DEVELOPMENT OF AN INSTRUMENT TO AUTOMATICALLY MEASURE DELAMINATIONS IN CONCRETE FLATWORK - DEMONSTRATION OF FEASIBILITY

Prepared for:

Canada Mortgage and Housing Corporation
Project Implementation Division
682 Montreal Road
Ottawa, Ontario
K1A 0P7

Prepared by:

B.H. Levelton & Associates Limited

This project was carried out with the assistance of a grant from Canada Mortgage and Housing Corporation under the terms of the Housing Technology Incentives Program (HTIP). The views expressed are those of the author and do not represent the official views of the Corporation.

6521-6/87

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STAGE I - DEMONSTRATION OF FEASIBILITY

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A Report Presented to

Canada Mortgage and Housing Corporation
Housing Technology Incentives Program
National Office
682 Montreal Road
Ottawa, Ontario
K1A 0P7

Project Officer: Frank C. Pelley

Prepared by

B.H. Levelton & Associates Ltd.
8805 Osler Street
Vancouver, B.C.
V6P 4G1

P.T. Seabrook, P.Eng.

N.A. Cumming, P.Eng.

in Cooperation with

J.A. Bickley, P.Eng.

March 3, 1988

File: 187-737

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1.0 INTRODUCTION

1.1 Background

Deterioration of steel reinforced concrete parking structures and similar structures is becoming a widespread and costly problem. In the case of parking structures, corrosion of the reinforcing steel is exacerbated by intrusion of chloride ions into the concrete. The chlorides are commonly introduced either by direct application of deicing salts or are brought in on vehicles, which then drip chloride-laden water onto the slabs.

As the reinforcing steel corrodes, the highly expansive nature of the reaction causes high internal stresses which eventually cause the concrete to split, or delaminate, along the plane of the mat of steel. Eventually the concrete cover spalls away, leaving shallow craters in the slab with exposed steel in the bottom.

Repairs commonly involve chipping out the unsound concrete, sandblasting or high-pressure waterblasting to remove the corrosion products, preparing the surfaces, and filling of the depressions with new mortar or concrete. In many cases a topping, membrane, or other surfacing may be applied to the repaired slab.

The Canada Mortgage and Housing Corporation, through its lending programs, is financially involved with numerous reinforced concrete parking structures, many of which have been damaged by chloride-induced corrosion. These structures are located throughout Canada, hence this research work has national implications.

The current method for detecting and quantifying delaminations involves a sounding technique in which a heavy chain or a hammer is used to locate those areas of a slab having a "drummy" sound. The boundaries are determined by tapping with a hammer, and the perimeter thus established is taken as the limit of delamination.

Several major difficulties are inherent in this process:

- it is a crude test at best, and is very labour-intensive;
- the results are somewhat interpretive, and difficult to reproduce from year to year. This is important from a maintenance standpoint if the progression of delamination is to be monitored;

- in the case of a repair contract, quantities often exceed the amount estimated on the basis of a chain drag survey, creating cost overruns and contractual difficulties.

In an attempt to address these difficulties, CMHC contracted with B.H. Levelton and Associates Ltd. (Levelton) to investigate the feasibility of developing an instrument that is capable of automatically and nondestructively detecting and recording delaminated areas. The study is funded under CMHC's Housing Technology Incentives Program.

1.2 Objectives

The ultimate objective of the project is to develop a prototype on-site surveying instrument which can be operated in a continuous mode by a single operator. The device would have the ability to automatically record and process data, and would ideally demonstrate improved reproducibility and accuracy over the conventional chain drag technique.

It is known that the technology exists to electronically detect delaminations. The study described herein was undertaken with the objective of demonstrating that the technology is effective and can be adapted to field use by a trained technician.

1.3 Scope

At least three electronic systems of locating delaminations are currently under study. The intent of Levelton's investigation was to demonstrate the performance of each to locate and quantify known delaminations, evaluate the results in terms of accuracy and reproducibility, and evaluate the potential of a preferred system for adaptation to the automated recording device envisioned.

The study also required an assessment of the commercial activity that might follow from the use of the HTIP funds.

1.4 Approach

The study was undertaken in three phases:

Phase I : A demonstration reinforced concrete slab was designed and cast. The slab was intended to simulate a typical parking structure slab, and was to contain a number of intentional defects simulating delaminations at the levels of the top and bottom reinforcement.

The slab was constructed at the Structures Laboratory of the Department of Civil Engineering, University of Ottawa.

Phase II : Three groups of researchers known to have developed different types of pulse-echo technology, with the potential for success in detecting delaminations, were invited to attend and survey the slab "blind", i.e. without prior knowledge of nature or locations of the defects in the slab.

Field work was completed between October 19 and 23, 1987. Levelton was in attendance to observe and evaluate the work.

Phase III: Following completion of the field work and submission of reports by the researchers, the data and systems were evaluated and this report was prepared.

2.0 CORROSION DAMAGE TO REINFORCED CONCRETE

2.1 Corrosion Mechanism

In its normal state, the highly alkaline environment of concrete promotes the formation of a protective film around steel and corrosion is inhibited. Typically a new concrete will have a pH of 12.5 or higher. If the pH is caused to fall below about 10, the protective film breaks down and corrosion can occur if water and oxygen are available in sufficient quantities.

Two primary means are recognized by which the pH of the concrete can be lowered.

2.1.1 Chloride Contamination

The infusion of free chloride ions into the concrete matrix lowers the pH and causes the protective film to break down. This mechanicsm is the most common means by which corrosion of steel in concrete is initiated, and has caused substantial damage to structures exposed to chlorides.

Chlorides may be introduced through:

- use of aggregates containing free chlorides;

- use of chloride-based admixtures;

- direct application of chloride-based deicing salts;
- indirect contamination by chloride-laden water dripping from vehicles.

The concentration of chlorides necessary to depassivate the steel is about 0.025 percent by total mass of the concrete. In most areas of Canada where deicing salts are liberally applied to roads, it takes only a few years of indirect contamination for the concentration in concrete parking structures to reach this level.

2.1.2 Carbonation

Under certain conditions of temperature and humidity, atmospheric carbon dioxide will react with hydroxides produced by the hydration of cement. This lowers the pH to about 8.5, creating an environment in which corrosion can occur. This phenomenon occurs only at the surface of the concrete, normally however, over a long period of time the depth of carbonation increases and can reach the depth of the rebar.

Bickley(1) has concluded that the appropriate conditions for carbonation exist in many Canadian cities, and that corrosion induced by carbonation can be expected to occur in the near future if it is not already occurring.

2.2 Delamination

Once corrosion has been established, it will continue as long as sufficient oxygen and moisture are available. The oxides produced by the reaction occupy many times the volume of the steel consumed, and result in substantial internal stresses in the concrete. These stresses cause the concrete to fracture around the rebar, or in more severe cases can create a larger horizontal fracture which extends across a number of bars. Typical examples of such delaminations are illustrated in Plate A1 in Appendix A and Photograph B1 in Appendix B.

The problem can become particularly pronounced at normally ocurring shrinkage cracks, or unsealed expansion or construction joints, where chloride-laden water has a free path to the steel. In such areas, or in more advanced cases, corrosion of the lower steel can also occur, causing a second level of delamination. Delamination is also frequently seen around the bottoms of columns (Photograph B2), where chloride-laden water is splashed or sprayed, or in beams below leaking cracks or joints.

The structural problems associated with delamination are:

- loss of protection of the steel;
- loss of bond between concrete and steel;
- loss of area of the steel.

In advanced cases the load capacity of the structure can be decreased.

3.0 MEASUREMENT AND DETECTION OF DELAMINATION

3.1 Sounding Techniques

The chain-drag technique is the method most commonly used for identifying and mapping delaminations. This procedure entails dragging a heavy chain along the slab surface until a hollow sound is heard. A typical chain-drag device is shown in Photograph B3.

Once a hollow sound is heard, it is necessary for the technician to stop and delineate the boundaries of the defect by tapping with a hammer. It sometimes helps if a small amount of sand is sprinkled on the surface. The grains will bounce when delaminated concrete is struck with a hammer and will not bounce if the concrete is sound.

The procedure is relatively effective for shallow delaminations in slabs of uniform thickness. Its effectiveness diminishes considerably as the depth of delamination increases, or if there are changes in slab thickness such as in a pan-joist type of construction:

Other limiting features are:

- only well defined delaminations will be found. Very small, or tight and narrow cracks will not give the characteristic hollow sound. Incipient cracks will also not be found;
- the depth of the delamination cannot be determined;

- the presence of more than one level of delamination cannot be detected;

- traffic and other noise can interfere with the survey.

Although the chain-drag technique is crude, is labour-intensive, and relatively expensive, it is the only means that is readily available on a commercial basis, and is therefore the primary choice of most engineers.

A device has been developed to automatically detect and record delaminations using a tapping or sounding technique. The device is reported to be commercially available, however, it does not appear to be in wide use. A comparison of the device's performance compared to a chaindrag survey did not show good results(12).

3.2 Sonic Techniques

For readers who are unfamiliar with the concept of ultrasonic inspection of materials, Appendix F provides a brief explanation.

Ultrasonic flaw detection in concrete has been studied for many years, and one type of device has been commercially available for about 15 years. It uses piezoelectric transducers to send and receive an ultrasonic pulse through the concrete and measures the time of flight. The procedure is most effective when the transducers are placed on opposite faces of the concrete member as shown in Plate A5(a).

This concept has formed the basis for intensive research in recent years. The thrust of the research has been to develop a system that can be used from only one side of the concrete, as shown in Plate A5(b) and (c), and to improve penetrating ability and resolution of the responses.

Recent published work has shown that several systems are capable of detecting delaminations, however, only one has reached a stage of commercial availability.

3.2.1 Pulse-Echo Techniques

Recent refinements of the ultrasonic technique described above have involved the development of equipment which records not only the time of flight of the pulse, but also displays the shape of the received waveform as a plot of amplitude versus time. A typical waveform is shown in Plate A2.

The configuration and design of the transducers is such that a pulse is initiated at a certain location on the concrete surface, and the signal reflected from the opposite surface and any intermediate flaws or discontinuities is received by a second transducer placed adjacent to the first. The flaws or discontinuities appear in the waveform as intermediate peaks.

In order to obtain reasonable penetrating power through the concrete it is necessary to use a low frequency ultrasonic pulse, typically between 50 and 200 kHz. At these frequencies the resolution is not optimum. A trade-off can be made by increasing the frequency. The resolution improves, but the depth of penetration diminishes. Much of the current research is therefore devoted to improving the transducers.

The behavior of the stress pulse in concrete is relatively independent of its age and maturity, after a strength level of about 20 MPa has been attained. Very mature concrete may allow the pulse to travel slightly faster, but this does not affect the interpretation of the results. The ability of the signal to penetrate a reasonable distance into the concrete depends primarily on the frequency of the pulse. This characteristic is not significantly affected by the age or maturity of the concrete.

3.2.2 Impact-Echo Techniques

The impact echo technique is essentially similar to the pulse-echo technique, but uses a mechanical impact rather than an ultrasonic transducer to create the pulse. More details are given in Appendix F.

One such impact echo system is available commercially on a proprietary basis. The proprietor claims great success, however, Levelton and others who have used the system have observed mixed results. The interpretation of the waveforms appears to be highly subjective, and in new applications much experimentation and calibration to known conditions appears to be necessary. The system does, however, appear to be capable of detecting delamination. Photograph B4 shows the system in use.

More recent research has entailed analysis of the signal as a frequency spectrum rather than as a simple waveform on a time basis. A typical frequency spectrum is shown on Plate A3. In this mode, it has been found that the signal is highly reproducible, and that peaks in the spectrum can be related to the depth of the reflecting surface within the concrete with relatively good precision. Appendix D contains an explanation of the physics involved.

An attractive feature of this work is that a special point-contact transducer has been developed, which does not require the use of the liquid or gel-type couplant used with other types of transducers. This makes field use of the transducer much more practical.

3.3 Radar and Thermography

Infrared thermography has been used to map delaminations with some success. Under certain atmospheric conditions, there is a temperature differential between the sound and delaminated concrete which can be recorded by commercially available infrared imaging equipment. This concept has the advantage of being capable of detecting delaminations through an asphaltic concrete overlay.

Best results are obtained when the deck is exposed to bright sunlight so that the deck is heated relatively uniformly. In the case of a parking structure, all but the top levels are shaded or partially shaded, and insufficient radiant heating would occur to render the procedure effective. Also, it is best if the camera can be mounted 4 to 5 m above the deck so a relatively large area can be scanned at once. In a parking structure, the height restrictions would limit the camera's field of view, requiring numerous passes to scan the entire surface.

It has been reported(4) that the results are not sufficiently accurate for preparation of contract documents.

Ground penetrating radar has been used to supplement the infrared thermography approach. The antenna is mounted about 150 mm above the deck surface and scans a pass about 500 mm wide. The system has been shown to have the capability of detecting delaminations, however, there is difficulty in identifying very shallow delaminations, and numerous false defect indications have occurred.

3.4 Other Techniques

A proprietary device known as an "Instrumented Delamination Detector" is available in England. Contact was made with the proprietor during the course of this study.

Despite this contact, little was learned of the device other than it measures an "energy" value of some type.

Another device, known as a "Delamtect" is essentially an automated chain drag. The device taps on the deck and the sound is recorded by microphones. An electronic package then sorts the sounds into sound and delaminated categories. Users have reported mixed results, and the device does not seem to be in common use.

4.0 FIELD TESTING PROGRAM

4.1 Test Specimen

The test specimen was cast as a steel reinforced concrete slab measuring 1.5 m x 3.0 m x 200 mm thick. It contained six simulated delaminations which were fabricated by placing three layers of 4 mil polyethylene sheeting into the concrete as it was cast.

The as-constructed details appear on Plate A4. Photograph B5 shows the finished slab.

Surveys were carried out along two grid lines drawn by Levelton on the test slab in a location that intersects the simulated delaminations. This was simply for convenience and efficient use of time and does not effect the representative nature of the data.

4.2 National Bureau of Standards

Representatives of the National Bureau of Standards, Washington, D.C. surveyed the slab using an impact-echo technique. Their technique employs a mechanical impactor such as those shown in Photo B6. A custom designed point contact transducer is used to receive the signal (Photo B7). The data is recorded electronically, mathematically transformed to a frequency spectrum, and displayed on a storage oscilloscope. A hard copy can be printed by a plotter. Photographs B8 to B10 show the equipment and the survey in progress. More details of the technique are included in Appendix D.

4.3 U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers Waterways Experiment Station, has developed ultrasonic pulse-echo equipment that is suitable for measuring the thickness of slabs. The system uses the custom-designed transducers shown in Photos B11 and B12, and an oscilloscope which has the capability of storing the signal on a disc, Photo B13.

The research carried out by the Corps has been largely devoted to developing improved transducers which are suited to measuring the thickness of slabs. This work has resulted in the design of a transducer which has proven more successful in this application than conventional transducers. It has a broad, flat configuration which has a much larger footprint than other transducers, and operates at a relatively high frequency. These two characteristics produce a relatively narrow beam of energy which allows smaller defects to be detected. However, because of the higher frequency the penetrating power suffers, and the maximum thickness of concrete that can be effectively surveyed is about 500 mm.

Photos B14 and B15 show the survey in progress. Castor oil is used as a coupling medium.

The equipment is capable of surveying continuously along a line, as opposed to testing discrete sites spaced at intervals along the line.

4.4 Techno Scientific Inc.

Techno Scientific Inc. is a privately held Canadian Corporation whose primary business involves research, development and manufacturing of transducers and sensors, automated nondestructive testing apparatus and robotics. The firm places emphasis on computer-enchanced data acquisition and processing.

TSI has developed to a preliminary stage an ultrasonic pulse-echo system for inspection of concrete. The features of their system are:

- highly specialized and effective transducers;
- digital data acquisition and signal processing;
- specialized software to allow summation and magnification of the signal.

Photos B16 to B19 show the equipment and the survey in progress.

5.0 RESULTS

5.1 National Bureau of Standards

The report of the National Bureau of Standards appears in Appendix D. Plate C1 shows the locations of the delaminations as reported by NBS with a transparent overlay showing the actual locations.

Time constraints did not allow the boundaries of the delaminations to be mapped precisely; once each defect was identified, it was surveyed at close intervals along two perpendicular lines. Hence, the defects were recorded as being rectangular in shape.

It can be seen that the locations and sizes of defects were identified with excellent precision. The depths were also measured reasonably accurately, with the exception of the smallest defects, where the depth could not be established.

5.2 U.S. Army Corps of Engineers

Plate C2 shows the defect characteristics as reported by the USACE, with a transparent overlay showing the actual defect locations. All the defects were located by USACE and the depths measured accurately. There was some difficulty in defining the boundaries precisely, and there were several spurious defect indications.

5.3 Techno Scientific Inc.

TSI's report appears in Appendix E. Plate C3 shows the locations of the delaminations as reported by TSI, with a transparent overlay showing the actual locations. It is seen that the correlation is poor. The largest and shallowest delaminations were detected, but the locations were not determined precisely. The smallest delaminations were missed, even at a shallow depth.

The analysis used by TSI was unable to identify the sizes or depths of the delaminations that were detected.

6.0 CONCLUSIONS

Both the NBS and USACE procedures were capable of locating delaminations and measuring their depth. The NBS system demonstrated excellent precision in defining the boundaries of the defects. The depths of the delaminations were also determined reasonably well, with the exception of the smaller or shallow ones.

The USACE system located all known delaminations and measured the depth accurately. It was less successful than NBS in defining the boundaries, and gave some false positive indications.

The TSI system was able to locate the larger or shallower delaminations, but the overall performance was poor in comparison to the other systems. The approach used by TSI did not identify the boundaries or sizes of defects.

It can be concluded, however, that ultrasonic pulse-echo and impact-echo technology is capable of mapping delaminations. The impact-echo technique is the most advanced and shows the most promise.

Certain features of the TSI system, such as the digital data acquisition, are relevant to the future development of this program, and there may be a possibility to combine the best aspects of the three systems evaluated herein.

7.0 DISCUSSION

7.1 Validity of Results

The program has demonstrated that ultrasonic techniques can be used to locate and map delaminations. The defects were intentionally small, certainly smaller than typical delaminations found in parking structures. The use of polyethylene sheets to simulate the delaminations created a situation which would be more difficult to detect than a typical air-filled delamination because the change in acoustic density is smaller. Hence, there was a high degree of success under circumstances that were significantly more demanding than an actual structure.

A crude chain drag survey was done on the slab. The results were negative with the exception of the largest shallow void, which gave a very subtle change in sound. The change was not sufficiently distinct to identify the edges of the defect. Hence, it has been further demonstrated that small, incipient delaminations can be identified by pulse-echo technology which would be missed by a chain drag survey.

7.2 Adaptability to Field Use

An important aspect of the program is to assess the feasibility of adapting the equipment to field use. It is clear that the ultrasonic transducers used by USACE and TSI have limited practicality because a grease or gel-based coupling medium is needed at each test location. Also, their large contact area limits their effectiveness on rough or uneven surfaces, and the physics of the transducers precludes any meaningful reduction in their size.

The NBS transducer is the more adaptable to automated field use, since only a point contact without a gel-type coupling medium is used. Any adaptation would need to address the following aspects:

- need for a more rugged, durable transducer;
- effect of rough and dirty slab surfaces;
- electronic data acquisition and recording;
- electronic data processing and analysis.

The major drawback of the system is that the survey must be conducted on a point-by-point basis, thereby limiting the precision unless the points are spaced very closely. To overcome this, a prototype device would need to accommodate a number of separate channels of data acquisition simultaneously. This creates another inherent difficulty: each of the multiple test locations would need to be impacted separately to avoid interfering with the signal of the adjacent channels.

Despite these practical limitations, it is believed that the NBS system shows good promise.

7.3 Electronic Data Acquisition

In order to develop a prototype instrument it would be necessary to design a system of electronic data acquisition and processing. The TSI system has demonstrated the feasibility of this aspect. Once their equipment was set up, the signal from each survey point was electronically digitized and stored on a disc. Each point took about 10 to 15 seconds to test, even when the transducers were moved from point to point manually. The NBS and USACE systems also had the capability to electronically gather and store the waveforms.

The next step would be to develop software to analyze the signals. The NBS system has made some advancement towards this goal, in that an electronic mathematical transformation is made to display the signal in a frequency domain rather than the time domain in which it is recorded. The nature of signals returned by delaminated and sound concrete can be relatively easily established, hence the challenge would be to develop software that can recognize the characteristics of each, and differentiate between these and other signals. This would involve a substantial amount of calibration to known conditions, so that the features that are characteristic of delaminated concrete can be identified and digitized for comparison.

8.0 COMMERCIAL VIABILITY

The problem of a chloride-induced corrosion is not unique to parking structures. Bridge decks suffer from the same problem, often to a degree much more severe than that seen in parking structures. Other structures exposed to aggressive environments also are subject to chloride-induced corrosion. These include marine structures, industrial plants, some types of pavement, etc. Hence, the potential market for this type of equipment is very large.

There are two modes in which an automated delamination detection system would be useful:

- as a maintenance tool to monitor the progression of delamination from one survey to the next. At present, the chain drag technique is not sufficiently reproducible to make such comparisons unless the progression is very pronounced;
- as an engineering tool to measure the quantity and depth of delamination for design and contractual purposes. At the moment, one of the greatest difficulties faced by owners, engineers and contractors alike is in estimating the area and depth of patching to be done in a repair contract.

It has been reported(13) that in the U.S. alone, there are some 300,000 bridge decks covering some 300 million square metres that are subject to corrosion damage. Hence, if a reliable process for evaluating and estimating repair needs is available at a reasonable cost, a substantial demand exists. Certainly the bridge deck applications would dominate, but applications involving parking structures would form a significant part of the overall market.

It is expected that three categories of users would acquire this type of equipment:

- municipal and regional highway and bridge authorities;
- consultants and contractors who specialize in this type of repair and restoration;
- building owners who hold a significant inventory and wish to monitor the condition of their parking structures as part of a planned maintenance program.

In 1988 dollars, a survey of a bridge deck or parking structure could realistically fetch between $ 1.00 and $ 1.70 per square metre. This would allow a typical parking structure or bridge to be surveyed for between $ 5,000 and $ 20,000, depending on its size. Hence, the potential revenue for a consultant using this equipment would be of the order of several hundred thousand dollars per year.

In a repair contract, the cost of patching can run from $ 50 to $ 200 per square metre. Hence, a quantity overrun of even 100 square metres can have a substantial impact on a construction budget.

Under these circumstances it is relatively easy to justify a large first-cost of a reliable instrument. As a comparison, the Ontario Ministry of Transportation and Communications is currently attempting to sell its infrared thermography and radar system for $ 250,000. There are reportedly a number of interested parties, even at this price level.

9.0 FUTURE DEVELOPMENT

The future prospects for this program appear highly favourable, both technically and economically. The next phase of the program should have the goal of developing a prototype instrument for demonstration purposes. Work should concentrate on two aspects:

- automation of the physical requirements of data acquisition: placing the transducers and creating the impacts;
- electronic analysis of the recorded waveforms.

A preliminary concept has been developed which entails a two-unit device. The major component would be a small dolly containing a power supply and electronic package for data acquisition and storage. The transducers and impactors would be gang-mounted on a second device which would be moved along the deck. A cable would connect the two components. The data analysis would be done remotely on an IBM compatible personal computer or main frame system, however, the field package would have the capability to display the waveforms so the technician could check the nature of the signals being received.

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APPENDIX A

DRAWINGS

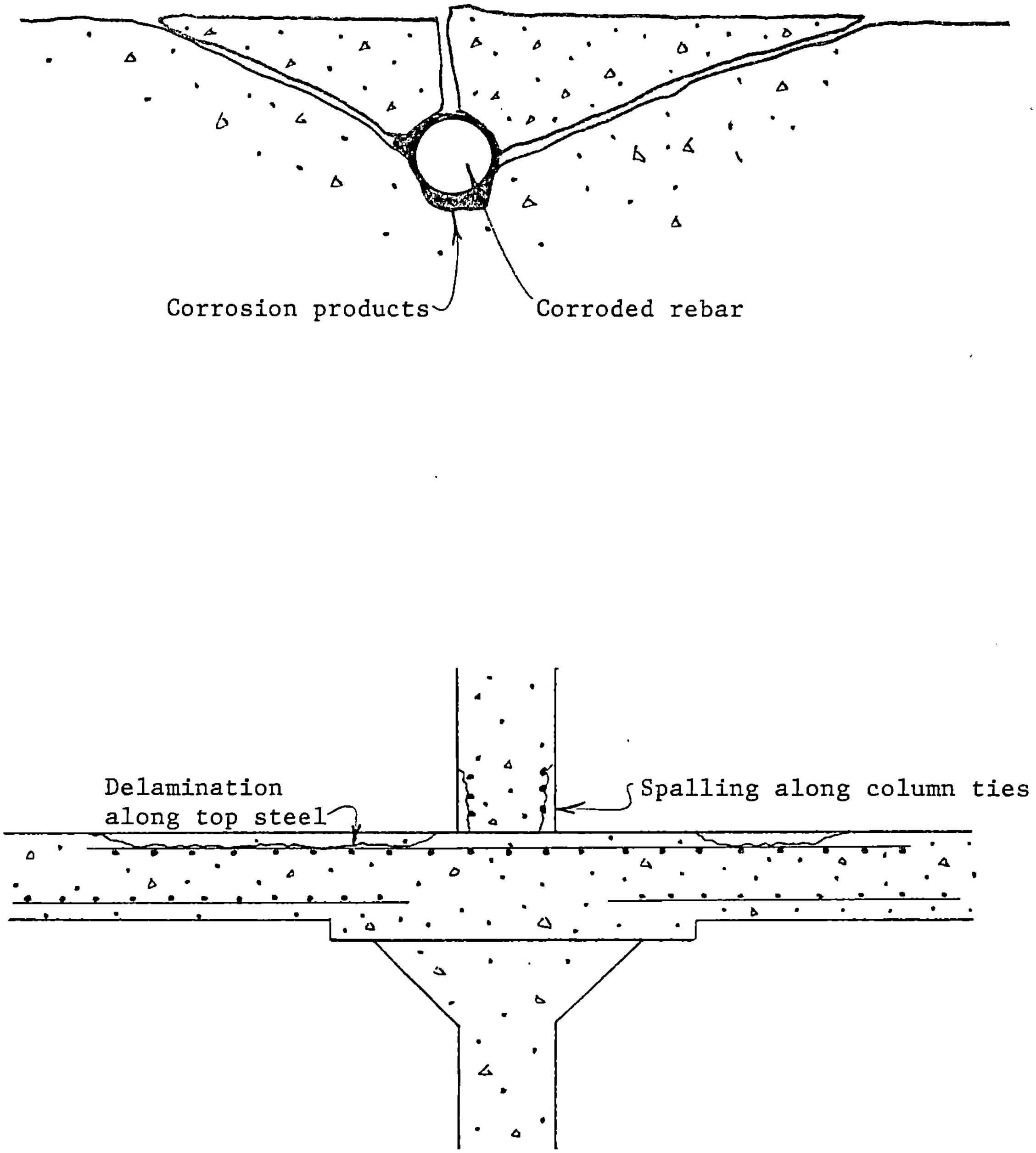


PLATE A1: Typical delamination and spalling due to corrosion

Reference: CSA Standard
CAN/CSA-S413-87

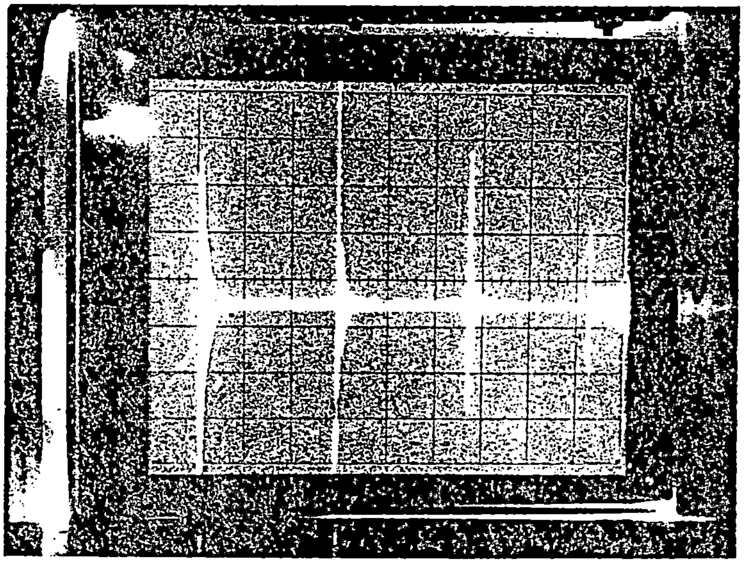
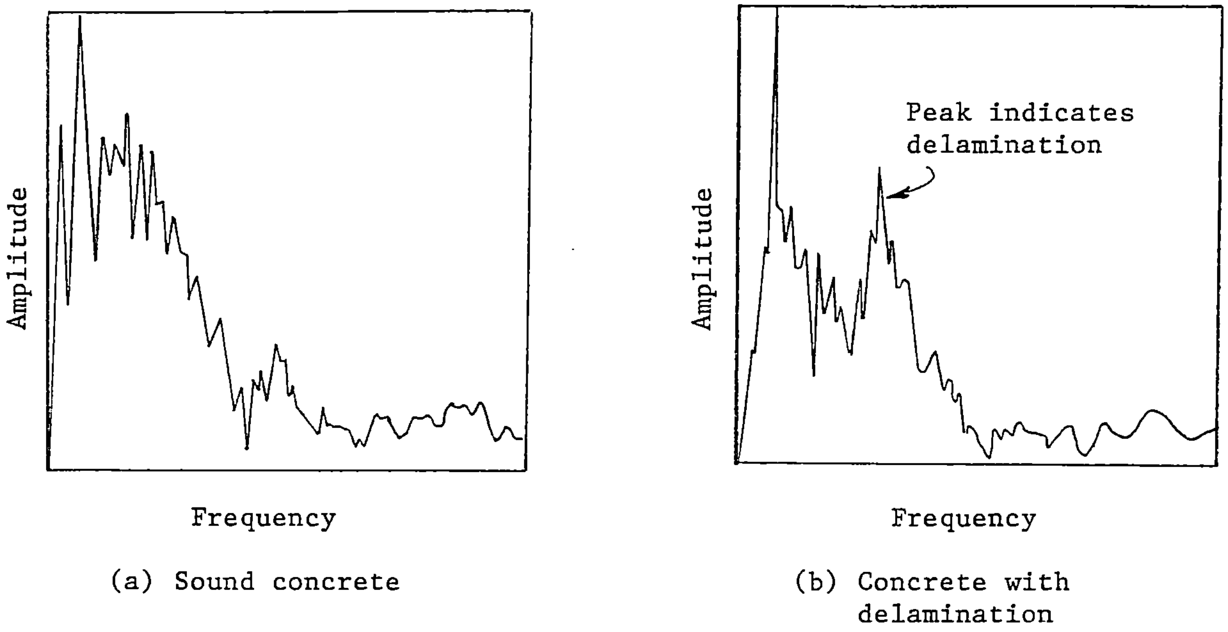


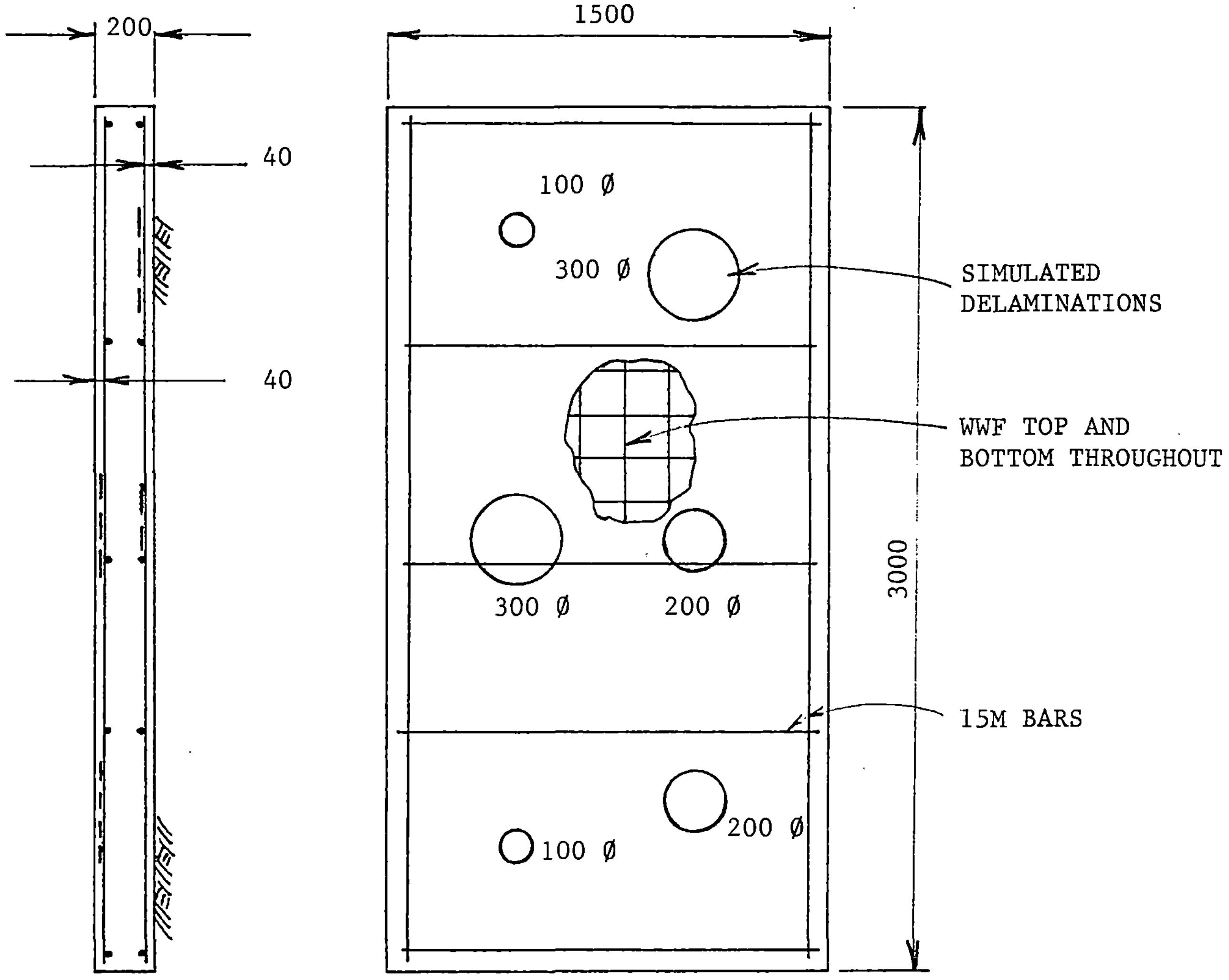
PLATE A2: Pulse-echo waveform.
Peaks in signal represent reflections from back wall or intermediate defects or discontinuities.



(a) Sound concrete

(b) Concrete with delamination

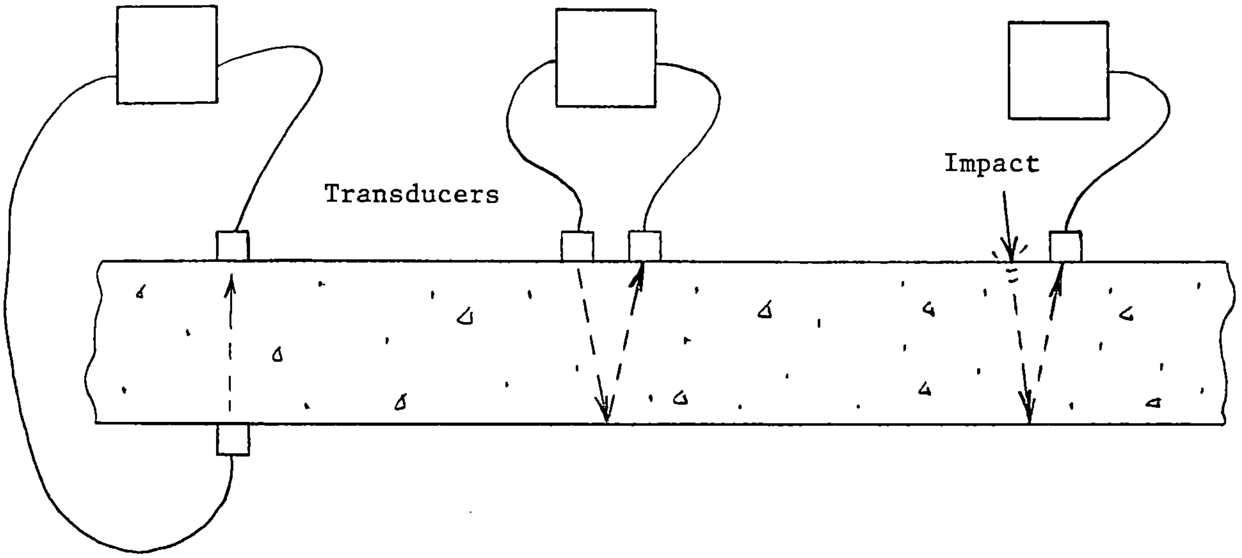
PLATE A3: Typical Impact-Echo Frequency Spectra



SECTION (NTS)

PLAN (NTS)

PLATE A4: TEST SLAB DETAILS



(a) Ultrasonic Direct Transmission

(b) Ultrasonic Pulse Echo (some systems may use a single transducer to send and receive signal).

(c) Impact Echo

PLATE A5: Various Sonic Test Configurations

APPENDIX B

PHOTOGRAPHS

PHOTO B1: Typical delamination along the plane of top rebar in a parking structure slab.

PHOTO B2: Typical corrosion damage to bottom of parking structure column.

PHOTO B3: Typical chain drag device used to locate delaminations.

PHOTO B4: Impact-echo equipment in use. Transducer is in left hand, Schmidt hammer is used in right hand to create pulse.

PHOTO B5: Finished test slab.

PHOTO B6: Impactors used by National Bureau of Standards to create the pulse.

PHOTO B7: Point-contact receiving transducer used by National Bureau of Standards.

PHOTO B8: National Bureau of Standards data processing equipment. Storage oscilloscope, computer and disc drive at bottom, plotter on top.

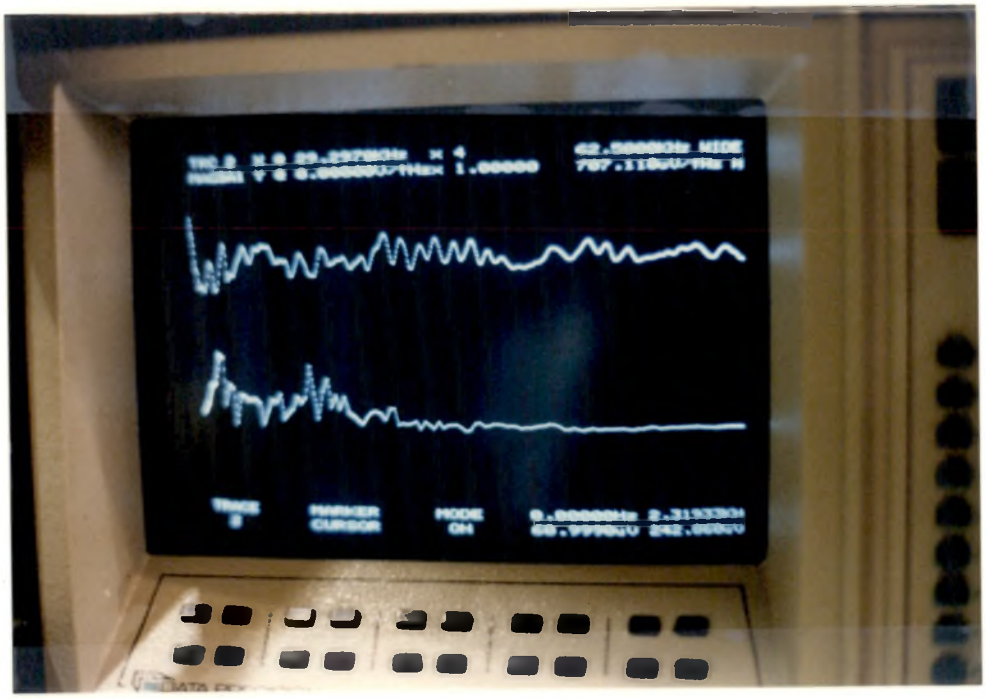


PHOTO B9: Typical signal display, NBS system. Upper plot is amplitude versus time. Lower plot is amplitude versus frequency.

Photo B10: NBS Survey in progress. Impact is created immediately adjacent to transducer. Readings are taken on regular grid pattern, in this case 100 mm intervals.

PHOTO B11: USACE transducers.

PHOTO B12: USACE transducers

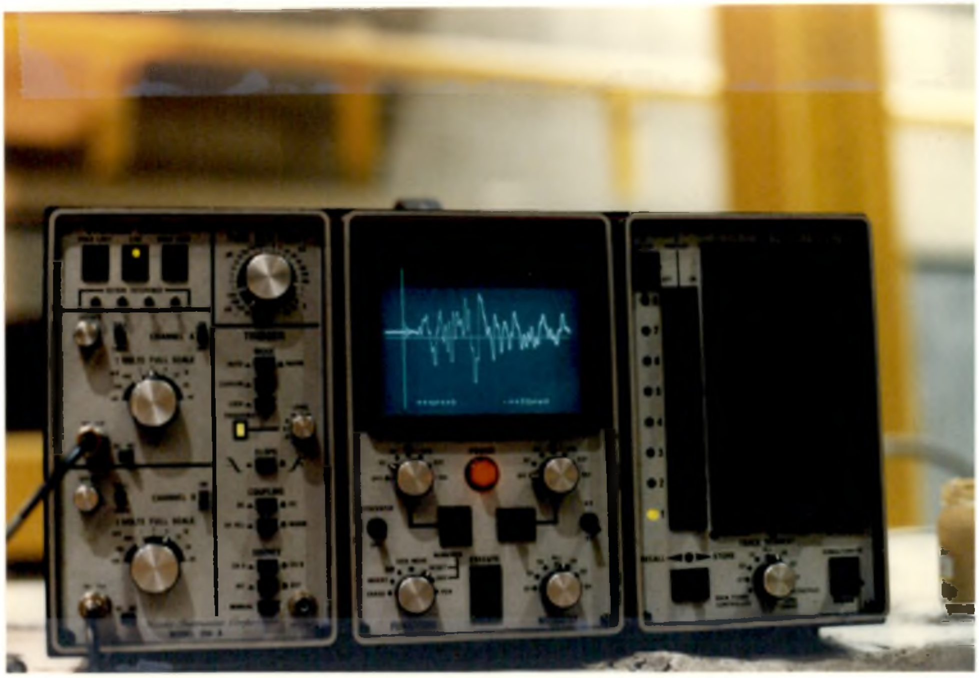


PHOTO B13: Storage oscilloscope used by USACE, showing typical waveform of amplitude versus time.

PHOTO B14: USACE survey in progress

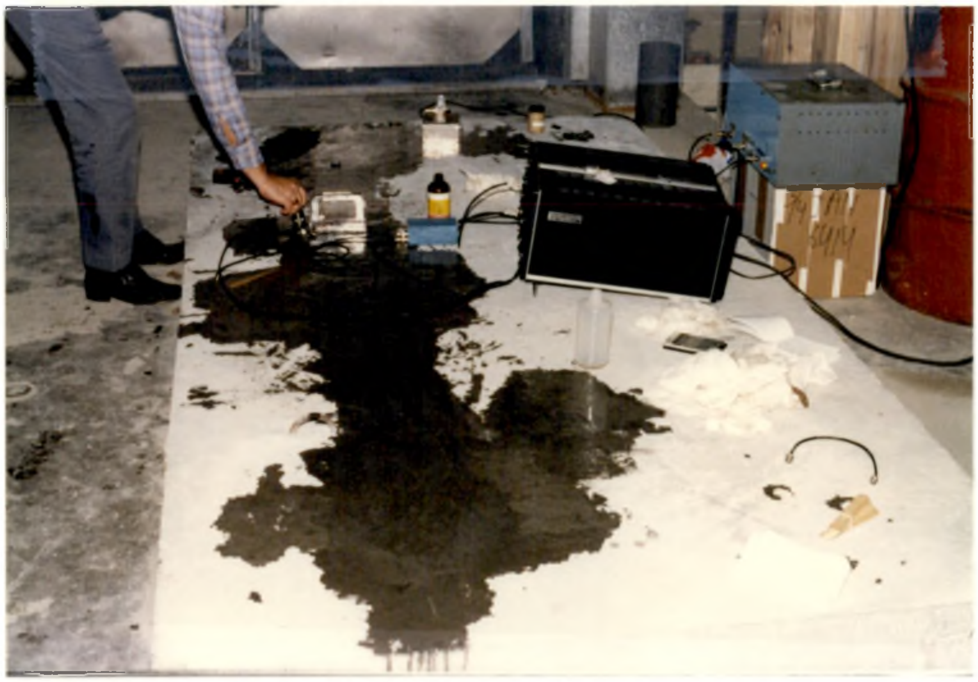


PHOTO B15: USACE survey in progress.

Photo B16: Techno Scientific's transducers.

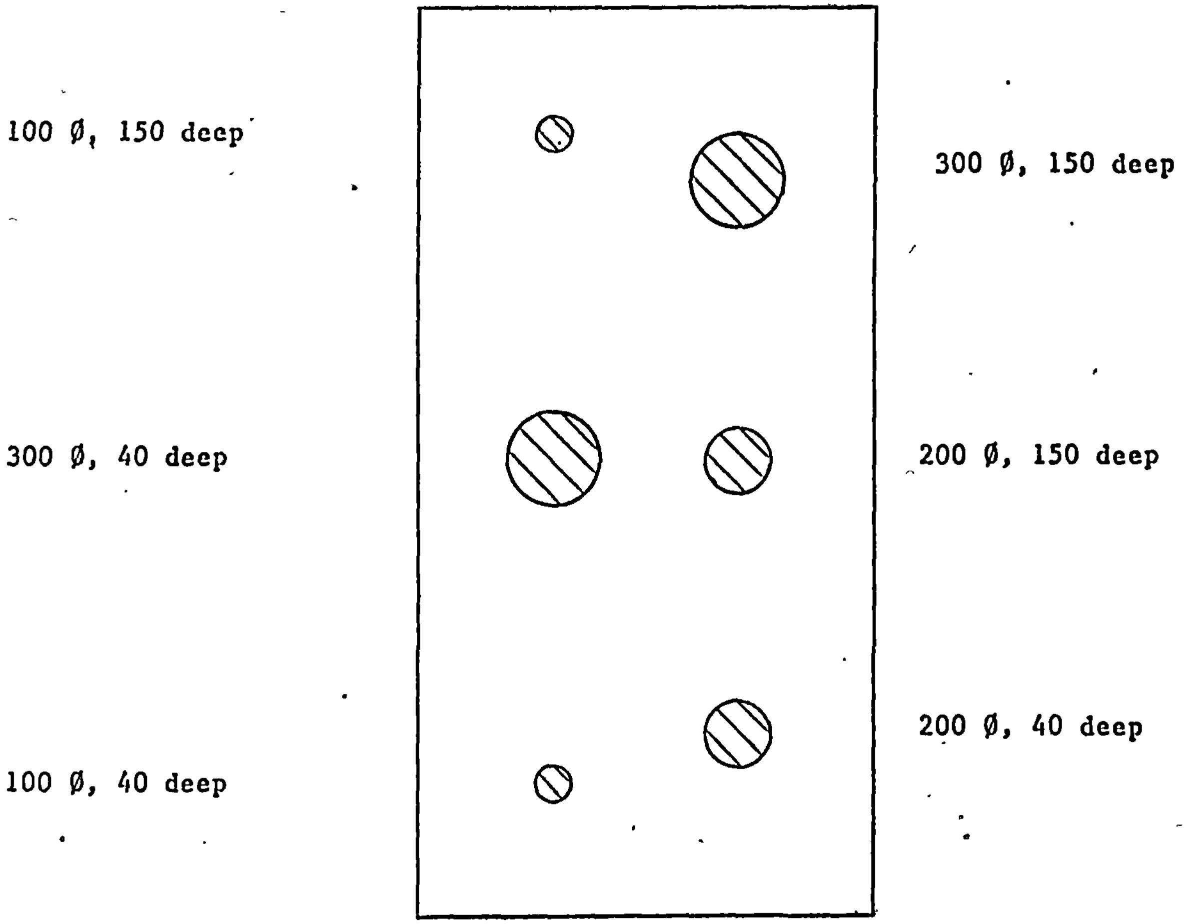
PHOTO B17: Techno Scientific equipment. An IBM PC comatible computer (not shown in photo) is used to record and process the signal.

Photo B18: Techno Scientific survey in progress.

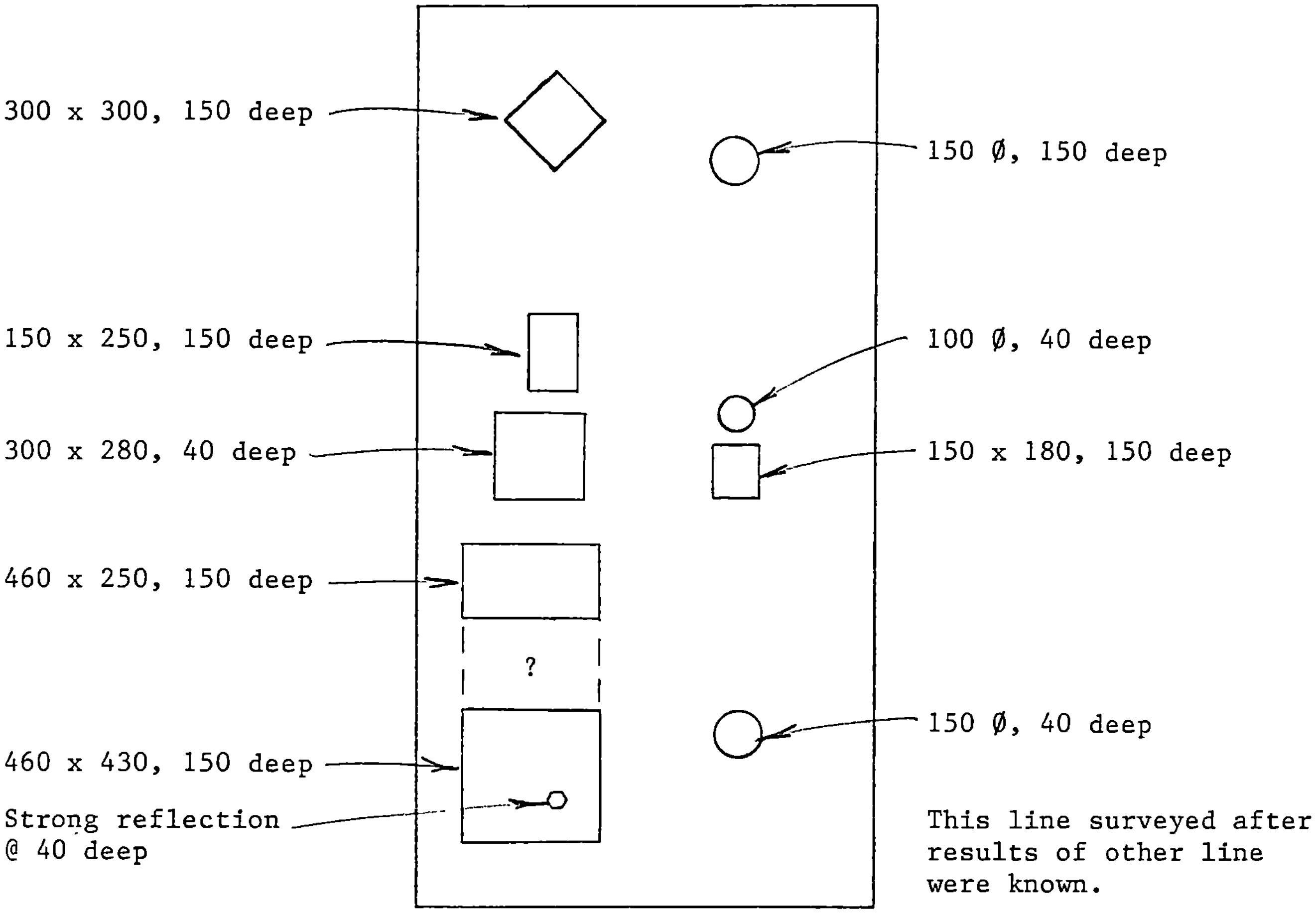
PHOTO B19: Typical waveform generated by Techno Scientific, displayed on computer monitor.

APPENDIX C

SURVEY RESULTS



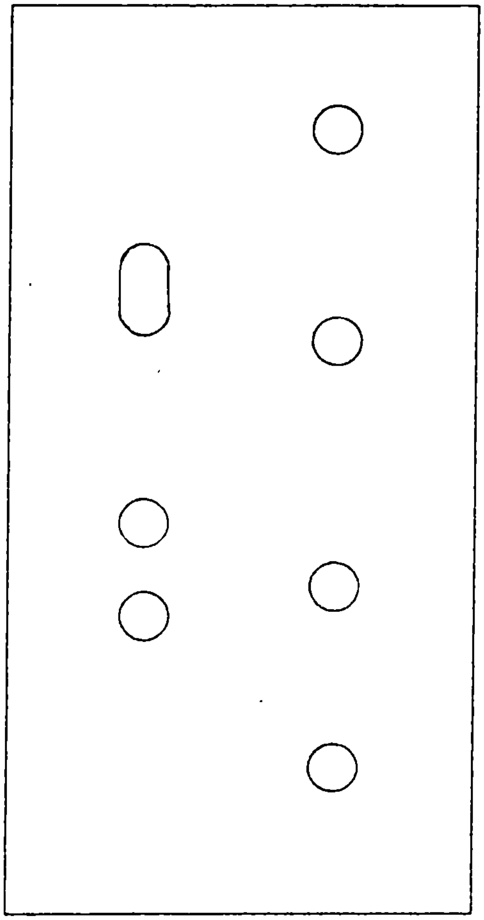
OVERLAY SHOWING ACTUAL LOCATIONS OF
DEFECTS IN TEST SLAB



This line surveyed after results of other line were known.

PLAN OF TEST SLAB
Scale: 1:25

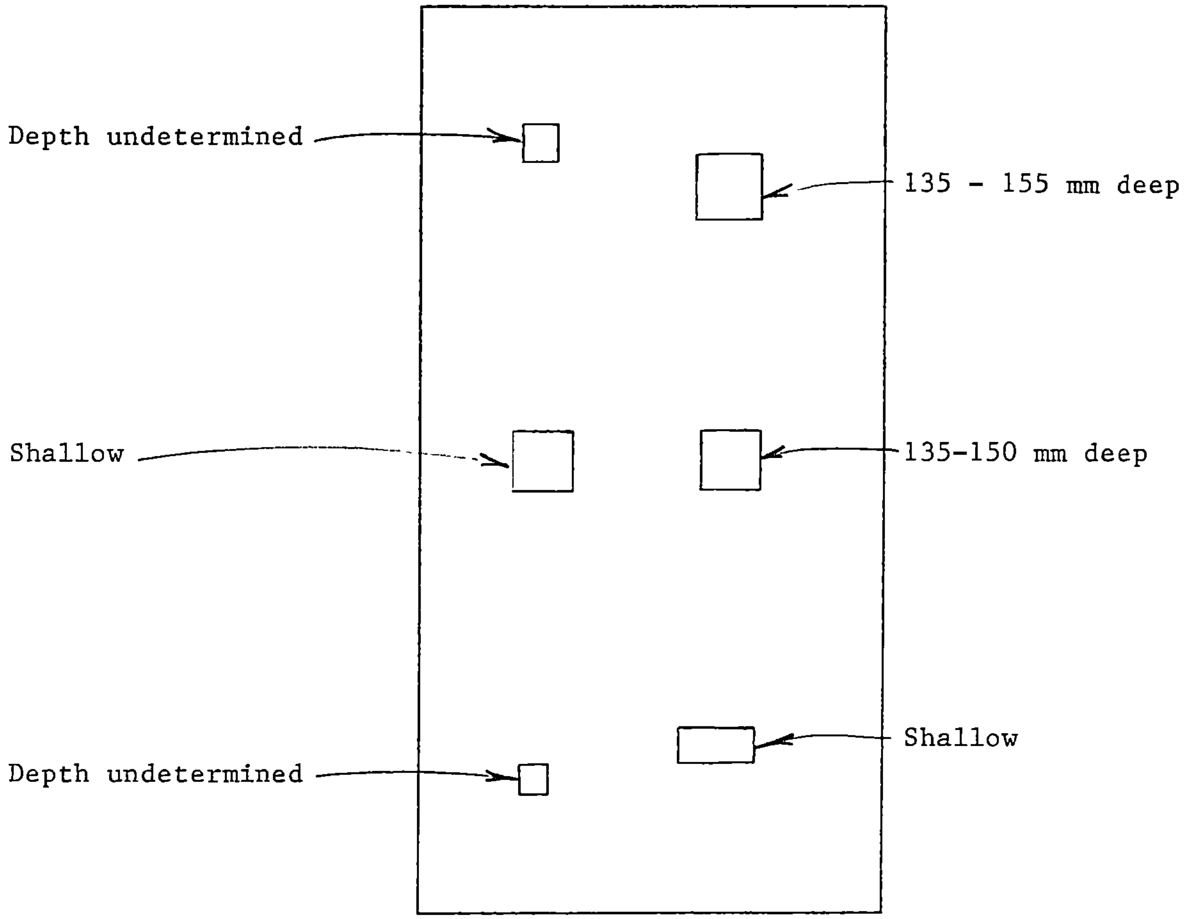
PLATE C2: LOCATIONS OF DEFECTS DETERMINED BY U.S. ARMY CORPS OF ENGINEERS



Sizes or depths of
defects were not
specified by TSI.

Plan of Test Slab
Scale: 1 : 25

PLATE C3: Locations of defects determined by Techno Scientific Inc.



PLAN OF TEST SLAB
Scale: 1:25

PLATE C1: LOCATIONS OF DEFECTS DETERMINED BY NATIONAL BUREAU OF STANDARDS

APPENDIX D

REPORT OF NATIONAL BUREAU OF STANDARDS

DETECTION OF SIMULATED DELAMINATIONS IN CONCRETE USING THE IMPACT-ECHO METHOD

INTRODUCTION

This report presents the results of the investigation performed by the research team from the National Bureau of Standards. The fundamental principles of the impact-echo method are reviewed for those who are unfamiliar with the technique. The equipment and test procedures used in the investigation are described, and the approach used in interpreting the data is explained.

BACKGROUND

Principle of Impact-Echo Method

The principle of the impact-echo technique is illustrated in Fig. 1. A transient stress pulse is introduced into a test object by a mechanical impact on the surface. The stress pulse propagates into the object along spherical wavefronts as P- and S-waves. In addition, a surface wave (R-wave) travels along the surface away from the impact point. The P- and S- waves are reflected by internal interfaces or external boundaries. The arrival of these reflected waves at the surface where the impact was generated produces displacements, which are measured by a receiving transducer. If the receiver is placed close to the impact point the displacement waveform is dominated by the displacements caused by P-wave arrivals. The displacement waveform can be used to determine the travel time, t, from the initiation of the pulse to the arrival of the first P-wave reflection. If the P-wave speed, C_p, in the test object is known, the distance, T, to the reflecting interface can be determined.

An impact-echo test system is composed of three components: an impact source; a displacement transducer; and a waveform analyzer. The force-time history of the impact may be approximated as a half-sine curve, and the duration of the impact is the "contact time". The contact time is an important variable because it determines the size of the defect which can be detected by impact-echo testing. As the contact time decreases, smaller defects can be discerned. However, the penetrating ability of the stress waves is reduced as contact time decreases. Thus the selection of the impact source is a critical aspect of a successful impact-echo test system. For the developmental work performed at NBS(1), contact times on the order of 30 to 60 microseconds have been used. For this investigation, a commercially available impactor was adapted for use as the impact source. The components of the impactor are shown in Fig. 2. The spherically-tipped mass (center) is propelled by the spring-loaded device (left). A 9 mm hardened steel ball was attached to the end of the device. The ball served to increase the repeatability of the input pulse and shorten the contact time of the impact. It is estimated that the impactor produced impacts with contact times ranging from 30 to 50 microseconds, depending on the characteristics of the concrete at the impact point.

The receiving transducer must be capable of accurately mesauring surface displacement. A conically-tipped transducer, developed at NBS as a reference standard for calibrating acoustic emission transducers, is used in current work. For this investigation, a special case was built to house the transducer so that it could be used on vertical surfaces. Figure 3 shows the transducer assembly and mechanical impactor used during this investigation.

A waveform analyzer is used to capture the transient output of the displacement transducer, store the digitized waveforms, and perform signal analysis. A suitable waveform analyzer should have a sampling frequency of at least 500 kHz. A pen-plotter is used for hard-copy output of the raw and processed waveforms.

Signal Analysis

During the initial development of the impact-echo technique (1,2,3), interpretation of the recorded waveforms was performed in the time domain. This required establishing the time of impact initiation and the arrival time of the first P-wave echo. While this was feasible, it was found to be time consuming. An alternative approach is frequency analysis of the displacement waveforms.

The principles of frequency analysis is illustrated in Fig. 4, which shows a solid plate of thickness T subjected to impact. The stress pulse generated by the impact propagates back and forth between the top and bottom surfaces of the plate. Each time the pulse arrives at the top surface it produces a characteristic displacement. Thus the waveform is periodic, and the period, t, is equal to the travel path (2T) divided by the P-wave speed. Frequency is the inverse of the period; thus the frequency, f_p, of the characteristic displacement pattern is:

$$f_p = \frac{C_p}{2T} \tag{1}$$

Thus, if the frequency of P-wave arrivals can be determined, the thickness of the plate (or distance to a reflecting interface) can be calculated:

$$T = \frac{C_p}{2f_p} \tag{2}$$

The frequency content of the recorded waveforms is obtained using the fast Fourier transform (FFT) technique. Appendix A gives additional background information on digital frequency analysis, and examples of its application may be found in References 1, 4, 5 and 6.

Figure 5 illustrates how frequency analysis works. In Fig. 5(a), an impact-echo test was performed over a solid portion of a 0.5 m thick concrete slab. In the amplitude spectrum, there is a frequency peak at 3.42 kHz. This frequency corresponds to multiple reflections between the bottom and top surfaces of the slab. Using Eq. (1) and solving for C_p, the P-wave speed is calculated to be 3410 m/s. Figure 5(b) shows the amplitude spectrum obtained from a test over a portion of the slab containing a disk-shaped void. The peak at 7.32 kHz results from multiple reflections between the top of the plate and the void. Using Eq. (2), the calculated depth of the void is 3410/(2 * 7320) = 0.23 m, which compares favorably with the known distance of 0.25 m.

Appendix A explains that the resolution in the amplitude spectrum (the frequency difference between adjacent points) is equal to the sampling frequency divided by the number of points in the waveform record. This imposes a limit on the resolution of the depth calculated according to eq. (2). Because depth and frequency are inversely related, it can be shown that for a fixed resolution in the frequency domain, the resolution of the calculated depth improves as the frequency increases, that is, as depth decreases.

PROCEDURE

The first step was to establish the approximate locations of the delaminations. Impact-echo tests were performed at 200 m intervals along the two lines (referred to as line A and line B). In the sound portions of the slab, the spectra had dominant peaks at 9.76 kHz. The absence of this peak indicated that a delamination was present at the test point. From the waterfall plots (Figs. 6 and 7), points A2, A7, A12, B3, B3, B7, and B12 indicated the presence of delaminations (Fig. 8).

Impact-echo tests were then performed at closer intervals to establish the approximate boundaries of the defects. Tests were performed along two perpendicular lines and the spacing between test points was 100 or 50 mm. The waterfall plots for the fine scans were examined and those points lacking a dominant peak at 9.76 kHz were identified.

RESULTS

The approximate boundaries of the delaminations are shown in Fig. 9. The boundaries are based on those test points which did not have a dominant peak at 9.76 kHz in their spectra.

The large delaminations along line B resulted in spectra with clearly defined high frequency peaks in the range of approximately 13 to 15 kHz. The depths of these delaminations were determined to be in the range of 135 to 155 mm. The depths of the other delaminations could not be established. The spectra obtained from the third delamination along line B were distinctly different (Figs. 10 and 11) from the other delaminations along line B. The spectra were dominated by low frequency peaks. This indicates the delamination is shallow, and the low frequency is attributed to the flexural vibration of the delaminated region. There is no high frequency peaks associated with the thickness frequency of the shallow delamination because the impact did not possess the required high frequency components. Since the slab was only several days old, the hardness of the surface was low and the contact time of the impact was too long. A similar response was obained for the large delamination along line A.

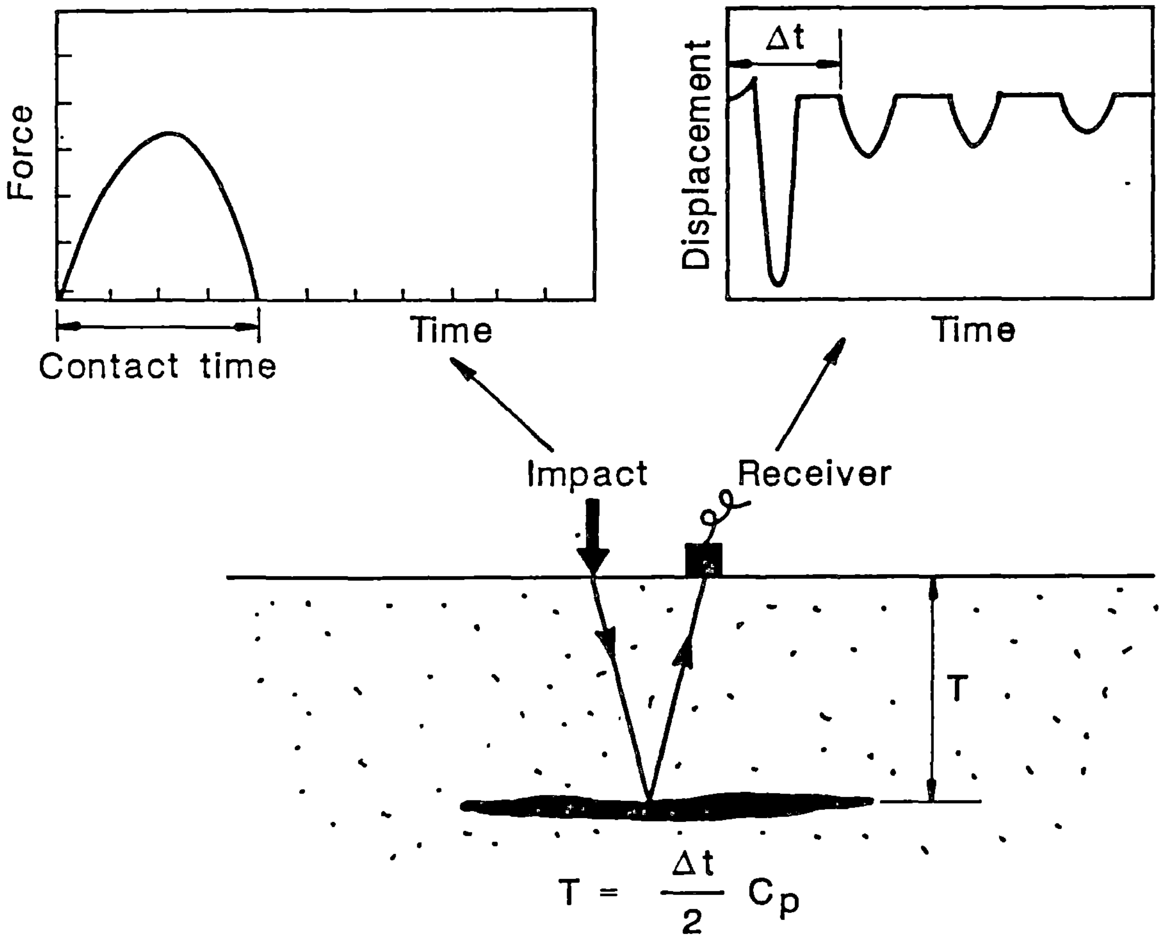


Figure 1 Principle of the impact-echo method.

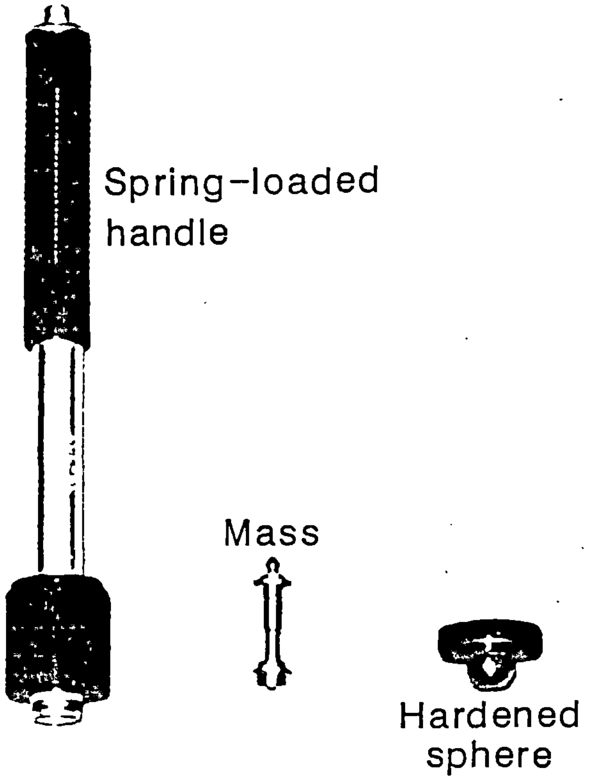


Figure 2 Modified mechanical impactor used in investigation

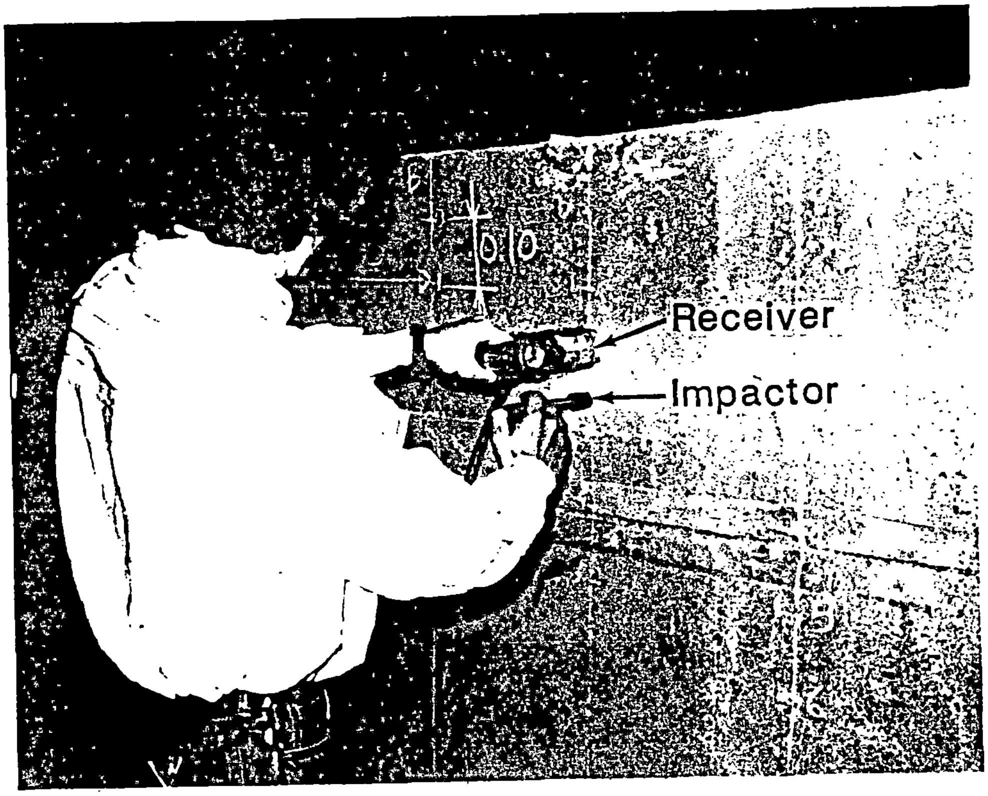
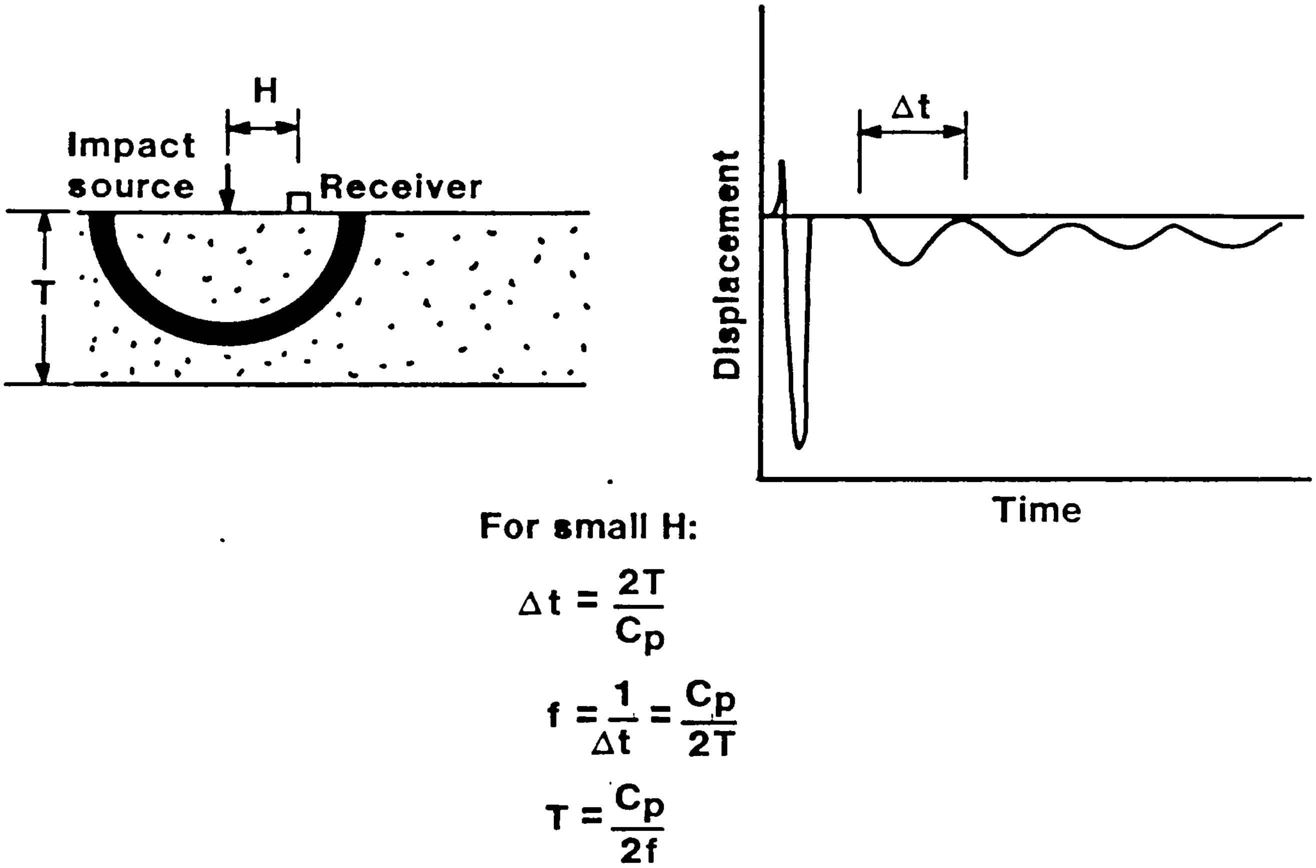


Figure 3 Impact-echo test being performed on test specimen



For small H:

$$\Delta t = \frac{2T}{C_p}$$

$$f = \frac{1}{\Delta t} = \frac{C_p}{2T}$$

$$T = \frac{C_p}{2f}$$

Figure 4 Principle of frequency analysis

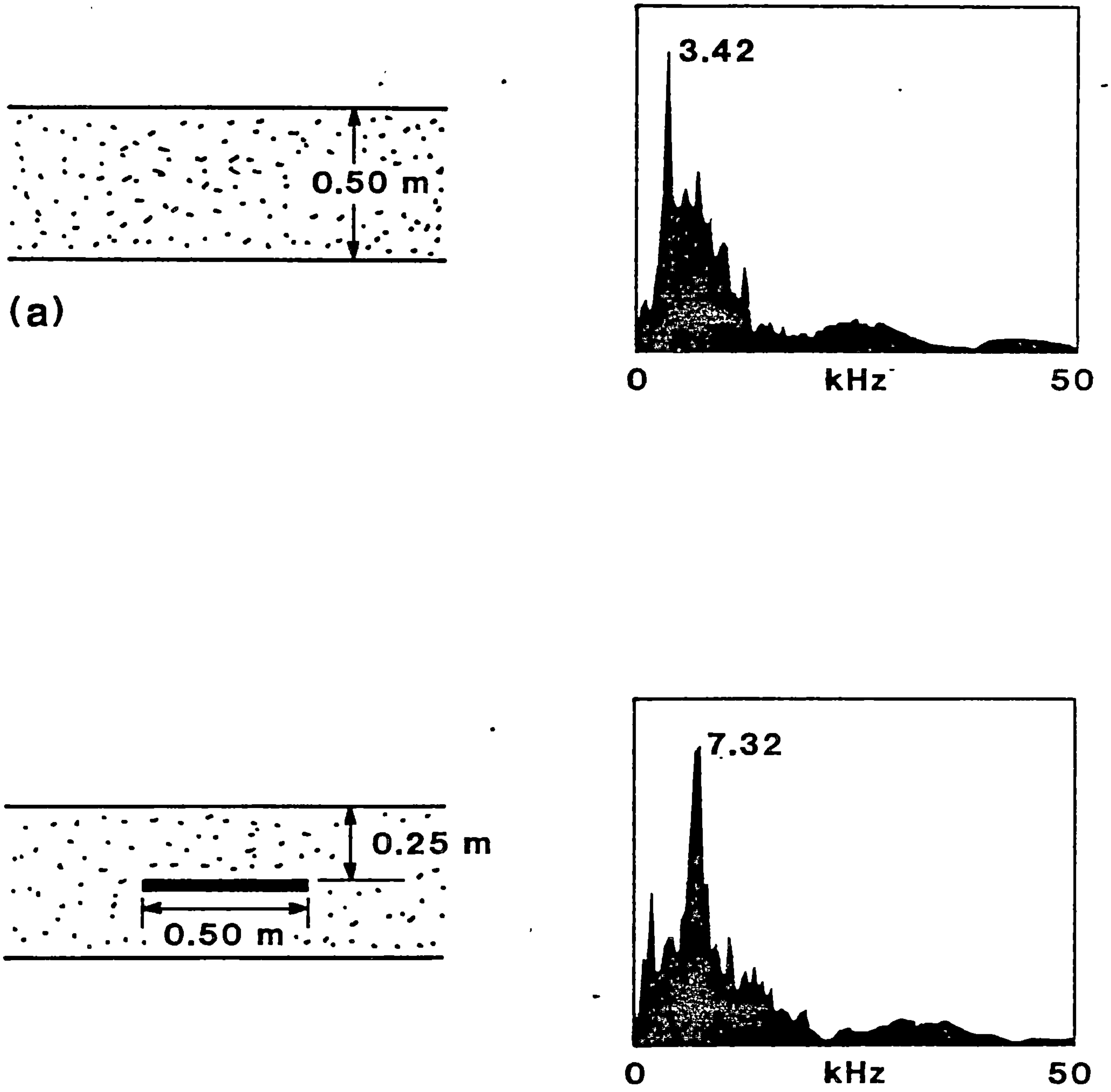


Figure 5 Examples of amplitude spectra: a) for test over a solid portion of a 0.5-m thick concrete slab; b) for a test over a disk-shaped void embedded in another portion of the same slab.

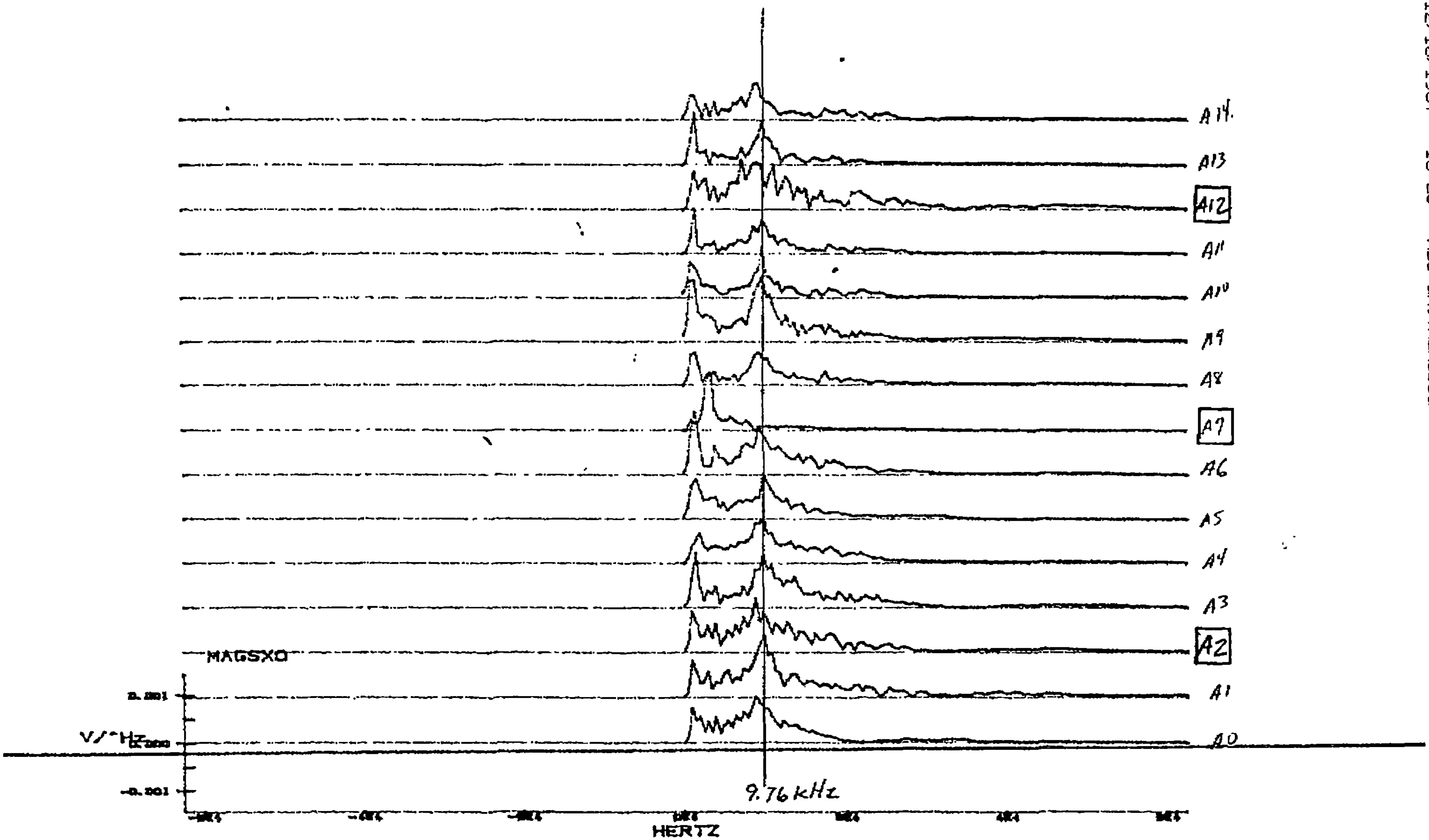


Fig 6: Scan along line A

adam slab

line B

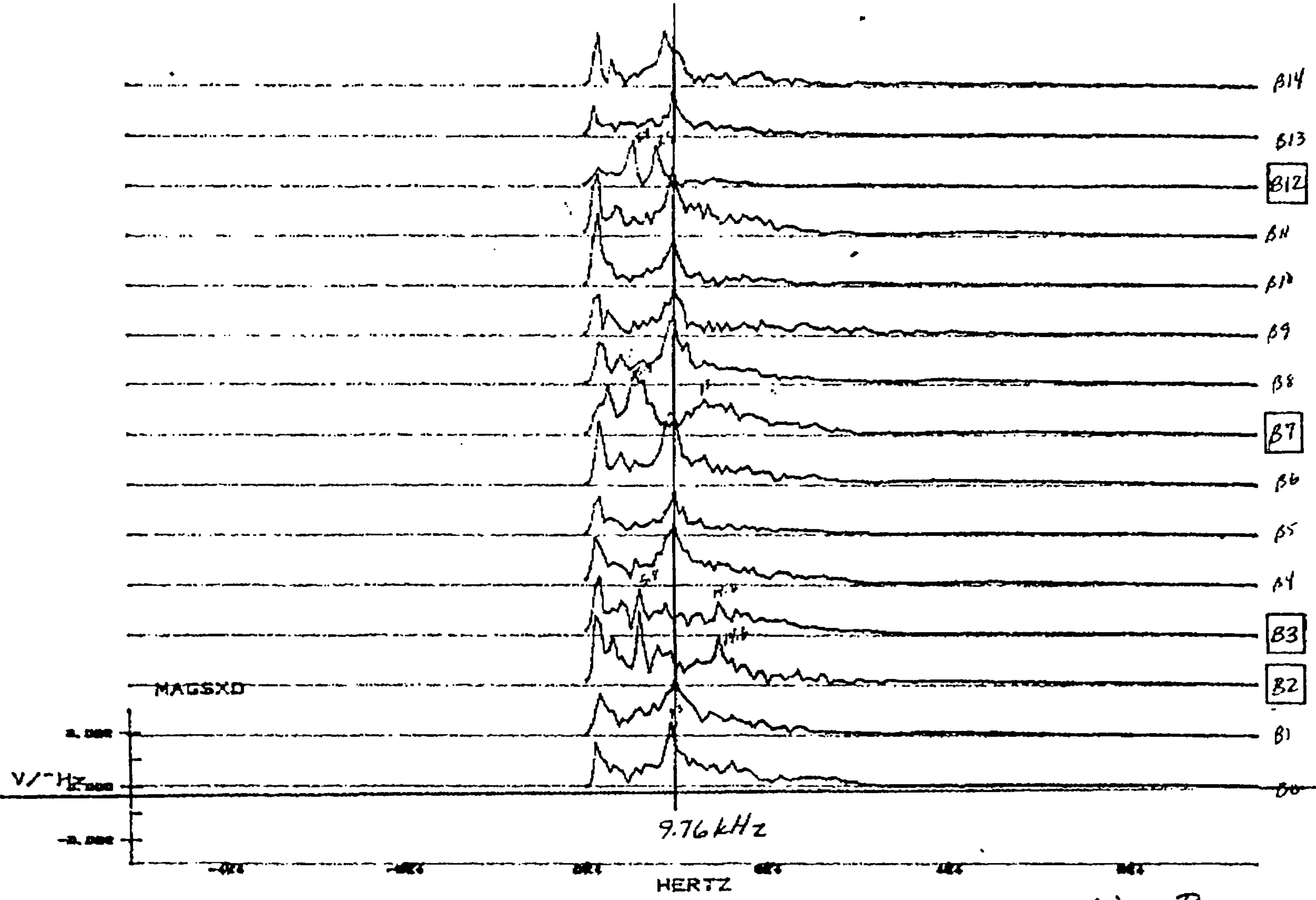


Fig 7: Scan along line B

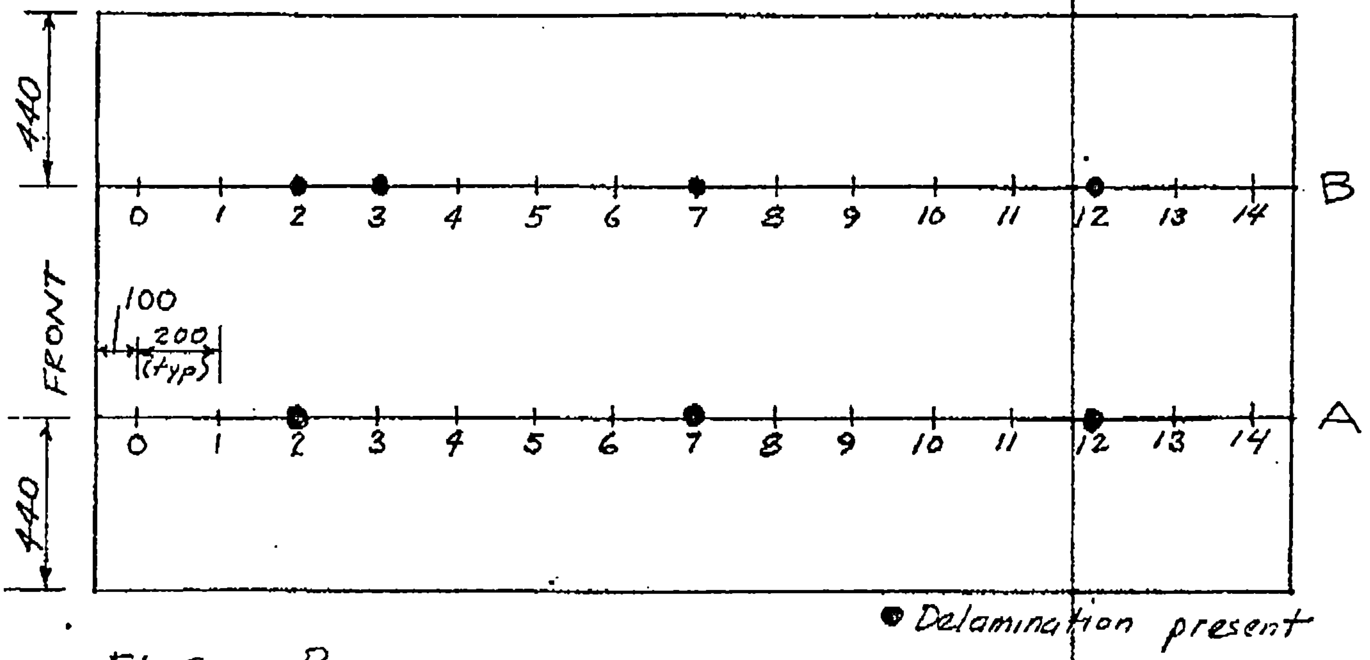


Fig 8 RESULTS OF COARSE SCAN

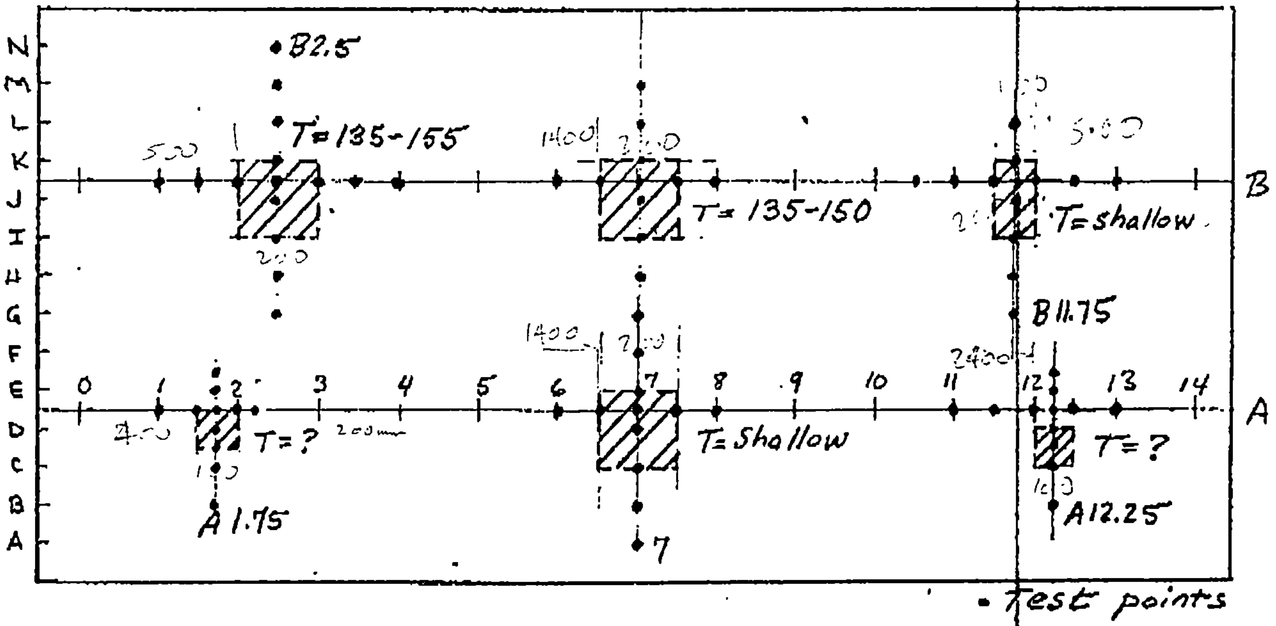


FIG. 9 RESULTS OF DETAILED SCAN

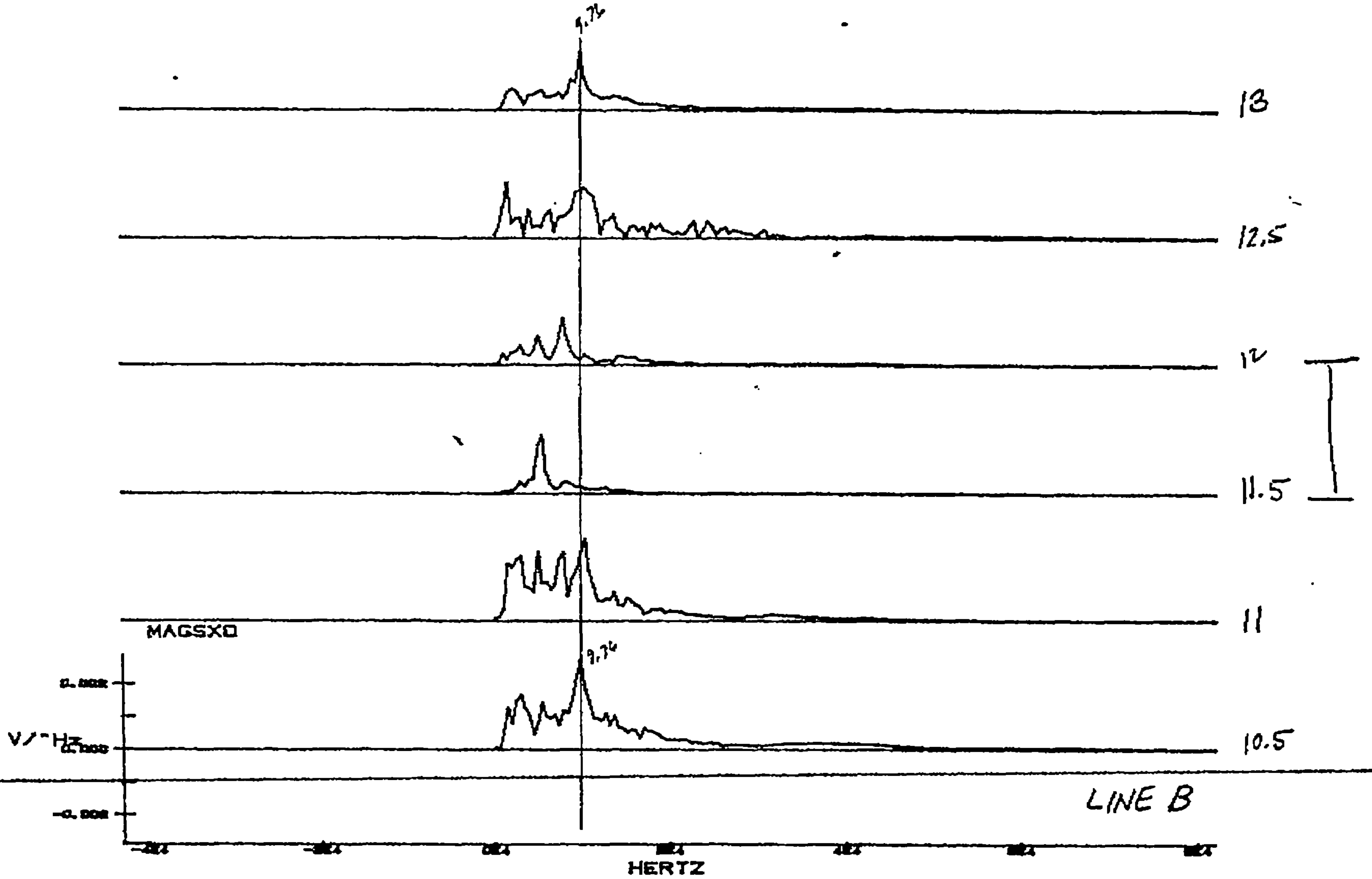


Fig 10: Low frequency response at B11.5

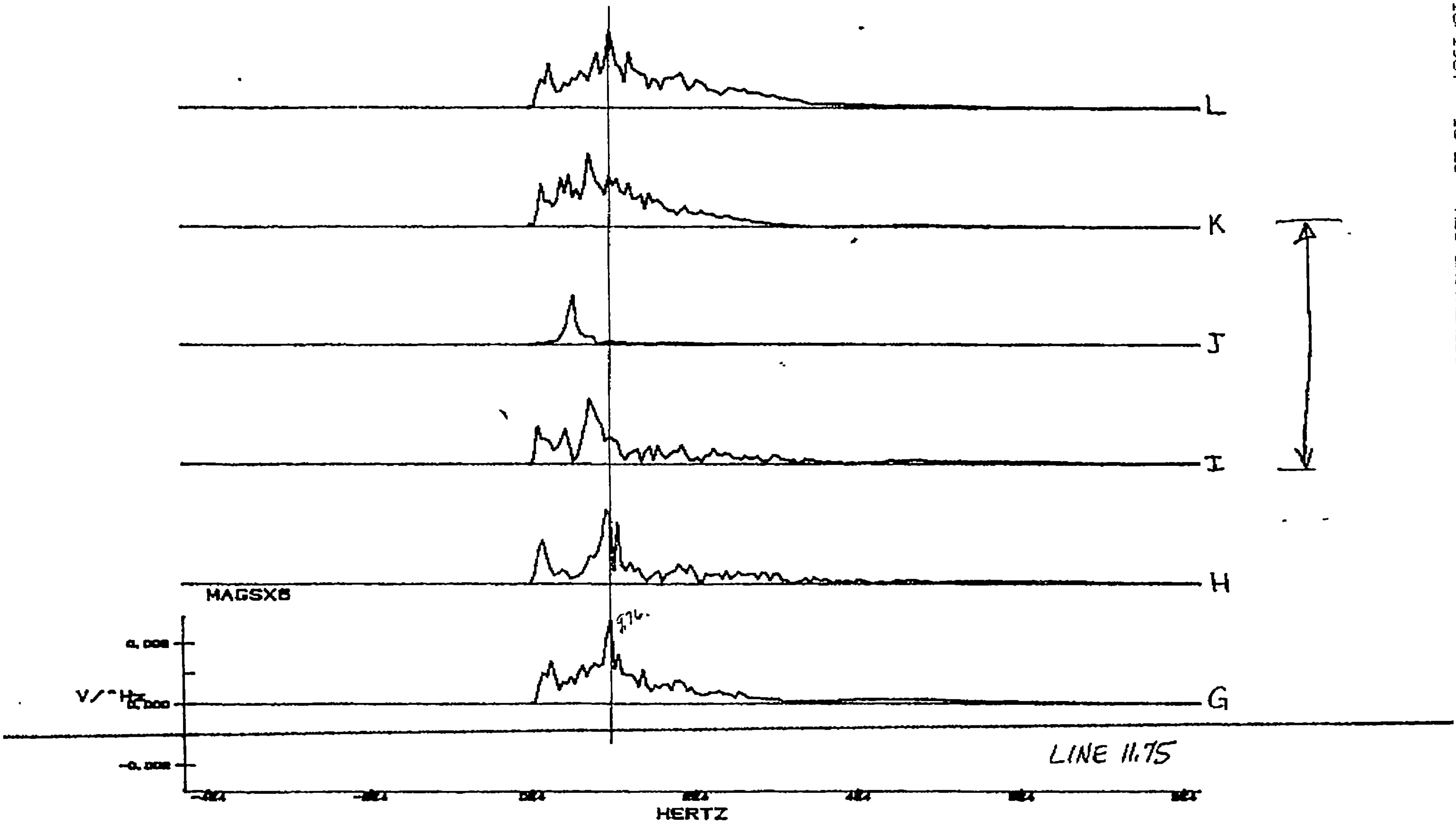


Fig 11: Low frequency response at 11.75J

APPENDIX A

Frequency Analysis

An impact on the top surface of an infinite plate results in multiple reflections of stress waves between the top and bottom surfaces. The multiple reflections give a periodic character to the displacement response at points close to the impact point. In finite solids containing flaws, multiple reflections occur between a variety of interfaces and free boundaries. As a result, time domain waveforms become complex and difficult to interpret. However, if the waveforms are transformed into the frequency domain, multiple reflections from each interface become dominant peaks in the amplitude spectrum - at frequency values corresponding to the frequency of arrival of reflections from each interface. These frequencies can be used to calculate the location of each interface. It has been found that, for impact-echo testing, data interpretation is much simpler and quicker in the frequency domain than in the time domain.

The transformation from the time to the frequency domain is based on the idea that any waveform can be represented as a sum of sine curves, each with a particular amplitude, frequency, and phase shift. This transformation is carried out using the principles of the Fourier transform. As an example, Fig. A1(a) shows the digital time domain waveform, g(t), given by the function:

$$g(t) = \sin 2\pi(20)t + 2 \sin 2\pi(40)t + 3 \sin 2\pi(60)t \qquad \text{(A.1)}$$

where t = time, s.

This function is composed of three sine curves of different amplitudes having frequencies of 20, 40, and 60 Hz.

The digital sample in Fig. A1(a) is made up of 256 discrete points. The time interval between points is 0.001 seconds; this is equivalent to a sampling frequency of 1000 Hz.

The objective of frequency analysis is to determine the dominant frequency components in the digital waveform. This is most easily accomplished by using the fast Fourier transform (FFT) technique. The FFT results can be used to construct the amplitude spectrum, which gives the amplitudes of the various frequency components in the waveform. The amplitude spectrum obtained by the FFT contains half as many points as the time domain waveform, and the maximum frequency in the spectrum is one-half the sampling rate, which for this example is 500 Hz. Figure A1(b) shows the initial portion of the computed amplitude spectrum; the peaks occur at 20, 40, and 60 Hz. Each of the peaks corresponds to one of the component sine curves in Eq. [A.1].

With the FFT technique, the frequency interval in the spectrum is equal to the sampling frequency divided by the number of points in the waveform. For this example, the interval is equal to 1000 Hz divided by 256, or 3.9 Hz. Since the frequency interval is proportional to the sampling frequency, a slower sampling rate enhances resolution in the frequency domain. However, to avoid errors in frequency analysis, the sampling frequency should be greater than twice the maximum frequency that appears in the time domain waveform.

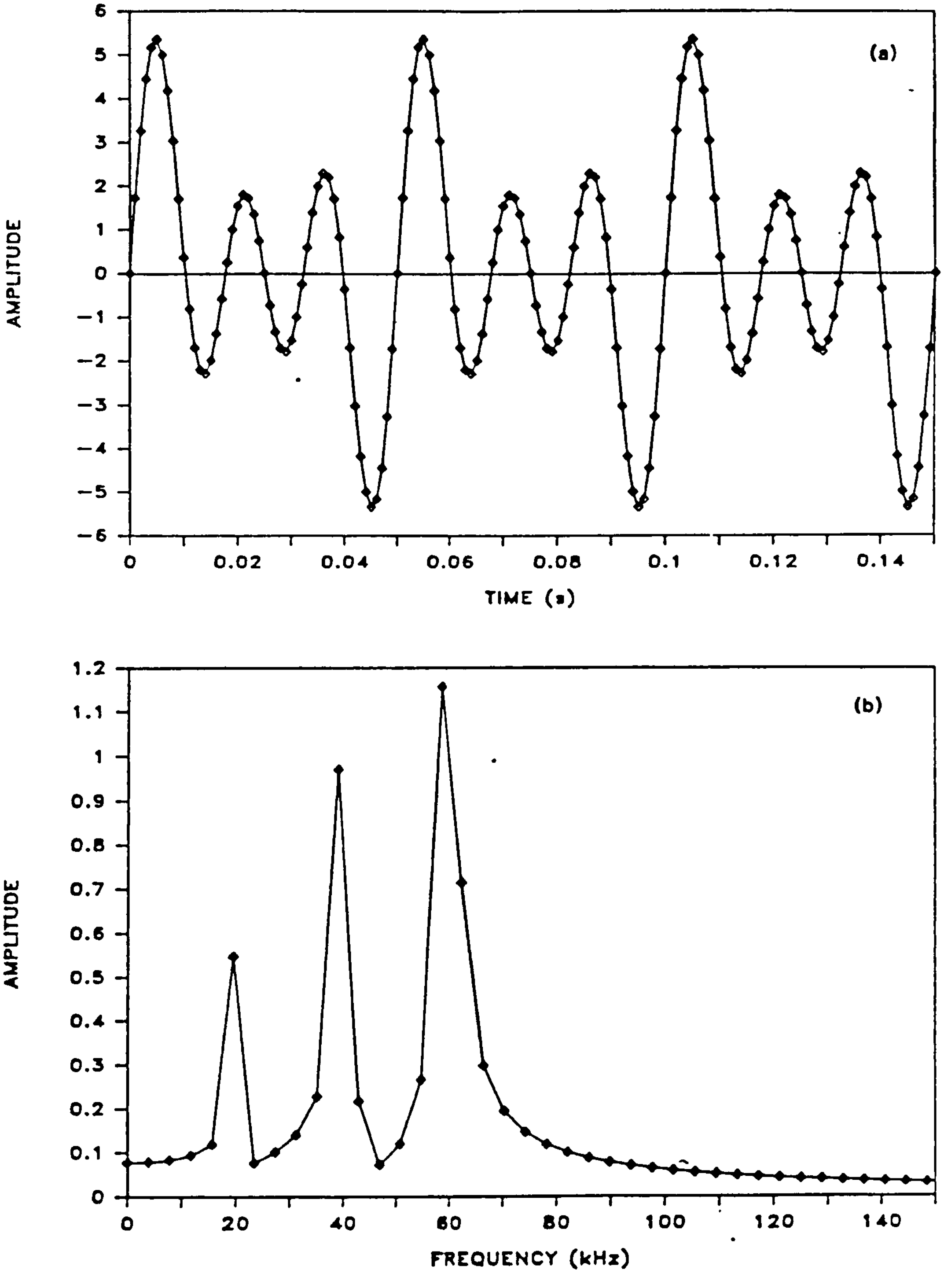


Figure A1 Example of frequency analysis using the fast Fourier transform technique: a) digital waveform, b) initial portion of corresponding amplitude spectrum.

APPENDIX B

Wave Reflection from a Concrete/Steel Interface

When a stress wave is incident upon an interface between dissimilar materials both reflection and refraction occur at the interface. The portions of the incident energy that are reflected and refracted depend upon the angle of the incident wave and the acoustic impedance (product of wave speed and density) of the two materials. At a stress free interface, such as concrete/air, and for normal incidence, almost total reflection occurs because the acoustic impedance of air is negligible compared with that of concrete.

If steel is embedded in concrete, wave reflections occur at the concrete/steel interface because the acoustic impedance of the steel is about 5 times that of concrete. However, the higher acoustic impedance of steel causes a difference in the nature of wave reflection at a concrete/steel interface compared with that at a concrete/air interface. This difference is explained qualitatively in Fig. B1, which shows an infinite concrete plate bounded by air (Fig. B1(a)) and an infinite concrete plate bounded on the bottom by steel and on the top by air (Fig. B1(b)).

First, consider the case where impact occurs on a surrounded by air (Fig. B1(a)). The P-wave generated by the impact is a compression wave (the particles are pushed together). When this wave is incident upon the bottom surface of the plate, it is reflected as a tension wave (the particles are pulled apart). This tension wave propagates back up through the plate to be reflected at the top surface as a compression wave, and the cycle begins again. Each P-wave arriving at the top of the plate is a tension wave which causes a downward displacement of the surface. The period between successive downward dips in the waveform is the time between successive P-wave arrivals, that is, the time for a P-wave to travel twice the thickness of the plate. Thus, if an amplitude spectrum were computed, the frequency value of the peak in the spectrum would be associated with twice the plate thickness.

Next, consider impact on the top surface of a concrete plate which is in contact with a thick layer of steel at its bottom surface (Fig. B1(b)). When the initial compression wave generated by the impact is incident upon the concrete/steel interface it does not change sign because the steel has a higher acoustic impedance than the concrete. Thus the incident wave is reflected as a compression wave. When this compression wave reaches the top surface of the plate it causes an upward displacement of the surface. However, since the top surface of the plate is a concrete/air, the incident compression wave is reflected as a tension wave. This wave propagates down through the plate and is reflected at the concrete/steel interface unchanged. When this tension wave reaches the top surface of the plate it causes a downward displacement of the surface. The incident tension wave is reflected as a compression wave and the cycle begins again. Therefore, in the surface displacement waveform (Fig. B1(b)), the periodicity of displacements (time between successive upward or downward displacements) is twice as long as in waveform obtained from the plate with free boundaries (Fig. B1(a)). This explanation has been verified by a finite element analysis of a layered concrete/steel plate.

The period in the waveform shown in Fig. B1(b) is equal to the time it takes for a wave to travel four thicknesses of the plate. Therefore, the value of the peak in the amplitude spectrum obtained by transforming this waveform is associated with four plate thicknesses. For equal thicknesses of the concrete plates, the peak frequency value in Fig. B1(b) will be half that obtained from the waveform shown in Fig. B1(a).

Based on this qualitative analysis, the frequency peak associated with reflections from steel bars would be expected to occur at a frequency value that is approximately one-half the value that would be obtained for reflections from a concrete/air interface at the same depth as the bars. Therefore, to determine the depth of a concrete/steel interface from the peak in an amplitude spectrum, Eq. (2) (derived for a plate with stress free boundaries) can be modified:

$$T = \frac{C_p}{2\ (2f_p)} \tag{B.1}$$

Figure B.2 shows the results of an impact-echo test on concrete slab containing a disk-shaped void and reinforcing bars. From tests over solid portions of the slab, the P-wave speed was found to be 3910 m/s. The large peak at 7.81 kHz corresponds to a depth of 0.25 m, which agrees with the planned distance to the void of 0.26 m. The high frequency peaks at 14.6 and 21 kHz are due to reflections from the bars. Using Eq. B.1, the corresponding depths are 0.07 m and 0.05 m, which agree with the planned depths of the bars. Thus the applicbility of Eq. B.1 has been verified.

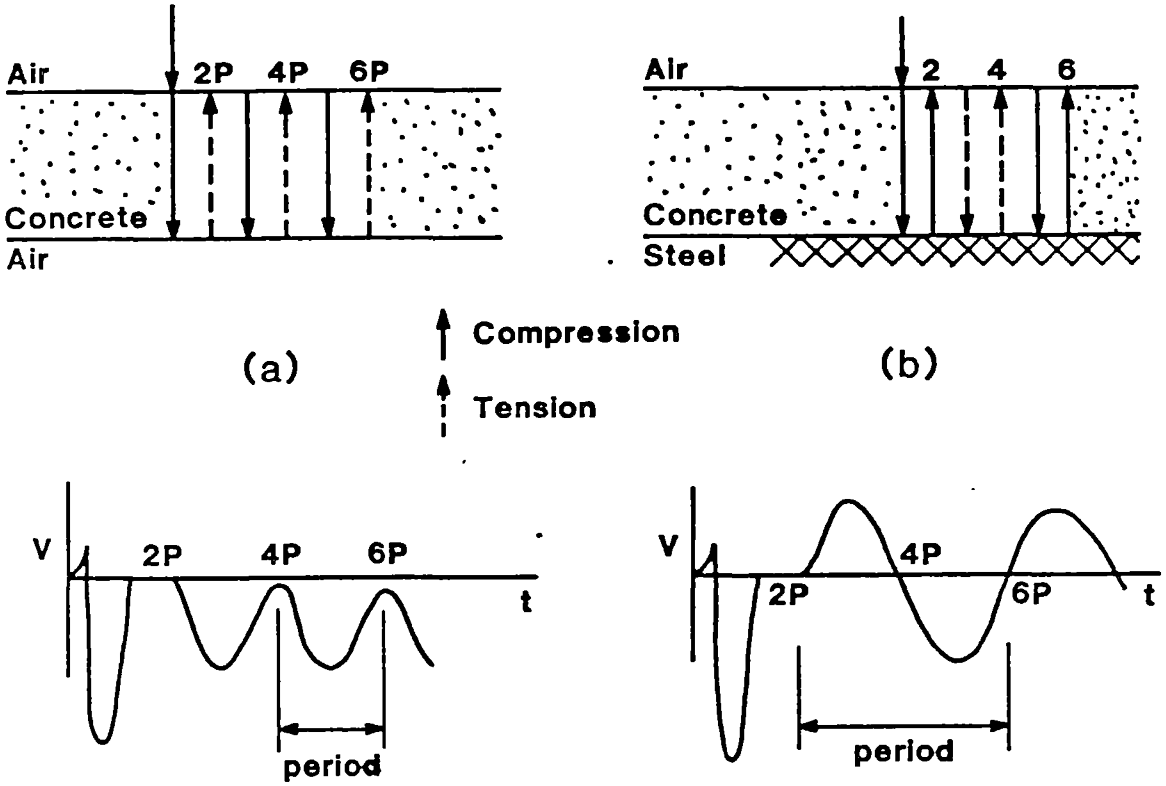


Figure B1 Effect of nature of the bottom interface of a plate on the resulting waveform recorded at the top surface: a) concrete/air interface, b) concrete/steel interface.

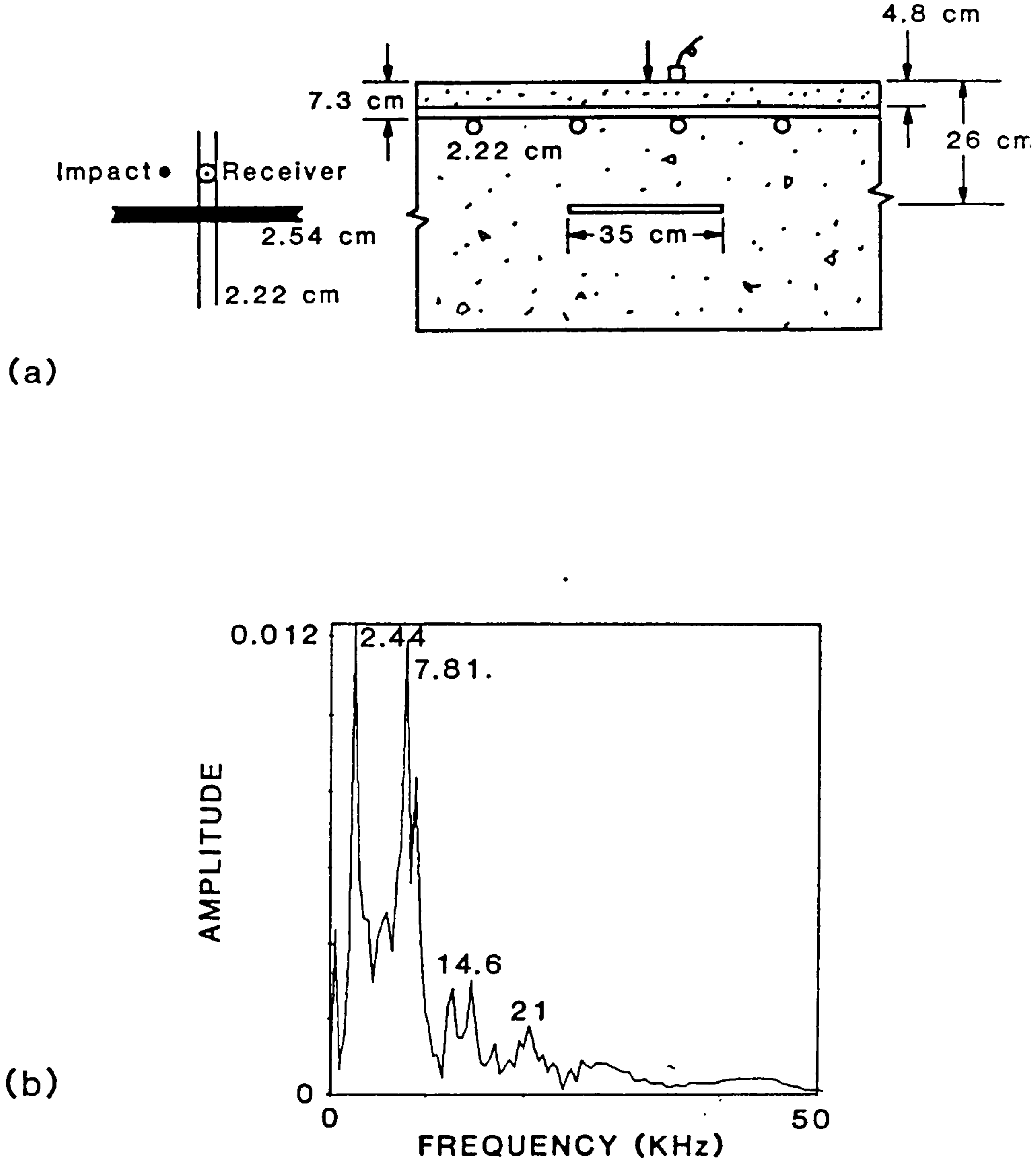


Figure B.2 Results of an impact-echo test on reinforced concrete slab: a) test geometry; b) resulting amplitude spectrum.

APPENDIX E

REPORT OF TECHNO SCIENTIFIC INC.

TECHNO SCIENTIFIC INC.
60 Caster Ave., Woodbridge, Ontario, L4L 4X2 (416) 851-9958, Telex 06-986766 TOR

ULTRASONIC MONITORING OF CONCRETE DELAMINATIONS

Confidential to Levelton and Associates and
Techno Scientific Inc.

December 1987

Prepared by: M. Macecek
C. Jaikaran

ULTRASONIC MONITORING OF DELAMINATIONS IN CONCRETE

INTRODUCTION

Techno Scientific Inc. (TSI) was approached by Levelton and Associates to test the feasibility of detection of concrete delaminations in thin slabs, six to ten inches thick. The problem is associated with the salt penetration and seepage in garage decks which results in corrosion of rebars. This splits the concrete and in turn destroys its load carrying capacity. At present a chain drag method exists where a series of chains are dragged and the operator listens to the change of sounds and he can roughly delineate the boundaries of delamination. The technology used by our company and detailed in this short report is the same as the one used for the concrete block which was not exactly optimized.

EXPERIMENTAL SETUP

A two-transducer pulse-echo technique was used and a scan was made on the concrete slab shown in Figure 1 with the details along two lines which reveal two delaminations. Scans every 10cm were recorded and digitized as shown in Figure 2. The quality of signals was good. Caster oil used by the previous group or lithium grease was used as a couplant. The horizontal surface contained the coupling fluid well. The measurements with the spacing of 10cm along the two lines are shown in Figure 3.

DISCUSSION

The results are based on two facts, constructive interference of amplitude and frequency. The frequency interference can only result from the laminations inside of the volume as opposed to the front or back of the wall and it is really the interference of the surface wave and the bulk wave arriving later. Analysis was also carried out on the basis of the magnitude of the signal. Two blots shown in Figure 4 depict the interference pattern. Based on this study we proposed with some high probability that delaminations exist in parts shown in the drawing. This problem is considered relatively simple and we have demonstrated this technology previously. Figure 5 shows a single transducer with 0.5 MHz frequency which we consider sufficient for measurements of this type. However for practical and fast measurements, a transducer with a coupling wheel may be considered to speed up the inspection. A simple portable device can be developed with performance far superior to the chain drag method.

CONCLUSIONS

Delaminations in thin concrete slabs can be reliably detected once the system is optimized and trained. The accuracy of the system should be far higher to the drag chain method and speed of operation could be considered significantly higher. While the laboratory system was not quite suitable for field work we believe that a moderate effort could yield a field instrument which will be capable of performing the desired tasks.

REFERENCES

1. Macecek, M. "Development of Portable Test Equipment Employing Ultrasonic Pulse-Echo Technique to Determine Flaws in Concrete". TSI Report to EMR, March 1986.

2. Macecek, M. "Pulse Echo Testing of Arctic Structure Mock-Up" TSI Report to Levelton & Associates Ltd., December 1987.

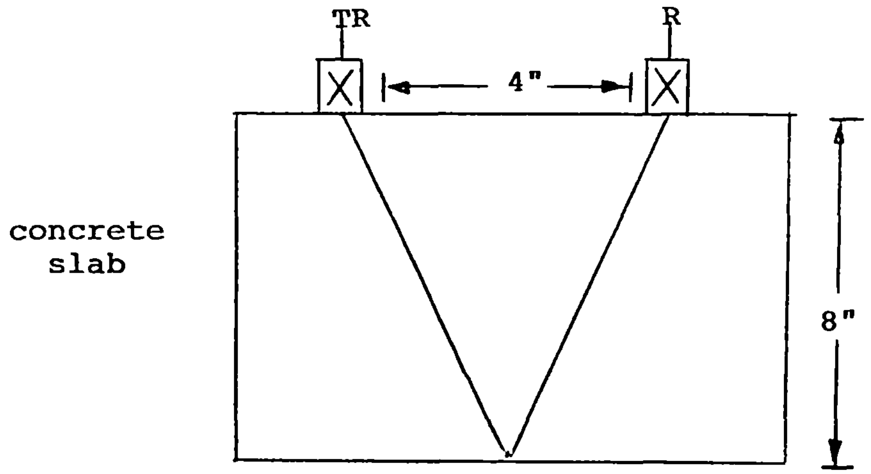


Figure 1. Experimental arrangement for inspection of concrete slab.

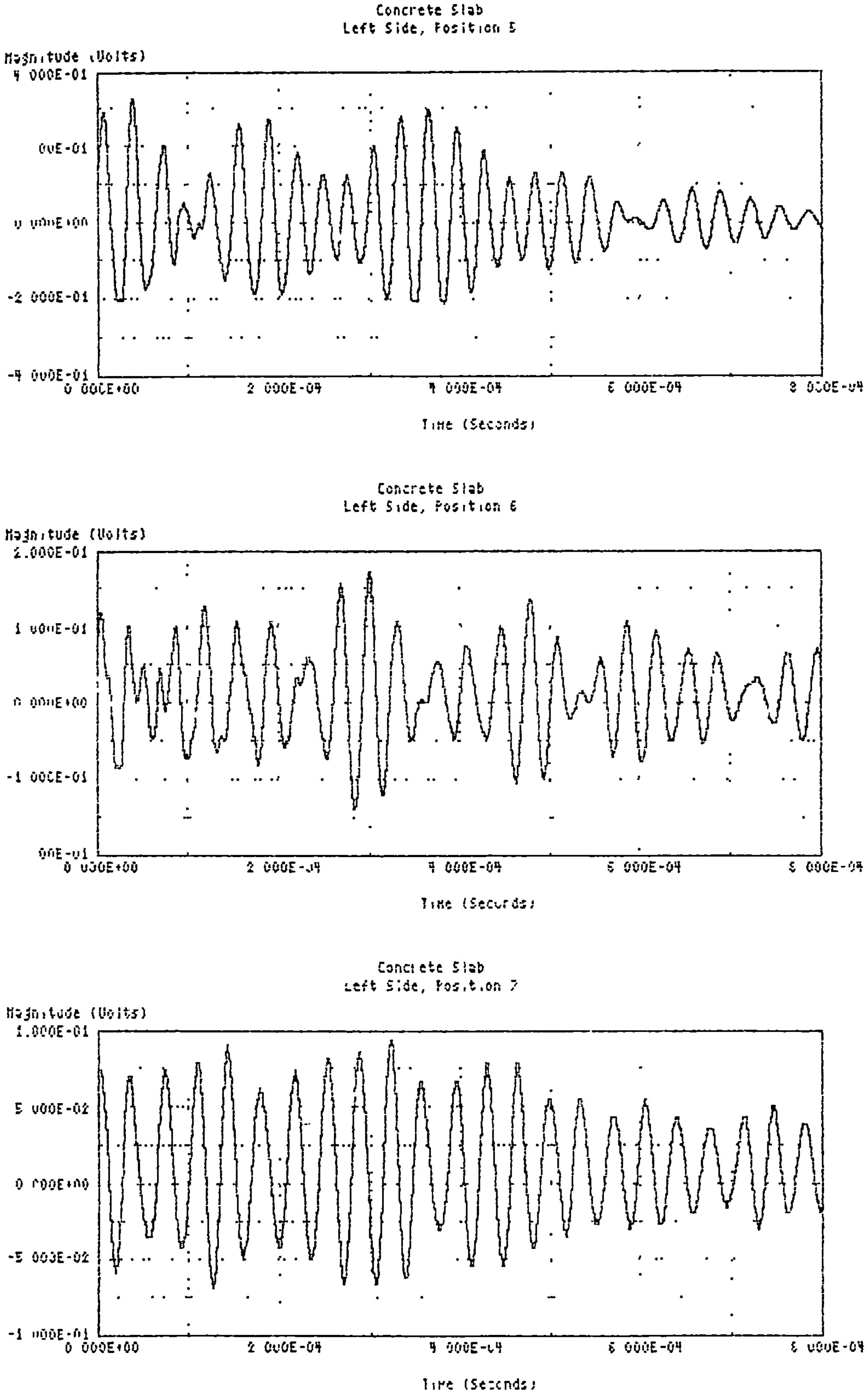


Figure 2. Examples of digitized ehco signals received on the slab.

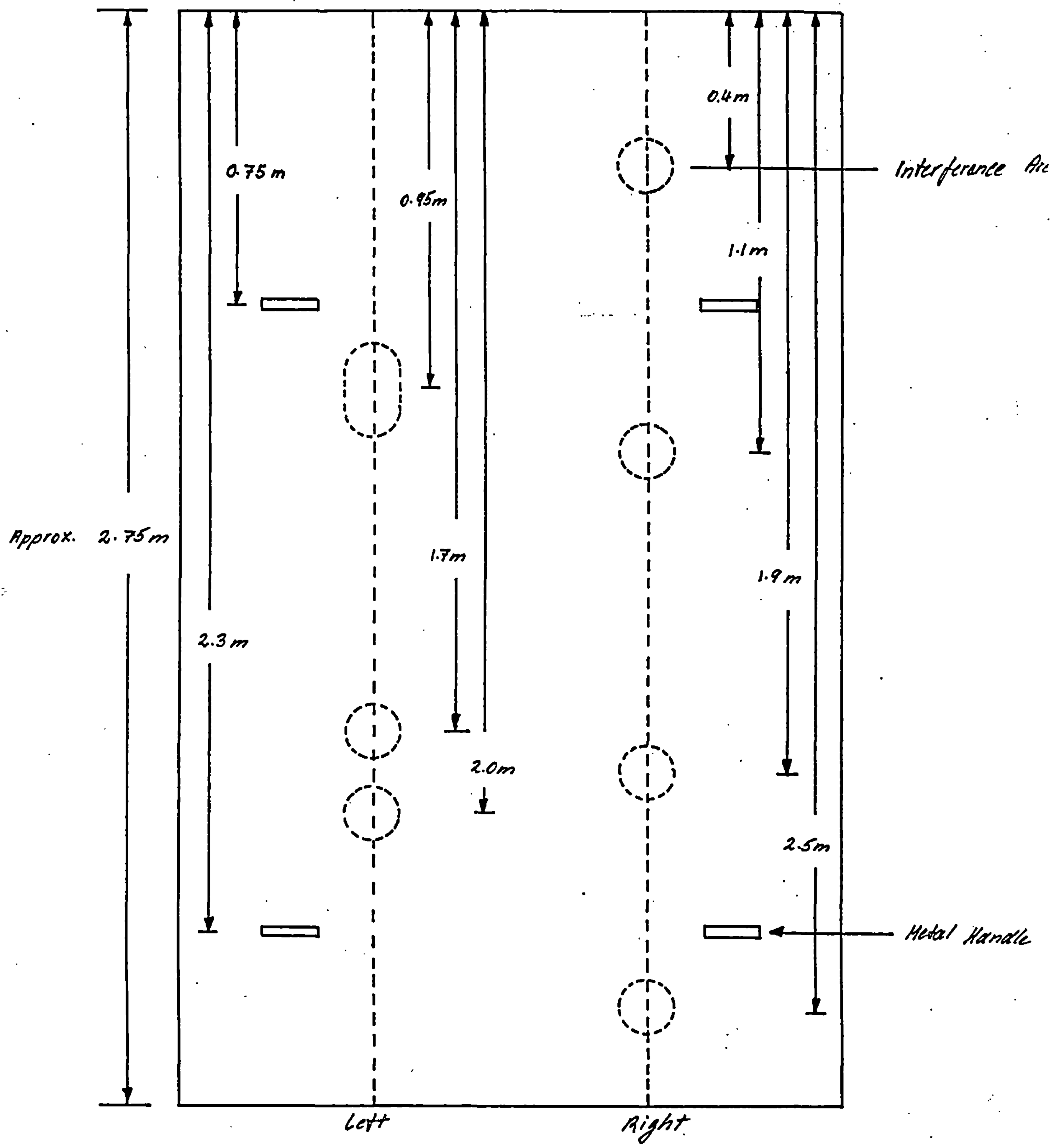
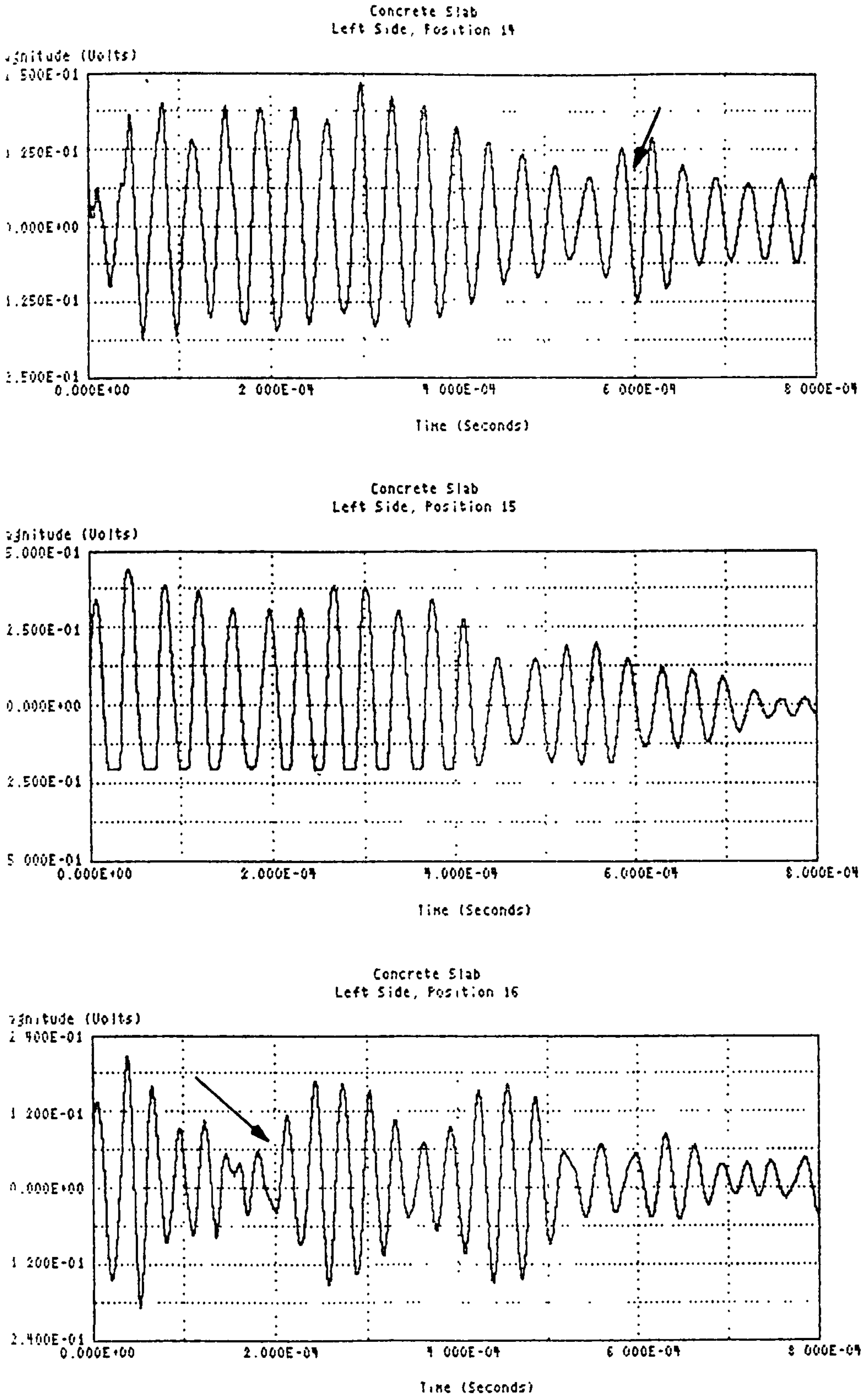


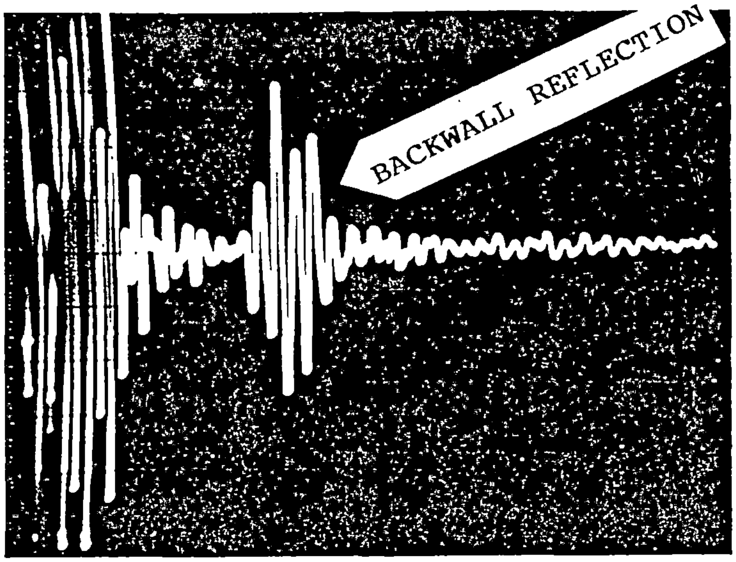
Figure 3. Layout of test block indicating the two scanning lines and probable delaminations on the side.



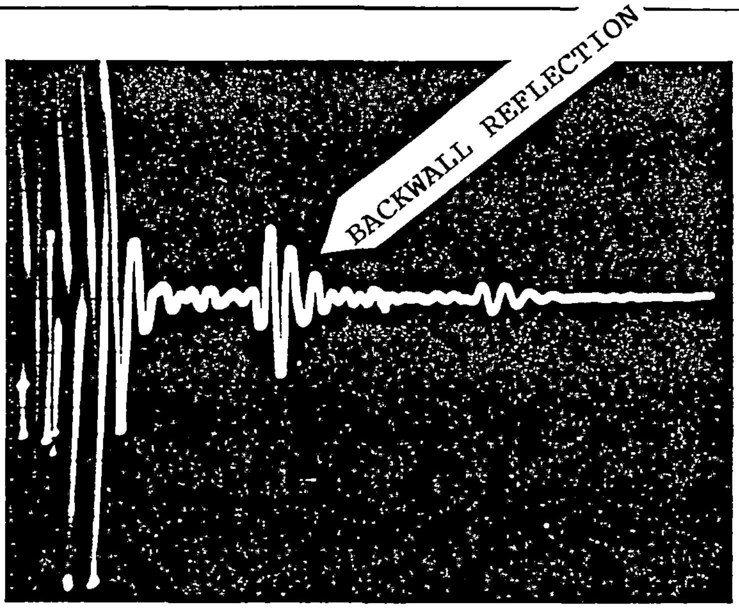
A) Interference caused by the echo signal from the backwall.

C) Interference caused by internal delaminations.

Figure 4. Examples of RF waveforms showing the interaction of the surface wave with the backwall and/or internal delaminations.



b) backwall reflection with 500 KHz transducer



b) backwall reflection with 1 MHz transducer

Figure 5. Pulse echo signals of 4" slab with 500 KHz and 1 MHz transducer.

APPENDIX F

ULTRASONIC INSPECTION OF MATERIALS

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The use of sonic and ultrasonic stress waves to identify and locate internal defects in a body of material is a technology that has been used for many years. It is currently widely used to locate cracks, voids and other discontinuities in metals. The technique has been adapted to concrete during the last 15 years.

The basic concept is described as follows. If one considers a homogeneous mass of a material, a stress pulse introduced at the surface will propagate through the material at a fixed velocity. As it travels through the mass, the amplitude of the wave decays. If the wave encounters a discontinuity, a portion of the energy will be reflected back towards the source. The remaining energy will be transmitted through, past or diffracted around the discontinuity. Eventually the wave reaches the opposite wall of the mass, where it is reflected from that interface. Thus, the wave continues to reflect back and forth between the two faces of the mass, while any intermediate discontinuities will also create reflections. Plate A5 illustrates this situation.

Two methods are used to create the stress wave. The first is the use of a piezoelectric crystal which converts electrical energy to mechanical energy and vice versa. When the crystal is excited by an electrical signal, it vibrates and creates a series of stress waves. When the crystal is incorporated into a transducer which is held in contact with a mass, the stress waves propagate through the mass. Conversely, when the crystal is held in contact with the mass, any stress waves arriving at the surface from within the mass will cause the crystal to vibrate, which generates an electrical signal. Hence, transducers of this type can both send and receive waves.

Two characteristics of the piezoelectric transducer are relevant here. The frequency of the vibration affects both the penetrating power of the stress waves and the width of the beam or column in which the waves travel. High frequencies create a very narrow beam which has high resolution (i.e. can detect very small discontinuities) but has relatively poor penetrating ability through a non-homogeneous mass such as concrete. The narrow, less powerful beam is rapidly scattered and decayed by the many changes in density and material as it travels through aggregate particles, cement paste, rebar, etc. Hence, when testing concrete it is necessary to use lower frequency vibration (50 to 200 kHz) to get better penetration, which results in a beam which diverges more rapidly and has poorer resolution.

The second important characteristic is the size of the crystal. A broad, flat crystal with a relayively large "footprint" will produce a narrower, more collimated beam than a small transducer. As the size of the crystal approaches that of a single point, the wave tends to become more spherical in shape and radiate in all directions, rather than being confined to a beam or column.

The second method of creating the stress wave is to use a mechanical impact. The returning stress waves are then detected by a piezoelectric transducer. Waves created in this manner are essentially spherical in shape and cannot be collimated into a beam. The main advantage the mechanical impact has over a piezoelectric transducer is a higher level of energy which can overcome the rapid decay which occurs with the latter type of pulse.

In all cases, a stress pulse is created at the surface of the specimen. It travels through the mass, is reflected by the opposite wall and returns to the surface of origin. A receiving transducer (which may be the same one that sent the pulse) then detects the arrival of the pulse. Any intermediate discontinuities will also reflect waves back towards the original surface, the arrivals of which are also detected by the receiving transducer. The time interval between the departure and arrival of the waves is measured precisely by the equipment.

Since the thickness of the specimen is usually known, and the velocity of the wave can be measured, a plot can be created showing signal amplitude versus time or signal amplitude versus frequency of wave arrivals.

By studying these plots it is possible for experienced engineers to deduce the nature of the disontinuity and its size and depth from the surface.