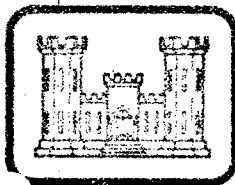


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DEVELOPMENT OF PROCEDURES FOR NONDESTRUCTIVE TESTING OF CONCRETE STRUCTURES

Report 2

FEASIBILITY OF SONIC PULSE-ECHO TECHNIQUE

by

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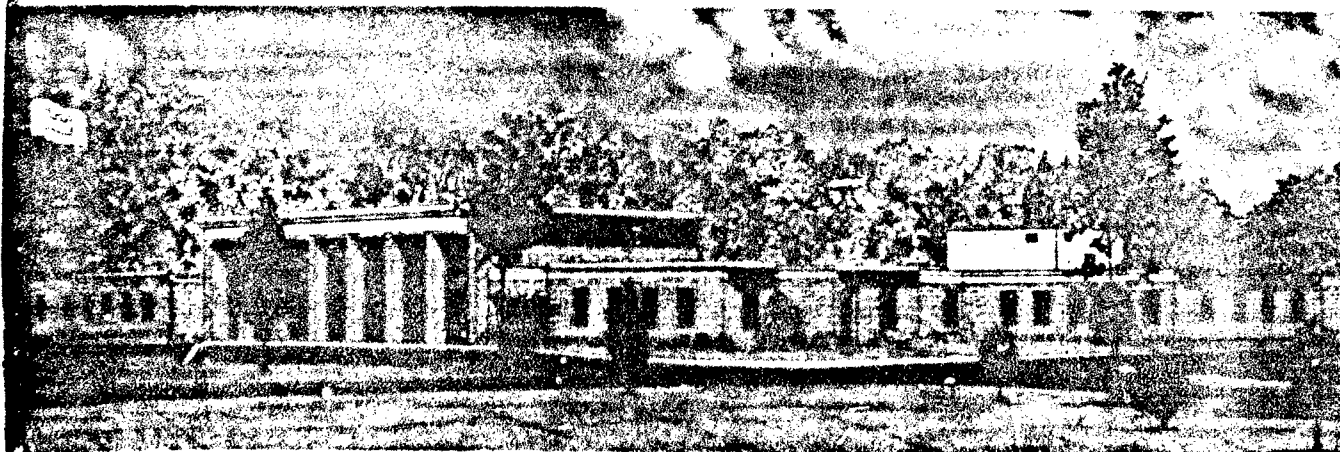
April 1980

Report 2 of a Series

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**DEVELOPMENT OF PROCEDURES FOR NONDESTRUCTIVE
TESTING OF CONCRETE STRUCTURES**

Title

Date

Report 1: Present Practices

October 1977

Report 2: Feasibility of Sonic Pulse-Echo Technique

April 1980

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20. ABSTRACT (Continued).

→ In situ pile lengths up to 70 ft have been measured successfully in soil with low damping characteristics. However, in soil with high damping characteristics the system has failed to measure length of 45-ft-long piles. Several ways to process weak signals and to put in stronger signals are being studied.

→ The system successfully measured the lengths of three drilled piers and detected the location of flaws in the piers incorporated by design at the University of Texas at Austin. Preliminary work at the U. S. Army Engineer Waterways Experiment Station (WES) indicates that the logarithmic decrement of the decaying echo energy is greater when soil rather than air is on the opposite side of a concrete slab. A transverse crack was easily detected in an 80-ft prestressed concrete pile tested before being driven. Preliminary work indicates that void detection and detection of discontinuities in concrete are feasible with the pulse-echo technique.

→ Measurements of thin slabs were found to be more difficult than measurements of piles. Because reflections of echoes in thin sections are of much higher frequency, elastic pulses containing higher frequencies must be introduced into the concrete. To record accurately the arrival of each echo, transducers must be prevented from ringing. A nonringing transducer was constructed and higher frequency energy was introduced into a concrete slab with a rebound test hammer. Tests using this special equipment indicate that crack detection, metal detection, and thickness determinations are feasible with the pulse-echo technique on thin sections.

→ Research should continue in an effort to provide a pulse-echo system that will be capable of nondestructive evaluation of all geometries of Civil Works structures. An ultrasonic unit of low frequency and high energy level should be designed to improve resolution above that of a sonic system for thin sections.

← Because the velocity of the longitudinal wave is a function of the geometry of the structure as well as of the elastic constants, accurate tables should be prepared to give the correct velocity when the element is not a long, thin member. Another alternative is to develop an ultrasonic system in which the velocity is independent of geometry and does not require corrections, making computations simpler.

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PREFACE

The work reported herein was performed to develop and determine the feasibility of using a pulse-echo technique as a nondestructive means of evaluating concrete structures. The study forms part of Work Unit 31553, Maintenance and Preservation of Civil Works Structures," and was partially funded by Work Unit 31138, "Investigation of Testing Methods and Apparatus," authorized by the Office, Chief of Engineers (OCE), U. S. Army. The principal investigators for Work Units 31553 and 31138 are Mr. J. E. McDonald and Mr. J. M. Scanlon, respectively. The OCE technical monitor was Mr. J. A. Rhodes (DAEN-CWE-DC).

This report is the second in a series of reports which will present results of work done to develop, adapt, and improve methods to enhance the capability for nondestructive testing of concrete structures. Experimental work was begun at the U. S. Army Engineer Waterways Experiment Station (WES) in 1976 to develop a pulse-echo system using the mechanical impact technique. Length determinations were first made successfully on long, thin members--ideal physical models--of aluminum and concrete in early 1977. This initial work was accomplished by Mr. A. Michel Alexander who reported the results at the "Symposium on Detection of Subsurface Cavities" held at Vicksburg, Miss., July 1977, and also at the Transportation Research Board Conference held in Washington, D. C., January 1978.

Since initial funding from In-House Laboratory Independent Research (ILIR) project "Development of Ultrasonic Pulse Technique of Determining Method and Degree of Deterioration of Concrete Exposed to Severe Environment" ended in 1976, work has continued under Work Units 31138 and 31553. Many field trips have been made to determine lengths of piles and to advance understanding of the complex nature of elastic wave propagation. The fieldwork was directed by Mr. H. T. Thornton, Jr.

This report was written by Mr. Alexander with technical assistance from Mr. Thornton. The work was performed under the direct supervision of Mr. Billy R. Sullivan, Chief, Engineering Physics Branch, and under the general supervision of Mrs. Katharine Mather, Chief, Engineering Science Division, Mr. John Scanlon, Chief, Engineering Mechanics

Division and Mr. Bryant Mather, Acting Chief, Structures Laboratory, WES.

The Commanders and Directors of WES during this investigation and preparation of the report were COL John L. Cannon, CE, and COL Nelson P. Conover, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

	<u>Page</u>
PREFACE	1
CONVERSION FACTORS, INCH-POUND TO METRIC (SI)	
UNITS OF MEASUREMENT	4
PART I: INTRODUCTION	5
Background	5
Purpose and Scope	5
PART II: DEVELOPMENT OF PULSE-ECHO SYSTEM	7
Principle	7
Apparatus	12
PART III: APPLICATIONS OF THE SYSTEM	16
PART IV: RECOMMENDATIONS FOR FUTURE DEVELOPMENT	19
REFERENCES	25

CONVERSION FACTORS, INCH-POUND TO
METRIC (SI) UNITS OF MEASUREMENT

Inch-pound units of measurement used in this report can be converted
to metric (SI) units as follows:

<u>Multiply</u>	<u>By</u>	<u>To Obtain</u>
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	0.0254	metres
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

DEVELOPMENT OF PROCEDURES FOR NONDESTRUCTIVE

TESTING OF CONCRETE STRUCTURES

FEASIBILITY OF SONIC PULSE-ECHO TECHNIQUE

PART I: INTRODUCTION

Background

1. A field test system is needed for nondestructive measurement of:

- a. The thickness of a concrete member.
- b. The depth to fractures or voids in concrete.
- c. The length of long, thin concrete piling where only one surface is accessible.

Experimental systems exist for measuring concrete pavement thickness, but greater penetration is desirable for other concrete structures. Ultrasonic thickness measurement of thin plates of metals, plastics, etc., is a well-developed and extensively used technique. However, these instruments are low-power, high-frequency systems and are not suitable for thin sections of concrete.

2. A test system is needed to assess the condition of concrete structures with respect to fracturing, loss of foundation support, sheared or broken piling, and location of voids in concrete. A sonic pulse-echo system has been assembled and preliminary tests show it is a feasible system for investigating concrete.

Purpose and Scope

3. The purpose of this investigation was to develop a pulse-echo system to investigate large concrete sections, and to conduct feasibility tests on the system. Because of delays and varied successes and failures in the field applications, it seems desirable to present the results and suggest recommendations for future development.

4. Although pulse-echo systems such as seismic and ultrasonic devices are well-developed for soils and metals, respectively, no acceptable system exists for concrete. All three types--sonic, ultrasonic, and seismic--operate on the principle of elastic waves. However, soil requires a long wavelength and metals require a short wavelength. Concrete, because of its acoustic properties, will transmit and reflect a mechanical wave better when the wavelength is longer than the wavelength required for metal and shorter than that required for soil. This is because the elastic properties of concrete such as modulus, compressional wave velocity, and other properties lie between soil and metal. The sonic pulse-echo device described in this report was developed with these facts in mind.

PART II: DEVELOPMENT OF PULSE-ECHO SYSTEM

Principle

5. The measurement of the time required for a pulse of sonic energy to pass from one boundary to another and back to the original boundary is used to determine the thickness of concrete with only one accessible surface. The reflection, or echo, from the opposite boundary will occur because of the difference in impedance of the concrete compared with either air, water, or soil at the reflecting surface. The impedance of a material is defined as the product of the density and propagation velocity of the disturbance in the material. This reflection technique is referred to as pulse echo.

6. The pulse-echo technique of measurement uses the accurate time base of an oscilloscope to measure the time required for the echo to return from a boundary to the surface where the energy was introduced by mechanical impact. A sonic pulse travels at the longitudinal wave velocity; for a long, thin member, such as a pile, the velocity is equal to $\sqrt{E/\rho}$ (Jones 1962). The ultrasonic wave velocity travels somewhat faster, depending on the Poisson's ratio of the material.

$$V_p = \sqrt{\frac{E}{\rho} \left[\frac{1 - \mu}{(1 + \mu)(1 - 2\mu)} \right]}$$

where

V_p = velocity of pile, ft/sec

E = Young's modulus, psi

ρ = density, lb/ft³

μ = Poisson's ratio

For $E = 6 \times 10^6$ psi,* $\rho = 150$ lb/ft³, and $\mu = 0.167$, the longitudinal sonic velocity will be equal to 13,620 ft/sec and the ultrasonic velocity will be 14,100 ft/sec.

7. Because the energy from an impact has low frequency content,

* A table of factors for converting customary inch-pound units of measurement to metric (SI) units is presented on page 3.

the longitudinal wave will be excited and the ultrasonic wave will not be excited. When low frequency energy (<20 kHz) is used to excite a long, thin structure the energy will exist in the form of the longitudinal wave and the total mass will be disturbed. When high frequency energy (>20 kHz) is used the energy will excite the ultrasonic wave locally and only the material in the path of the signal will be disturbed. The medium surrounding the structure will affect the damping of the wave more in the case of longitudinal excitation since the whole structure is being disturbed.

8. There are a number of ways which can be used to detect an echo from the base of a pile where soil damping is critical. By exciting a pile with energy whose waveform has frequencies above 20 kHz an ultrasonic wave can be generated that is not influenced significantly by the damping of the soil around the structure. By use of a signal enhancer or averager the weak signal of the echo can be brought out of the noise. A third alternative is to develop a high energy impact with an impactor having a mass of several hundred pounds. This is not the most desirable way since the mass of the impactor would hinder portability and accessibility to some surfaces, and possible damage to the structure would prevent the use of the impactor in some situations.

9. The phenomena of damping and scattering, and the type of transducer to be used are three aspects that must be considered in the development of a sonic or ultrasonic unit (Carlin 1960). First, there is the problem of damping. As a mechanical disturbance propagates through a material, the energy is dissipated by damping elements within that material. Damping converts the sound energy to heat. There is no change in the shape of the mechanical wave due to damping; only the amplitude of the wave decreases with distance. Damping is greater in concrete than in more homogeneous materials such as metals. The soil around a structure or foundation material further increases the damping.

10. The second area of concern is incoherent and some coherent scattering. As the elastic wave moves through a material the energy can redistribute itself and change the form of the wave. Energy is conserved but the waveform is altered as the wave encounters various interfaces and

particles within the concrete. Some of the effects of scattering are mentioned below.

11. First, some of the energy that is introduced into the structure as compressional wave energy will be converted to shear wave energy. Second, compression wave energy can be altered so that a tension wave can develop. Third, high frequency components will be reduced to low frequency components causing a decrease in resolution. Finally, a concentrated beam of energy will spread out reducing the intensity of the original waveform. Thus a waveform can be altered in various ways due to the phenomenon of scattering without reducing the total energy, but reducing the useful portion of the total energy for these purposes.

12. The third aspect to be considered is the type of receiving transducer to be used (Bouche 1977). The undamped transducer is a common type used in ultrasonic systems. However, without electronic circuitry to prevent ringing, the ringing can interfere with the measurement. Undamped transducers ring or oscillate when excited mechanically or electrically if the excitation energy has a frequency near the resonant frequency of the crystal. They are very sensitive and useful for detecting the first arrival of a low-energy mechanical pulse.

13. When a mechanical pulse arrives at the measurement surface the transducer will respond instantly to that energy but will not reproduce the pattern of that energy. When a mechanical pulse is introduced into a structure an undamped transducer responds to the motion and will continue to ring at the natural frequency of the crystal, concealing the arrival of an echo if it should arrive before the ringing damps out (Hopkins 1968). This problem will occur in the measurement of short sections because of the brief time required for the return of an echo.

14. Generally, damping and scattering can be overcome by generating the input energy by impact. Because the energy developed is sufficiently large from an impact made on concrete, a series of echoes will be produced before the energy is damped out. The impact need not be of such magnitude as to produce surface failure. An elastic impact is sufficient for most circumstances.

15. The force versus time curve will have the same shape generally

whether the mass of the hammer is a few ounces or a few hundred pounds. The smaller hammer produces a higher frequency impulse with a lower force level. Figure 1 is a force-time trace from a 12-lb hammer striking a concrete surface. The impact also produces energy with low frequency content that tends to overcome the effects of scattering because the accompanying wave length is larger than the grain and particle sizes of the concrete (Stein 1964). The concrete then appears homogeneous to the stress pulse. The elastic wave will see the bulk characteristics of the material rather than the local changes in the elastic properties of the various component materials.

16. The third problem of a ringing transducer for low frequencies can be solved by using a damped transducer (Bouche 1977). The transfer ratio, or its input-to-output ratio, can be made flat over some frequency range. These transducers not only record the time of the first arrival but they also reproduce electrically the pattern of the remaining mechanical motion. Phase as well as magnitude relations are accurate. When the mechanical motion ceases then the signal from the transducer also ceases. Spurious signals are reduced significantly.

17. As long as the wavelength of the elastic pulse is shorter than the time for an echo to return to the surface where the pulse is introduced, such a transducer will not conceal the arrival of an echo.

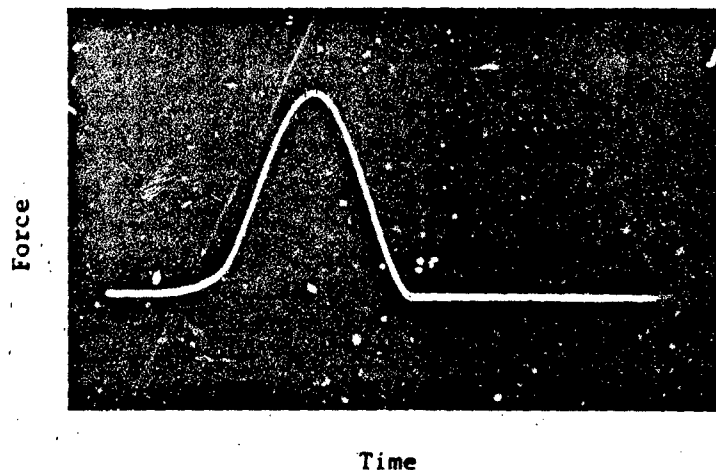


Figure 1. Force versus time curve of an impact from a 12-lb hammer

This type of transducer will also permit recording the frequencies of the reverberations in the test item until they damp out. With the undamped type of transducer the ringing of the crystal will interfere with the frequency of the reverberations thereby preventing the recording of the true mechanical motion. When a mechanical pulse is produced with a transducer rather than an impact, one can produce repetitive signals that can be observed on a conventional analog oscilloscope (Weber, Grey, and Cady 1976). When an impact is applied, only one pulse is introduced into the structure, a transient or "one-shot" signal.

18. Transient signals are difficult to capture and analyze on a conventional oscilloscope. The storage oscilloscope is used to capture a transient impulse. Use of a digital processing oscilloscope (DPO) for analyzing transient signals is a significant improvement above that of the storage oscilloscope. The DPO has a computer memory that gives the user considerable capability of analysis. Signals can be compressed and expanded vertically and horizontally and a part of the signal can be examined. The memory capacity enlarges what can be seen on the screen in time and amplitude, making it possible to display the echo signal with the first impact. As it is a digital oscilloscope, it is suited to the computer and signals can be easily stored on tape and entered into a computer file.

19. Two of the several phenomena that occur with elastic-wave propagation may be developed into cavity detection techniques. First is the concept that surfaces are either fixed or free (Stein 1964). If a compression pulse is introduced into the structure and the opposite surface or interface is fixed in position, the pulse will reflect as a compression pulse. However if the opposite surface is free, as in air, a compression pulse will reflect as a tension pulse.

20. Another phenomenon that might provide valuable information on voids and cavities is acoustic impedance (Carlin 1960). The degree to which an interface between two media reflects and refracts acoustic energy depends on the acoustic impedance of each medium. For example, suppose that an echo of small amplitude is observed in a structure. If it were smaller than expected from the attenuating effects in the

structure, this would indicate that the medium in contact with the concrete absorbed a large percentage of the incident pulse. By knowing the acoustic impedance of water, soil, or air, it may be possible to determine what is in contact with the concrete.

Apparatus

21. The components that make up the sonic pulse-echo system are as follows: Digital processing oscilloscope, accelerometer, camera and magnetic tape unit for obtaining permanent recordings, means for generating a stress pulse, and associated signal conditioning equipment. Sources for generating a stress pulse include an instrumented hammer, a powder gun, pellet gun, a hammer, exploding wire bridge, shock tube, and steel spheres (Figure 2).

22. The generation of a stress pulse by impact involves complex factors which influence the shape of the pulse. To measure short sections, the impact must cease and the hammer separate from the concrete surface in a time shorter than the time required for the pulse to make one transit from the surface to the point of reflection and back to the surface. For a given hammer the person swinging the hammer can influence the force level of the pulse but not the pulse width. The pulse width, which is the time required for the hammer to separate from the surface, is dependent on the length of the hammer head and the properties of the materials in both the hammer and the concrete. Pulse width is not affected by how fast the operator swings the hammer (Stein 1964).

23. Hammers that can be used to make pulse-echo measurements are shown in Figure 3. The frequency of reflections will be low on long sections and high on short sections. Therefore, it is necessary that the impact have the correct frequency content in order to excite the sections so that the maximum amplitude of the echo is developed. The hammers shown in Figure 3 will generate load pulses that have different frequency contents. The smallest hammer mass is 3 lb. the next is 12 lb. The largest hammer is a 20-lb hammer and the lead anchor weighs 26 lb. Figure 4 shows the frequency content of the 3-lb hammer.

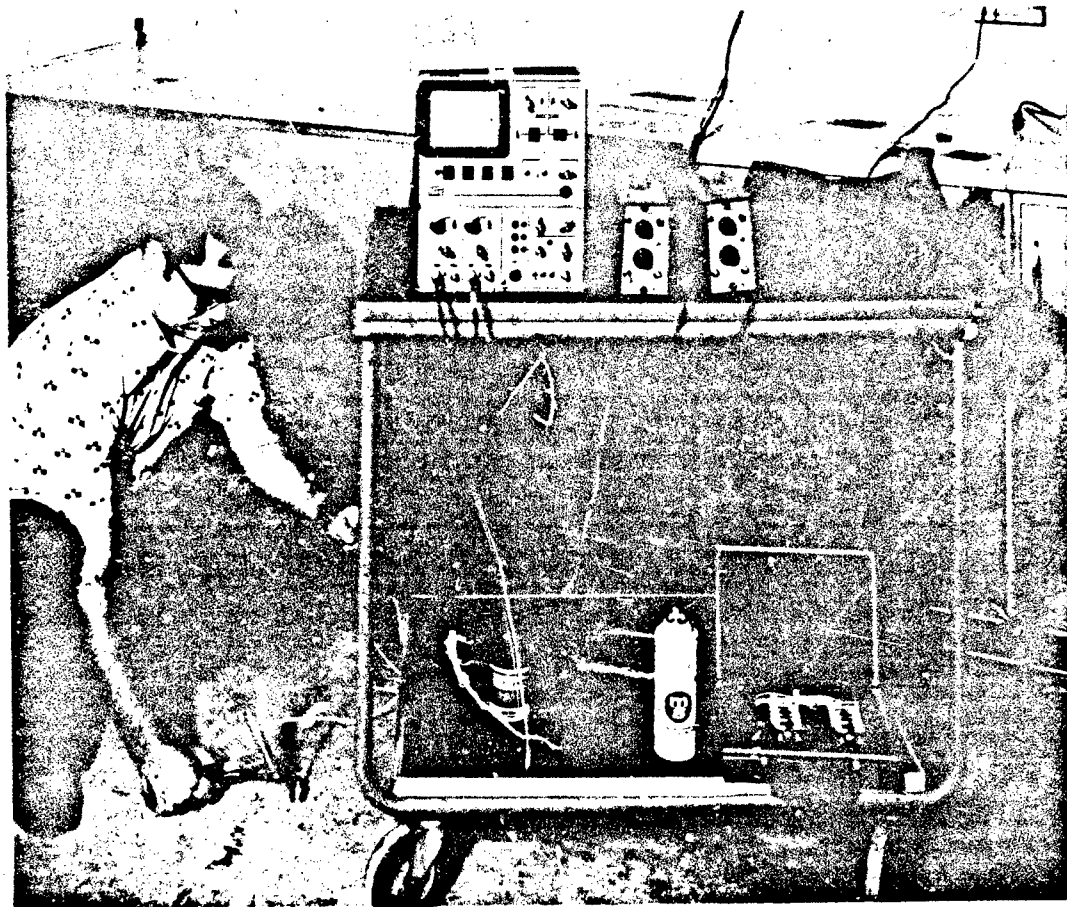


Figure 2. Pulse-echo apparatus

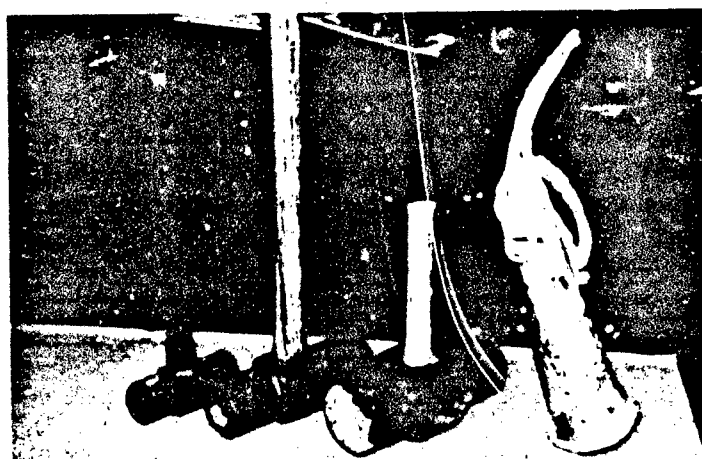


Figure 3. Various impactors used in pulse-echo measurements. Three sledge hammers are shown at the left and a lead boat anchor at the right

24. The spectrum of the 3-lb hammer is flat up to 1000 Hz and has energy up to 2100 Hz. If the section were short enough that the frequency of reflection was greater than 2100 Hz a smaller hammer would be necessary. If the section were longer, then one would not need to excite the structure with higher frequencies and could use a larger hammer. The frequency content curve for the 12-lb hammer is shown in Figure 5. The spectrum is flat up to 500 Hz and shows energy up to 1360 Hz. Although the energy level is uncalibrated in the photograph the amplitude of the energy at each frequency is larger for the 12-lb hammer than it is for the 3-lb hammer. The small hammer being used in Figure 2 is manufactured by PCB Piezotronics, Inc., and can be modified to give different frequency spectra by changing the tip of the hammer head from steel to aluminum or plastic or by adding an aluminum or steel extension to the rear of the head (Halvorsen and Brown 1977).

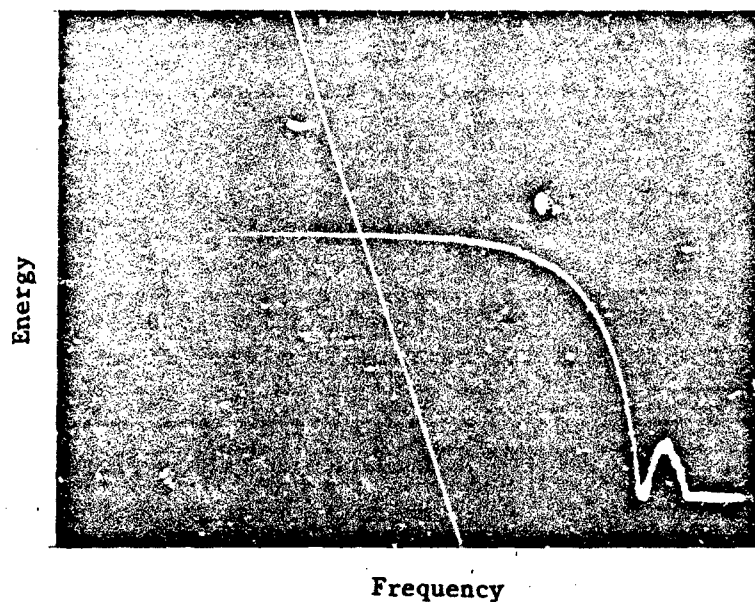


Figure 4. Energy spectrum of an impact with a 3-lb hammer

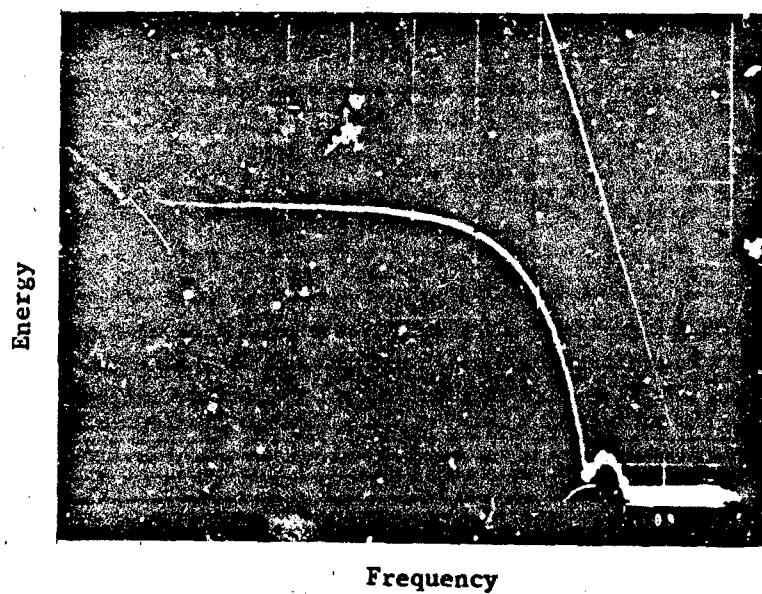


Figure 5. Energy spectrum of an impact with a 12-lb hammer

PART III: APPLICATIONS OF THE SYSTEM

25. The system has had a limited amount of testing and evaluation. Most of the tests were made under controlled laboratory conditions. The first length determinations were made on an aluminum beam. The velocity of the beam was known, it was homogeneous, and had low attenuating characteristics. A concrete cylinder was then tested by placing it upright on a foam rubber pad to produce a pronounced impedance mismatch so that more signal would be reflected than refracted. By assuming a velocity of about 14,000 ft/sec the 12-in. length was confirmed.

26. The next test was made on a 65-ft pile under an overlook structure in Monroe, La. This condition added the factor of a driven pile in soil with about half of the pile bounded by soil. A slab floor with concrete beams supporting the slab on the piles introduced new factors into the measurements. However, the technique worked and it was possible to confirm the length of the pile, as already known from plans. It was learned from these tests that the introduction of additional transmission paths and boundaries due to complex geometry produced a fairly complex series of reflections.

27. The next testing was a field trip to Kingsland, Ga., to make length determinations of piles underneath an ocean terminal. Here new factors were introduced. Piles were driven into the bay and penetrated the rock strata below. Because of the added reflections from rock, soil, water, and a superstructure, consisting of a slab with girders and caps above the piles, some difficulties were encountered in resolving the correct echo. However, through estimation of undesired echoes by calculating multiple times for second, third, and fourth echoes from shorter transmission paths, it was possible to narrow the possibilities down to two or three more probable lengths. Had knowledge of the rock foundation and construction details been available the other reflections might have been eliminated with more certainty.

28. About 200 pile lengths were determined in Honolulu, Hawaii. These piles were from 6 to 14 ft in length and supported 12 military housing buildings. Although a low longitudinal velocity of 10,000 ft/sec

was encountered and attenuation of the signal was high, the length determinations were successful.

29. At Austin, Texas, three drilled piers of known lengths installed by the University of Texas were measured and also the presence and locations of two faults incorporated by design were detected. Because surface-wave energy concealed the echo energy from the bottom of the piles and the reflections from the faults, it was necessary to use an electronic filter and attenuate the higher frequency surface-wave energy.

30. Figure 6 shows an 80-ft prestressed concrete pile, 14 by 14 in. in cross section. This pile was measured in a pile yard at Metairie, La., as a first step in determining the velocity of similar piles driven into the Atchafalaya Basin levee near Morgan City, La. A typical series of echoes is shown in Figure 7. Because the damping is minimal when the pile is in the air rather than in soil, 10 to 15 echoes could be recorded.

31. Tests made on the pile foundation of an inverted T-wall that permitted a pipeline to pass through a levee on the Atchafalaya River near Morgan City, La., were not successful. Even with a 20-lb hammer

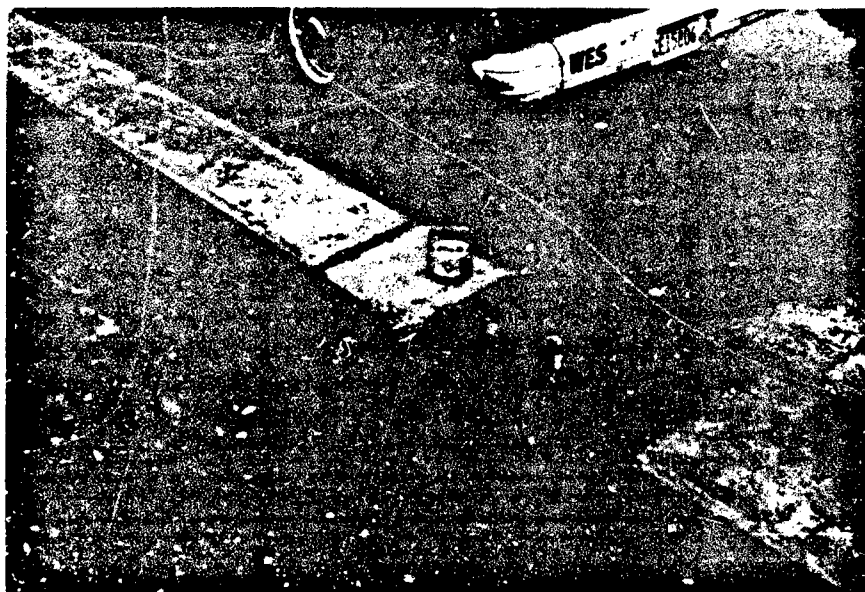


Figure 6. 80-ft pile at Metairie, La.

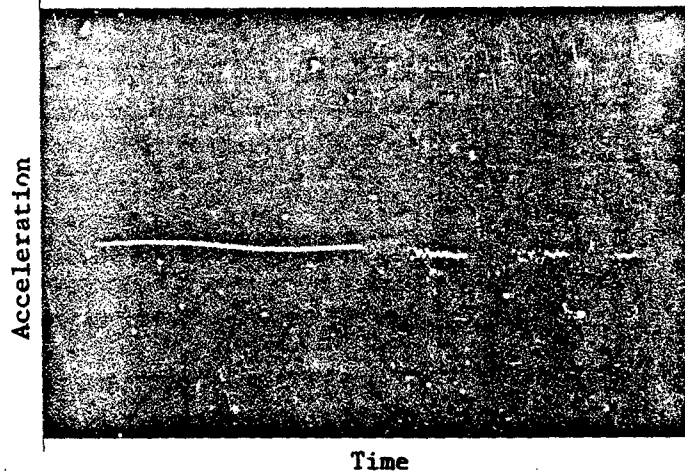


Figure 7. Typical arrivals of wave from end of pile

there was insufficient signal put into the 80-ft piles to produce an echo. The damping of the surrounding soil prevented sufficient longitudinal vibration of the piles to be detectable.

32. Failure to receive an echo from the 80-ft pile bounded by clay was caused by the skin friction which restrained the movement of the pile. A longitudinal wave was produced in the pile by an impact with a hammer. The longitudinal resonance resulting in the pile was so damped that a single cycle of oscillation could not be detected. This corresponds to a critically damped system where no oscillation will occur due to the amount of damping presented by the soil. This problem can be solved by using a high frequency source to excite a P-wave in the pile which is unaffected by the skin friction and therefore by the damping of the soil, and an echo would be received so that the length of the pile could be determined.

33. Later a field trip was made to Port Gibson, Miss., to attempt to determine the lengths of piles being driven for a bridge. The length of 45-ft piles was not measured due again to the damping of the soil.

PART IV: RECOMMENDATIONS FOR FUTURE DEVELOPMENT

34. Several possible developments to improve the pulse-echo technique are discussed below. Several of these may be used together. The possibilities include:

- a. Improvements in the detection of useful reflections.
- b. Summing the received signals to improve the signal-to-noise ratio.
- c. Use of a spectrum analysis.
- d. Improvements to the signal input.
- e. Use of ultrasonic rather than sonic waves.
- f. Improvements in calculations of E by use of geometrical corrections to the methods.
- g. Model investigations of cavity detections under slabs.

35. Because structures of complex geometry produce signals that have many reflections, it is difficult to recognize the reflections coming from the surfaces of interest. When there are multiple reflections, analysis is required to pinpoint the location of each. An electronic filter eliminates some of the extraneous reflections. A filter is basically a manually operated spectrum analyzer so a real-time spectrum analyzer would be a significant improvement. The spectrum analyzer covers the complex waveform of a signal that varies in time and contains a band of frequencies into separate frequencies displayed as individual peaks.

36. Where noise and damping are problems, the addition of a signal-enhancement device would be a significant improvement. One can sum a series of transients by making a number of impacts and the signal can be improved considerably. The parts of the signal that are desired are all in phase and add constructively, while the random noise will cancel out. This is a common technique used in making seismic measurements and is ideally suited for the shorter wavelength concrete measurements.

37. Transducers can be specially built to have a flat transfer ratio over a short range of frequencies. When it is known that some

defect may lie between the two known depths, the range of echo frequencies within that specified band can be easily calculated. If there is energy reflecting off of an unwanted surface at a frequency higher or lower than the specified band for that transducer, the transducer will not be sensitive at that frequency and the noise will not be recorded.

38. A repetitive controlled source of energy would improve measurements, allowing a surface to be explored much faster and permitting the operator to adjust controls.

39. Efforts should be continued to measure lengths and detect flaws with P-waves rather than longitudinal waves as P-waves are independent of geometry and only relate to the elastic constants of the material. Electric impactors that can generate high energy, high frequency pulses should be tested with the hope that ultrasonic waves will be produced rather than waves that resonate a structure. Since ultrasonic waves have constant velocity for constant elastic properties it becomes much easier to interpret the data from measurements.

40. The longitudinal equations by Pickett (1945) are only exact for long, thin cylinders or bars. As the ratio of length to cross-sectional dimension decreases the velocity of the elastic wave decreases. The maximum velocity is called the bar velocity and is equal to $\sqrt{E/\rho}$ for the long, thin members. The minimum velocity can be as low as the Rayleigh wave velocity (Wasley 1973). Corrections have been developed by Spinner and Tefft (1961) for calculating the dynamic E from the longitudinal equations of Pickett corrected for geometry. Tables should be made from these corrections to give velocities with various dimensions.

41. Preliminary tests indicated that the logarithmic decrement of the damped vibrations of a slab from a mechanical impact is greater when the opposite face is bounded by soil as opposed to air or water. Air or water tends to reflect energy back to the surface while soil tends to absorb the energy. Measurement criteria should be established for detecting voids by constructing a laboratory model slab and placing the slab on different configurations of model voids containing air or water. Because different materials have different acoustic impedances, variable

amounts of energy will be refracted into the material. It may be too optimistic to expect to identify a type of material, but it may be feasible to detect the presence or absence of a foundation material using acoustic principles. Figure 8 illustrates a typical damped vibration of a slab resting on a soil foundation.

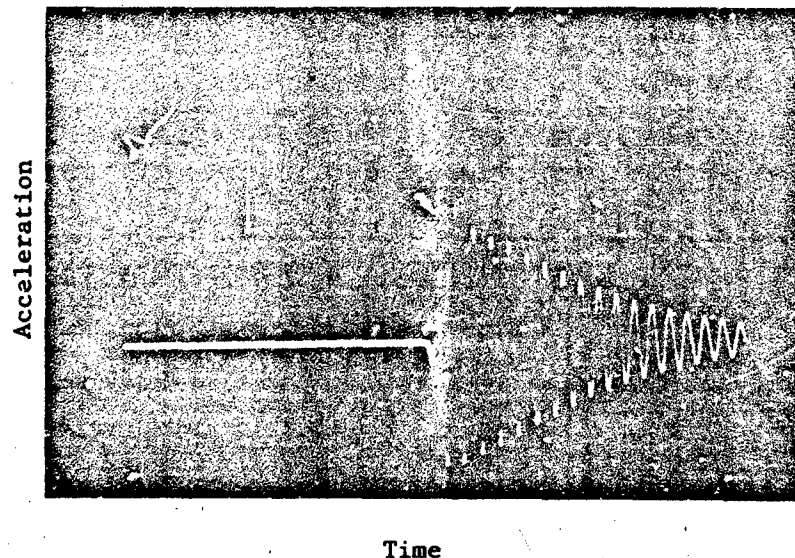


Figure 8. Damped vibration of a slab

42. Introductory tests show promise for thickness determinations and flaw detection in thin sections. A nonringing transducer has been constructed that will record the arrival of all echoes without obscuring the presence of an echo by the ringing produced from an earlier one. Spectrum analysis of the excitation pulse from a rebound test hammer shows that the pulse contains frequencies up to 36 kHz. As the velocity is equal to two times frequency times length, one can excite the longitudinal mode in concrete down to about 2-1/2-in. minimum thickness. A laboratory slab should be constructed with a designed internal flaw as well as some metal reinforcement and tested.

43. Initial work was done on a floor slab over a basement supported by concrete girders and many echoes were detected. Although metal reinforcement seemed to be detected in the slab as well as in the girders, it was not conclusive because the plans showing steel

distribution were not available. The frequencies of all reflections were determined with a real-time spectrum analyzer. Figure 9 shows a model SD335 spectrum analyzer manufactured by Spectral Dynamics Corp.

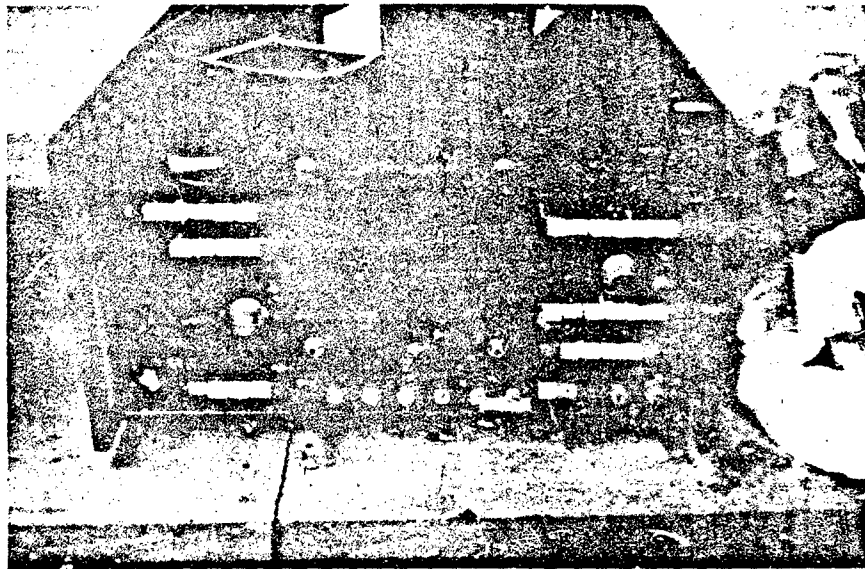


Figure 9. Spectrum analyzer

44. Tests made on a pile in New Orleans revealed that the system would detect cracks. Figure 10 shows the cracked pile. Although the crack completely traversed the cross section, the prestressing cable kept the two parts of the pile together. The crack was 16.2 ft from the impact end and the total length of the pile was 81.6 ft. As the crack was located at almost 20 percent of the length of the pile from the end of which the signal was input, four reflections were seen from the crack before the fifth reflection added to the large reflection from the end of the pile. The oscilloscope trace in Figure 11 showed two more reflections from the crack before the trace ended. The velocity in the pile was 14,245 ft/sec.

45. A shear wave was generated by impact in a pile having a rectangular cross section. For cylindrical piles it would be necessary to construct a band that encircles the pile with an impact plate that could be struck with a hammer to generate a torsional motion. Tests on the

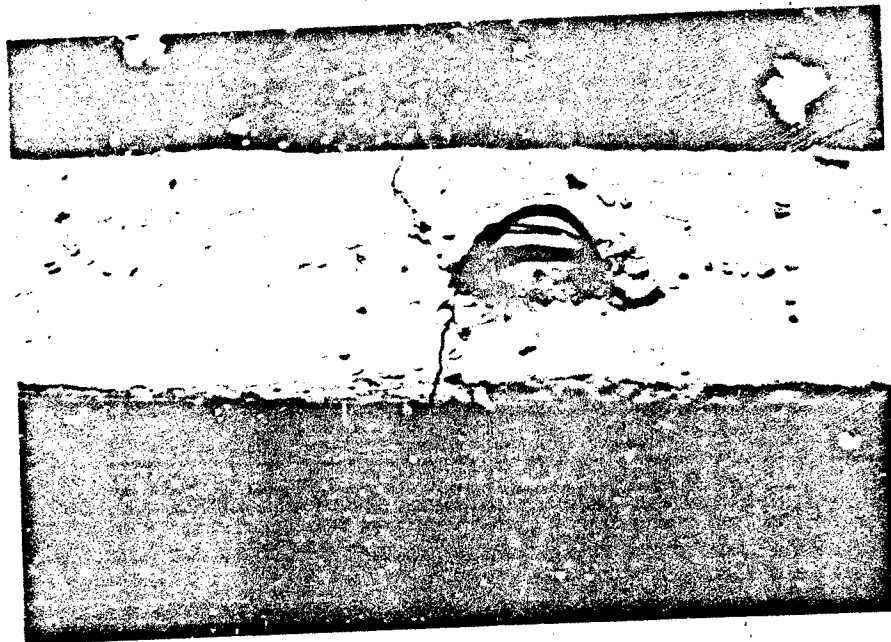


Figure 10. Cracked pile

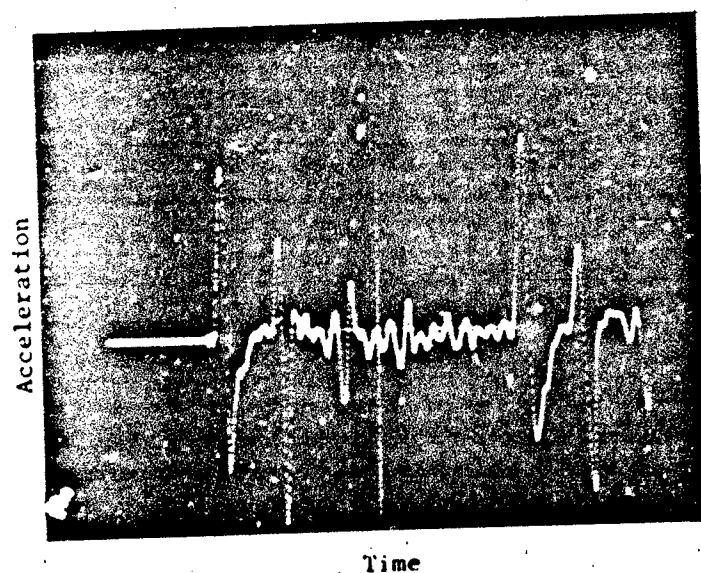


Figure 11. Arrivals of pulse from end of pile and from a crack

cracked pile shown in Figure 10 revealed that shear waves are better than longitudinal waves for crack detection.

46. The pulse-echo technique has the potential for detecting cracks, voids, and faults in and underneath concrete structures. The benefits of such a system are obvious. The work that would have been required on the Georgia wharf to determine the length of the piles of 55-ft typical length by other methods would have been tremendous. The piles were in 30 ft of water, 20 ft of soil, and 5 to 10 ft of rock in typical locations.

47. Nondestructive techniques would appear to be the key to mapping subsurface conditions and as appropriate signal analysis techniques are developed their full potential can be achieved.

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In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Alexander, A Michel

Development of procedures for nondestructive testing of concrete structures: Report 2: Feasibility of sonic pulse-echo technique / by A. Michel Alexander. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1980.

25 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; C-77-11, Report 2)

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1. Concrete structures. 2. Concrete tests. 3. Nondestructive tests. 4. Pulse echo techniques. 5. Sonic tests. I. United States. Army. Corps of Engineers. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; C-77-11, Report 2.

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