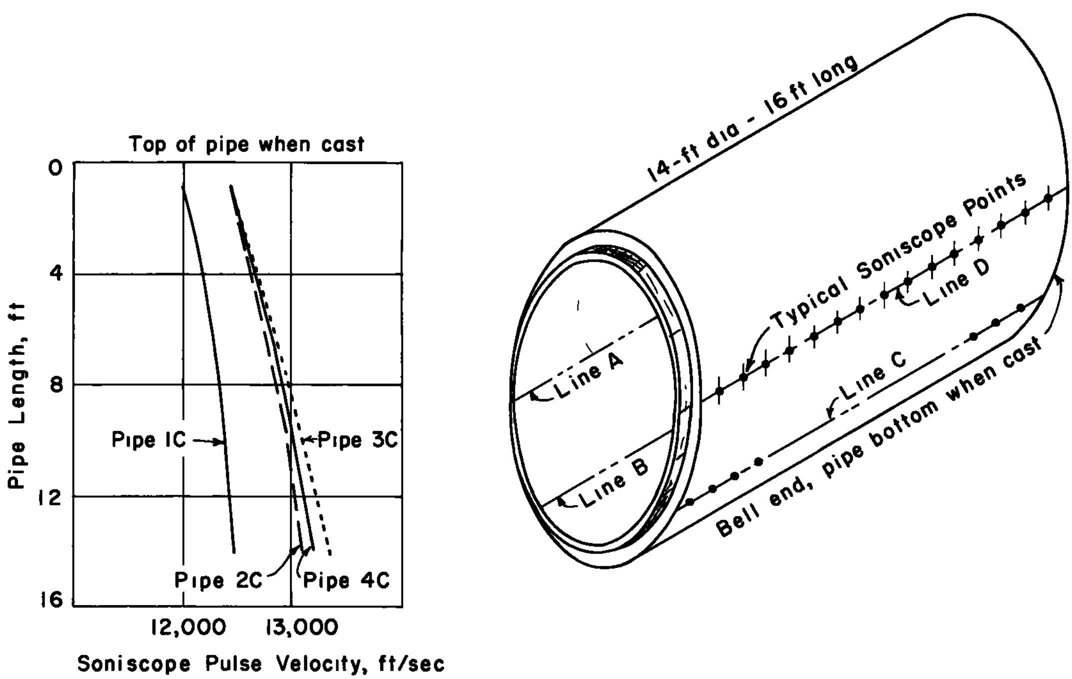

Figure 3. Variation of soniscope pulse velocity with length, lightweight concrete pipe.

area oil refinery. Here the soniscope was used to verify the acceptability of newly placed concrete in the walls of a large oil skimming tank where surface irregularities had caused the owners to fear the existence of internal discontinuities such as honeycomb voids and voids at lift joints. A series of 89 soniscope measurements in 8- and 10-in. thick walls revealed that the concrete was consistently homogeneous and entirely satisfactory, thus discounting the need for any doubt on the part of the contractor or the owner as to the concrete's quality. The average measured pulse velocity for the one-month old concrete tested was 12,650 ft/sec. The concrete mix was 1:1.9:2.5 by wt, developing a 28-day compressive strength of 5,000 psi. San Gabriel aggregates, produced from nearby alluvial deposits of granitic and gneissic rock, were used in the concrete. The owner was accordingly satisfied by the qualitative report of the concrete's condition, based on the pulse velocity tests.

Another instance of the soniscope's use for in-place testing of concrete was at a local aircraft plant where visual observation of a building's structural performance indicated the existence of unusual material. These tests were made to assist in the analysis by the designers of excessive, progressive deflections that were occurring in a second-floor, flat slab floor system. The visibly questionable performance of the concrete evidenced by 2- to 3-in. midspan deflections in 30-ft spans caused concern over the acceptability of the concrete placed in the structure. Pulse velocity measurements indicated concrete having a modulus of elasticity less than that generally adopted in design and of less than normal quality. It was suspected that deflections due to sustained plastic flow would be similar to those which occurred in the highly flexible structure.

The following data summarize both the findings of the pulse velocity measurements made through the second story floor slab and the physical charcteristics of concrete beams and cores taken for testing from nearby floor areas of excess deflection:

Concrete Compressive Strength:	4, 500 psi, average
Concrete Mix Proportions:	1:5. 5
Young's Modulus of Elasticity: (from stress-strain measurements).	2, 700, 000 psi, weighted average
	1, 700, 000 psi, minimum
Modulus of Rupture:	720 psi, average
Unit Weight:	142. 3 pcf
Soniscope Pulse Velocity:	11, 600 ft/sec

It was concluded, following laboratory tests of samples of the concrete cut from the structure and after the evaluation of extensive consulting advice, that the excessive deformation was the evidence of initially underestimated deflection characteristics in the design combined with the use of a low-alkali Type II cement with unusually high shrinkage characteristics which would likely be accompanied by excessive plastic flow or creep. Since there has been no evidence of overstress in the structure, no major remedial measures have been necessary, and the building has been fully occupied.

In this case the value of the pulse velocity tests was in indicating the early necessity for more comprehensive coring and strength testing and in providing data in support of the final conclusions drawn from the results of the subsequent laboratory tests.

DETERMINING TRENDS IN EXISTING STRUCTURES

A trend toward deterioration is a matter following next in importance the existing condition of the concrete in any structure. Knowledge of such a trend, once established, permits the scheduling of maintenance and repairs to control the rate of deterioration and also facilitates an estimate of the probable future service life of the structure.

To date no definite deterioration, not previously corrected, has been noted in any of the Big Creek dams. These dams have an average age of 29 years and one is 44 years old. There has been a slight reduction in pulse velocities in the last year or so in some of the older structures, but the changes are of the same order of magnitude as those caused by changes in moisture content and are still too small to indicate a definite trend. Data presented in England in 1955 by Jones and Gatfield (Department of Scientific and Industrial Research Road Research Laboratory; Road Research Technical Paper No. 34) in the paper "Testing Concrete by an Ultrasonic Pulse Technique" give the effect of drying on the wave velocity in concrete beams of various mix proportions. It is shown that complete saturation of a specimen can increase in longitudinal pulse velocity by as much as 1 percent for a rich mix and 4 percent for a lean mix. From the foregoing it is indicated that pulse velocities for a structure may vary under certain field conditions by as much as 500 ft/sec due to changes in concrete moisture content. To minimize soniscope variation not directly attributable to normal instrument variation, it is the Company's practice to schedule the Big Creek soniscope program at the same time each year to approach as nearly as possible similar conditions of concrete moisture content and stress induced by temperature and water loading.

The influence of moisture content variation on pulse velocity interpretation at these dams has yet to be analyzed. Annual variations in concrete moisture content and in climatic conditions probably have a measurable effect, for the dams are located over a wide range of climatic zones. Opposite extremes in exposure conditions are represented by Dam 7 in the warm, dry San Joaquin Valley foothills in contrast with Florence Lake Dam in an area of locally high precipitation at elevation of over 7, 000 ft in the Sierras.

the compressive strength of the concrete will vary with the compressive strength of the coarse aggregate.

Once sufficient testing has been done to establish the above relationships for a particular range of aggregates and mixes, it will be possible more closely to evaluate the probable compressive strength of concrete in an existing structure by use of soniscope measurements. Through this type of appraisal the Company hopes in the future to develop a useful tool to assist in accurately judging the competence of its structures.

Pulse Velocity Tests in Miscellaneous Structures

An example of the soniscope's usefulness on a "one test series" basis to appraise the condition of concrete was illustrated by tests recently conducted at a Los Angeles

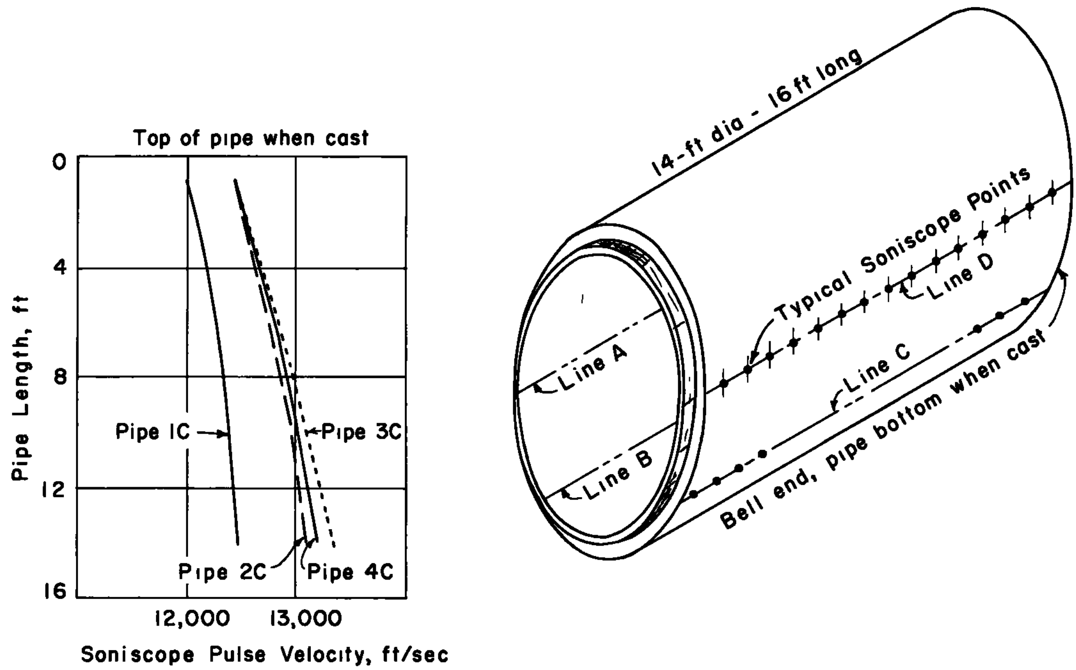

Figure 3. Variation of soniscope pulse velocity with length, lightweight concrete pipe.

area oil refinery. Here the soniscope was used to verify the acceptability of newly placed concrete in the walls of a large oil skimming tank where surface irregularities had caused the owners to fear the existence of internal discontinuities such as honeycomb voids and voids at lift joints. A series of 89 soniscope measurements in 8- and 10-in. thick walls revealed that the concrete was consistently homogeneous and entirely satisfactory, thus discounting the need for any doubt on the part of the contractor or the owner as to the concrete's quality. The average measured pulse velocity for the one-month old concrete tested was 12, 650 ft/sec. The concrete mix was 1:1. 9:2. 5 by wt, developing a 28-day compressive strength of 5, 000 psi. San Gabriel aggregates, produced from nearby alluvial deposits of granitic and gneissic rock, were used in the concrete. The owner was accordingly satisfied by the qualitative report of the concrete's condition, based on the pulse velocity tests.

Another instance of the soniscope's use for in-place testing of concrete was at a local aircraft plant where visual observation of a building's structural performance indicated the existence of unusual material. These tests were made to assist in the analysis by the designers of excessive, progressive deflections that were occurring in a second-floor, flat slab floor system. The visibly questionable performance of the

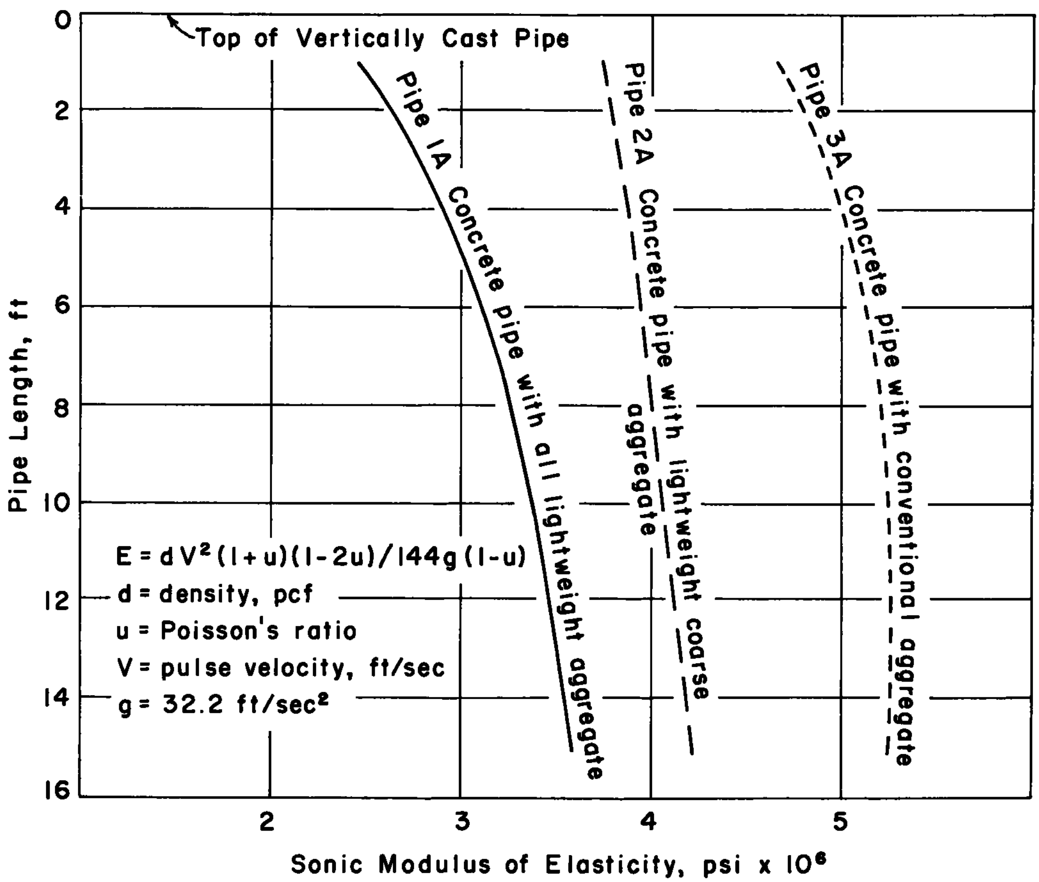

Figure 4. Variation of sonic modulus of elasticity with pipe length.

To illustrate the results of the Company's Big Creek soniscope tests, reference is made to Figure 2 which shows the average pulse velocities measured from 1951 to 1957 at many of the structures tested. No significant trends indicating decreased concrete quality are shown. On the contrary the pulse velocities at the Vermilion Dam outlet structure and service spillway bridge have increased substantially with age. This concrete was placed in 1953 and first soniscoped in 1954. To date the average pulse velocity at the outlet structure has increased by about 1,400 ft/sec, indicating a substantial rise in concrete strength with age. The comparatively cold climate at this location as well as the use of low-alkali, Type II cement in the concrete probably contributes to the slow attainment of maximum pulse velocities.

To date some experimental tests by other soniscope users comparing pulse velocity build-up with age have indicated that an increase in pulse velocity will parallel the usual compressive strength gains and will reach a near-maximum velocity within a few months after placement of the concrete. Findings at Vermilion Dam suggest that structural concretes without admixtures, except for air entrainment, will under certain conditions continue to show pulse velocity increases after the period generally accepted for nearly complete strength build-up.

Figure 2 shows that where no trends toward either increasing or decreasing concrete quality are indicated, yearly variations in pulse velocities at a given structure generally do not exceed about 2 percent; and in the past five years the greatest pulse velocity variation has not exceeded 3½ percent for any structure except at Vermilion Dam. These variations are cited to indicate the range of random deviations that have been measured over an extended test period.

It is believed that one of the very useful applications of the soniscope is in the periodic retesting of structures over a period of years, for the pulse velocity trends in a structure are useful indicators of its present performance as well as of its future physical condition. This is accordingly among the most economical test methods now available for appraising the condition and performance of massive concrete structures.

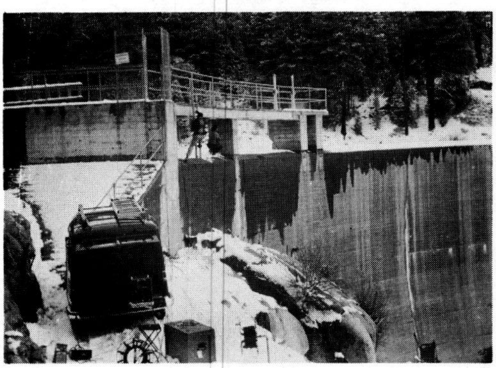

Figure 5A. Soniscope testing at Bear Dam; Big Creek-San Joaquin Hydroelectric Project.

EXPERIMENTAL TESTING

Soniscope testing has been of value as a qualitative test to contribute to the knowledge of a material proposed for a new or otherwise unusual application. When used with other standard tests, the pulse velocity test data will tend to either verify or cause question of such data. This was the case with tests conducted on samples of lightweight concrete to be used in large diameter, lightweight concrete pipe proposed for installation in the condenser cooling water system of the Edison Company Huntington Beach Steam Station. Engineering studies indicated that a reduction in cost of several hundred-thousand dollars could be effected in an offshore, pipe-placing trestle if 14-ft inside diameter conduit made with lightweight aggregate concrete and having only two-thirds the weight of normal concrete were utilized. Soniscope tests were performed to supplement other physical tests, and the combined results of all the tests indicated that conduit made with this type aggregate would be acceptable. It was found that the elastic properties of the lightweight pipe were satisfactory for the use intended and that lightweight concrete could be placed and vibrated in vertical steel forms and be free from damaging segregation or rock pockets. Sections of the pipe are shown in Figure 5, before installation.

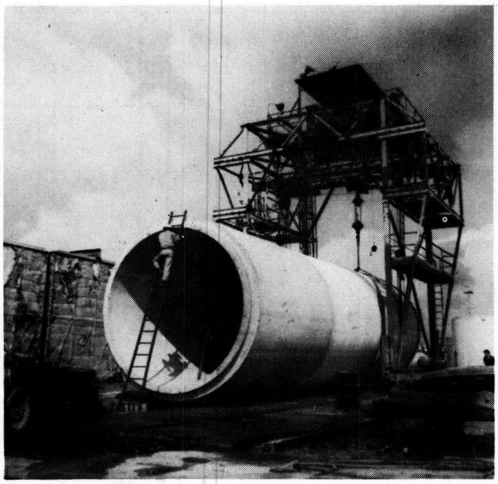

Figure 5B. Fourteen foot diameter lightweight concrete pipe; Huntinington Beach Steam Station.

Reference is made to Figure 3 which illustrates the variation of pulse velocity with pipe length for vertically cast, lightweight concrete pipe and to Figure 4 which presents the variation of the sonic modulus of elasticity with pipe length as determined by pulse velocity measurements using the general relationship:

$$E = dv^2 \frac{(1+u)(1-2u)}{144g(1-u)}$$

in which:

E = sonic modulus of elasticity, psi
d = concrete density, pcf
v = pulse velocity, ft/sec
u = Poisson's ratio
g = 32.2 ft/sec^2

TABLE 2

EXPERIMENTAL TESTS ON CONCRETE PIPE[1]

Pipe No.	Sacks Cement cy	Type of Pipe	Date Made	Date Soniscoped	Avg Pulse Velocity ft/sec	Avg Sonic Modulus psi (x10^6)	Test Cylinder Density pcf	Test Cylinder Comp Strength psi
1 A	8 7	All Rocklite aggregate	8/18/56	9/18/56	12,800	3 09	106 0	4185
2 A	9 3	Rocklite coarse with natural concrete sand	8 29 56	9/18 '56	13,400	3 91	121.0	4835
3 A	7 0	Conventional	9/13/56	9/18/56	13,600	5 08	147.0	4500
1 B	8 0	Conventional Centrifugally spun	Not known	9/18/56	14,700	6 03	150 0	5500
1 C	8.5	All Rocklite aggregate	9, 13, 56	2/26 57	12,260	2 55	101 7	3620
2 C	8 5	All Rocklite aggregate	9/15, 56	2/26/57	12,740	2 83	100.9	3750
3 C	8 5	All Rocklite aggregate	9, 18 56	2, 26, 57	12,850	2 99	101.2	3710
4 C	8 5	All Rocklite aggregate	9/19/56	2/26/57	12,890	2 86	99 5	2970

[1] All pipes were cured in 60 hr steam with the exception of 1 B which was cured in air

The variation in pulse velocity with height as cast is attributed to the tendency of lightweight aggregate to float to the top of the fluid concrete leaving the more dense paste at the bottom. Similar pulse velocity increase with depth occurs in normal concrete where the dense coarse aggregates settle downward leaving excess moisture and air voids near the surface of the fluid concrete.

The design mix for the lightweight concrete was $1:1\frac{3}{4}:2\frac{1}{4}$ by volume, and the expanded clay shale aggregate used in the mix was manufactured by the Rocklite Company. Tests were made on pipe sections composed of lightweight coarse aggregate and natural sand as well as on conventional concrete pipes both vertically cast and centrifugally spun. Summarized results of these tests are contained in Table 2.

The average sonic modulus of elasticity calculated from pulse velocity measurements for the all-lightweight aggregate pipe 1A, shown on Figure 4, was 3,100,000 psi, with a corresponding average compressive strength determined by physical tests to be 4,400 psi. In comparison, soniscope measurements of concrete pipe 2A made using lightweight coarse aggregate and natural concrete sand indicated an average sonic modulus of 3,900,000 psi. Concrete pipe 3A made using all natural San Gabriel aggregates exhibited an average sonic modulus of 5,100,000 psi.

Although the moduli of elasticity of the lightweight pipe are relatively low when compared to those of conventional concrete pipe, the compressive strengths of both are of the same magnitude. It was believed that with aging the sonic modulus of elasticity of the lightweight pipe would approach 3,000,000 psi and be acceptable.

Figure 1 shows the correlation of pipe pulse velocity with test cylinder compressive strength for lightweight concrete tested at the Huntington Beach Steam Station.

One of the subsidiary findings was that for the monolithically cast pipe, of the diameter and length used, high-frequency vibration during placement must be carefully controlled to assure the production of homogeneous concrete. The forms for pipe number 1C were vibrated during casting by 8 high-frequency pneumatic form vibrators, whereas the successive pipes, 2C, 3C and 4C were more effectively vibrated by 10 vibrators. This explains the lower pulse velocities measured in pipe 1C. Although the density of the test cylinder taken from pipe 1C approximated the density of the test cylinders from the other pipes, there was no doubt that the concrete in the cast pipe section was of lower density than the concretes in pipes 2C, 3C and 4C.

The example cited above also indicated the usefulness of the soniscope in providing quality control using an expeditious non-destruction test method.

Experimental tests have been conducted on materials other than lightweight concrete pipe including wood and steel. Substantial data have been collected in an attempt to determine the relationship of pulse velocity to the actual elastic modulus of wooden power pole cross arms, but to date no usable correlation has been developed.

INTERPRETATION OF PULSE VELOCITY TEST DATA

The measured pulse velocity through a concrete specimen is a property whose proper interpretation must recognize that the transmitted series of compression waves will tend to find the fastest and best path between transducers. Accordingly, a high pulse velocity over a given measurement path is not proof that zones of lower pulse velocity material do not exist adjacent to or in the line of a straight line path, for the compression waves will tend to follow the line of shortest transmission time—deflecting where necessary to bypass lower velocity zones or partial cracking. Therefore, discretion should be exercised when comparing the results of physical tests on test cylinders, beams, or cores with pulse velocity measurements, because the usual physical tests of compressive or bending strength of a test specimen will often be influenced by the average or weakest portion of the test specimen, whereas the pulse velocity test will be somewhat differently affected by variations in composition of the material tested.

The interpretation of pulse velocity measurements should, therefore, be tempered by awareness of all circumstances and conditions surrounding the material tested as well as by the test procedure. This is not unique to soniscope testing, for many test results are subject to wide variations if testing techniques are permitted to vary. Since there are often variables which affect the pulse velocity of a given concrete, the pulse velocity measurement at a given time by itself cannot be an explicit indicator of compressive strength or durability or modulus of elasticity; yet pulse velocities can nonetheless be a very useful property to use, together with all other known data, in evaluating the condition and capabilities of a given concrete.