ADVANCES IN THE USE OF THE "MODIFIED SHOCK TEST" SYSTEM

BY

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INTRODUCTION

History of Integrity Testing

Probably the first published work on the integrity testing of *piles* was by Dvorak from Hungary, 1969, who used basic seismic equipment to determine the length of pre-cast driven) concrete piles. The real break through in pile testing came from work at the CBETP, France by Davis & Dunn, with the publishing of the paper which is now regarded as the integrity testing "Bible", "From Theory to Field Experience with the Non-destructive Vibration Testing of Piles", 1974 (2). In the late 70's John Higgs worked with CBETP and along with Dr Davis, started to devise a transient dynamic test, later designated the "Modified Shock Test", their findings being published in the paper, "Integrity Testing of Concrete Piles by Shock Method", in 1979(3). John Higgs continued to develop the technique and with the advent of modem, fast computers have produced a fast and efficient method of testing piles culminating in the paper "Single End Shock Test {SST)" in 1987(4).

Theory of Modified Shock Test

In simple terms, the modified shock test is a seismic test using a hammer blow as the force and a transducer to pick up the resultant vibrations With the application of digital filtering techniques an accurate mechanical admittance vs. frequency plot is obtained which can then be interpreted using the concepts developed by Davis & Dunn, 1974. The following can be calculated:

Pile Head Stiffness is proportional to the inverse slope of the initial part of the mechanical admittance vs. frequency plot. This relates to the compression loading characteristics of the pile as would be found in a dead load test on the pile represented as a displacement vs. load graph. As the pile is only minimally excited this indicates only the elastic behavior of the pile/soil structure and not total load bearing capacity.

Pile Length & Discontinuities

The pile length maybe determined from a seismic trace measurement of time for the sound wave to travel to the base of the pile and return, and this is calculated simply by:

$$\frac{\textbf{Time in Milliseconds}}{2} \times \textbf{Velocity (speed of sound in pile)} = \textbf{Length}$$

In the modified shock test the pile length or any length to any reduction of section or other anomalies, is determined from the frequency spectra and the following formula used:

$$\textbf{Length} = \frac{\textbf{Velocity (speed of sound in Pile)}}{\textbf{2 x Delta F (difference in frequency between successive similar resonance peaks)}}$$

In essence, the program looks for resonance frequencies, which occur more than five times, indicating a true frequency response. The calculation is then carried out and the resultant depth noted. With the calculated length and measured time, the program then calculates the cross section of the pile at various locations measured by the frequency responses.

Range of Stiffness Expected

To be able to compare whether the pile is functioning correctly, the program procedures model values of the pile admittance with various end conditions. "E" min represents a pile with no base support. "E" max represents a pile with infinitely rigid base and shaft clamped along its entire length. These parameters are used for comparative purposes.

Shear & Compression Mode

Piles can be tested in two modes: compression and shear modes both from the top of the pile. The shear mode is obtained by placing the receiving transducer on the side then striking the pile inducing the principal shear wave. The compression tests are obtained by a hammer blow at the top of the pile using a vertical velocity transducer producing the compression waves as the principal wave.

Interpretation of Results

The program produces a large stream of data, not all of which is not relevant to the interpretation of the results in physical or structural terms. The printed results are in three sections: the mechanical admittance curve, the dynamic load test plot and the pile model. Information is available on all of these plots and the relevant information from these plots is indicated below.

Mechanical Admittance Plot

For a sound pile the mechanical admittance graph should have a relatively flat initial angle and then the graph should have an equally spaced regular wave pattern. For defective piles the pattern is completely broken up as in essence there are numerous different frequencies from each contiguous section. The general shape of the admittance curve for piles can be represented as a reasonably symmetrical wave pattern with a number of small spikes.
The major annotation of the Mechanical Admittance plots is the first line of text, being the stiffness. The stiffness itself is as discussed above, the E prime or overall structural stiffness of the pile. The "E" max represents the pile in an optimum condition and the "E" min is the pile in its worst condition. The stiffness values should fall between this "E" max and "E" min, if not, there are serious problems with the pile. None of the other information is immediately relevant as the model and load plot translates the results into engineering terms.

Pile Model

The pile model is a diagrammatic representation of the pile diameters at various depths. It also gives the total] depth of pile at the velocity for the various materia1s used in the pile construction. As this is normally a standard velocity, the actual] depths to the change of section can be variable, particularly where the material] has faults such as honeycombing or loss of section.

Dynamic Load Test Plot (Vertical)

This graph estimates the response in a simulated load/deflection graph from a load test carried out on the pile. This would be the result from a dead weight pile loading test in compression on the pile. The first point of the graph is the result from the stiffness of the pile and the second point indicates the maximum elastic value of the pile. The settlement being on the vertical axis the load in tonnes on the horizontal axis.

DEVELOPMENT OF TECHNIQUES FOR OTHER STRUCTURAL ELEMENTS

The principles behind the Modified Shock Test have been outlined above and its original and principal use for the integrity testing of new stand-alone piles, and in particular concrete piles.

Over the past 10 years with the development of the system we have considered how the same principles or similar principles can be applied to other civil engineering structural elements. As described above Stiffness is probably the most important aspect of the Modified Shock Test, so we considered that if the Stiffness of other elements could be determined it could be used to check structural adequacy. Stiffness is derived from a number of conditions, quality of the shaft concrete or other material, end support conditions, clamping or effective clamping of the shaft through the soil and the support to the top of the pile. Hence any change in any of these conditions changes the stiffness of the pile or element under test. The first experiment was to test insitu concrete light poles. The stiffness was greatly reduced and closer to the "E" min mode] rather than "E" max. Concrete poles with cracking or loss of section showed even lower stiffness values, and in addition, the pile model indicated reduced diameters at the defect locations.

We then moved to a more complex situation of a column in a building (refer Figure 1). In this case the element is clamped at both ends with no effective clamping along the shaft. Once again results were encouraging and in particular columns with defects were readily distinguished once again by the reduced stiffness of similar columns and also by the reduced diameters from the pile *models* (5). In this case empirical analysis of the results proved the best method to identify the defective columns, but a series of load tests indicated that actual load deflection curves from both the static load test and modified shock tests were similar up to a deflection of about 6mm. We therefore adopted a deflection criteria of 6mm for load deflection reporting, unless a larger deflection was specified.

Over a number of years we proved that we could obtain meaningful stiffness or load deflection values for elements with differing end support conditions, such as light poles and columns.

Beams

Beams are much more complex as they not only have clamped end support conditions but also "clamping" through the floor at the top of the beam (refer Figure 2). Results from beams have not proved as accurate as far as stiffness is concerned due to the unknown clamping effect of the floor. Analysis of beam stiffness results are generally taken on an empirical basis, supported by the reduction in section in the pile model corresponding to any defects in the beams. Beam analysis was very successful in determining the effect of fire damage in beams in a multi-storey building in Jakarta (6). Saturation testing was carried out on the beams, with dead weight load testing on five beams used as a correlation to determine what stiffness values were acceptable from the modified shock test and hence what beams needed repairs. This proved to be a cost effective method of testing 100 beams or more for each floor of the 12 storey building. Subsequent trials on wooden beams with wooden decking proved an effective method to determine infested and reduced section beams (7).

Void Detection

Lack of contact grout behind tunnel linings has over the years been a problem without economic solution. The authors carried out a number of trials with limited equipment resources in the early *80's* and proved that voids could be detected due to a great reduction in the stiffness values (8). With the development of fast computers the technique became more reliable and Dr. Davis (9) successfully used the technique to determine integrity of contact grout in the Channel Tunnel. In recent years with the use of notebook computers allowing on-site analysis the technique has become very reliable. Two recent contracts successfully carried out were void detection in a large diameter brick lined tunnel at Geelong, Victoria (10} and voids below a concrete lined reservoir at Bunbury, Western Australia (refer Figure 3) (11).

Void detection is relatively simple, in that for instance, in the Geelong tunnel tests were taken around the periphery of the tunnel at approximately 2m centres and at 2m spacings along the tunnel. The 500m tunnel was tested over four (4) Sunday shut downs and voids were detected by reduced stiffness values in the order of 50%, with substantiation of the void by extensive necking in the pile model. Voids were confirmed later by drilling and grouting (refer Figure 4, for typical results). Similarly the testing of an existing concrete lined reservoir in Bunbury, W A indicated the presence of voids in the same way and once again these were confirmed by drilling.

This type of void detection is now therefore a well proven technique using the modified shock system in the micro seismic mode, irrespective of the lining or pavement material, whether brick, masonry, concrete, timber or even steel.

Integrity of Non-Concrete Elements

In early 1991, the authors undertook a large bridge inspection program for 136 bridges in Indonesia (12). A large volume of the work was concentrated on assessing the integrity of the masonry piers and abutments to support the steel bridge superstructures. Using simple seismic techniques with a single channel seismograph and visual interpretation it was evident that seismic waves were suitable to determine integrity of these elements. Once again, with the continued development of fast computers, the technique became more amenable to an engineering solution, with the production of stiffness values or load deflections curves, coupled with the model to determine where anomalies exist (refer Figure 5). To date we have tested timber, masonry, brickwork, combination brickwork and masonry foundations, piers and abutments and have had success in determining the structural integrity of these elements.

Other interesting projects have been similar testing of two brick chimneys; one for a Jam Factory and the other an historic Shot Tower and masonry piers, abutments and timber columns for railway bridges in Victoria.

The use of the modified shock test for non-concrete elements was further developed in the determination of voids or defects in small diameter brick lined sewers. Without knowledge of each others developments the University of Edinbur~13) was researching methods to detect voids behind tunnel linings at the same time the authors were testing a 1.2m diameter brick lined ovoid sewer in Melbourne (14) and having better equipment and programs we achieved similar if not more accurate results than the University of Edinburgh. In addition to the modified shock testing along the tunnel, reflective seismic testing was carried out from the surface to determine any voids and soil profiles (refer Figures 6 & 7). The system proved successful with results being confirmed by soil drilling, down the hole seismic cross shooting and CCTV surveys of the tunnel.

Timber Pile Testing

Out of necessity rather than a search for new applications {as there are over 300,000 timber piles in use around the coastline of Australia), we continued development of the computerised system to determine the integrity and capacity of in-service timber piles.

The main problem with timber piles is that timber is not a homogeneous material. It has sound velocities, which vary by as much as 100% in traverse directions and it has defects from numerous sources. We were fortunate to
, be able to test 60 timber piles at a wharf in South Australia and used these tests to develop successful ways to test timber piles (refer Figure 8). The success of timber pile testing can be attributed to changes and developments in the computerised system, which amplifies the raw data signals and then filters the data without loss of information at the analysis stage.

Timber Pile Testing

After our initial success we were fortunate to be assisted by the Port of Melbourne Authority (15) to develop the system further, and having tested over 3,000 timber piles over the past 2 years, with numerous timber types we are confident we can determine the integrity of timber piles, see Figure 9 for a typical pile test result.
The system can detect the presence of marine borers with results indicating a large loss of section in the pile model, and stiffness values reduced by 50% or more. Stiffness values or load deflection values are affected by the support to the pile from the crosshead and any additional bracing, but defects in the pile shafts still reduce the stiffness values significantly. We have determined that the use of stiffness values will allow for detection of defective piles, but as yet we have not determined how closely the load deflection estimates at a deflection of 6mm compare with actual load values.

Conclusion

Over the past 10 years and with continued development of both fast computers and the modified shock test program itself, we have adapted the test to determine the integrity and structural adequacy of differing structural elements.

The successful completion of numerous projects have indicated that the modified shock system can be used to assist structural engineers to determine the adequacy of elements within the Structure, be it in some instances by empirical assessment rather than by the use of accurate models. Over time we have developed experience which allows greater conjecture in the models used to derive stiffness and load deflection estimates. With feedback from dead load tests we have been able to refine the models and to predict the behavior of a greater range of Structural elements.

With the use of battery operated notebook computers, the potential for the testing of elements becomes a practical possibility and the only restraints appear to be the promise of sufficient force to excite the element under test.

Clearly this is a modem day tool, which can be used, in a varying number of situations and the results indicate successful applications giving useful engineering information.

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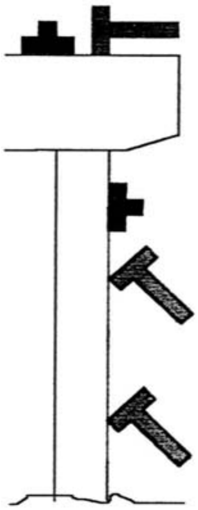
Shock testing of structures

Methods of data capture

Pile



Compression test from top of pile or support structure

Shear test from side of pile

Compression test from side of pile - larger separation of transducer and impact device.

FIG. 1: COLUMN / PILE CLAMPED TOP & BOTTOM

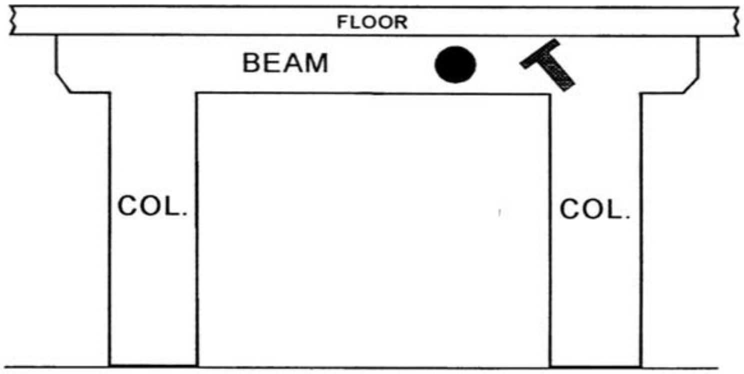
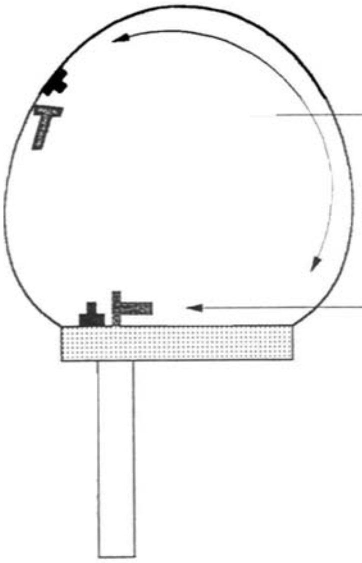


FIG. 2: BEAM CLAMPED BY FLOOR

Insitu Testing of Elements

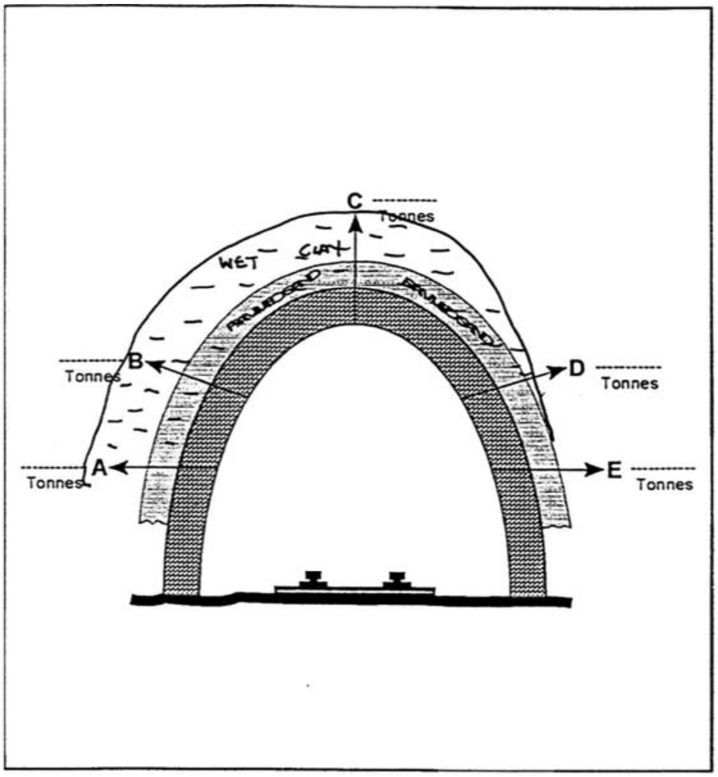


Compression or shear test inside the
tunnel to determine voids behind
the lining.

Compression test on the floor slab or
other similar structure to determine voids or
piled support below the slab.

FIG. 3: TUNNELS, LININGS & BASE SLABS

A



GEELONG RAILWAY TUNNEL
MICRO SEISMIC SURVEY

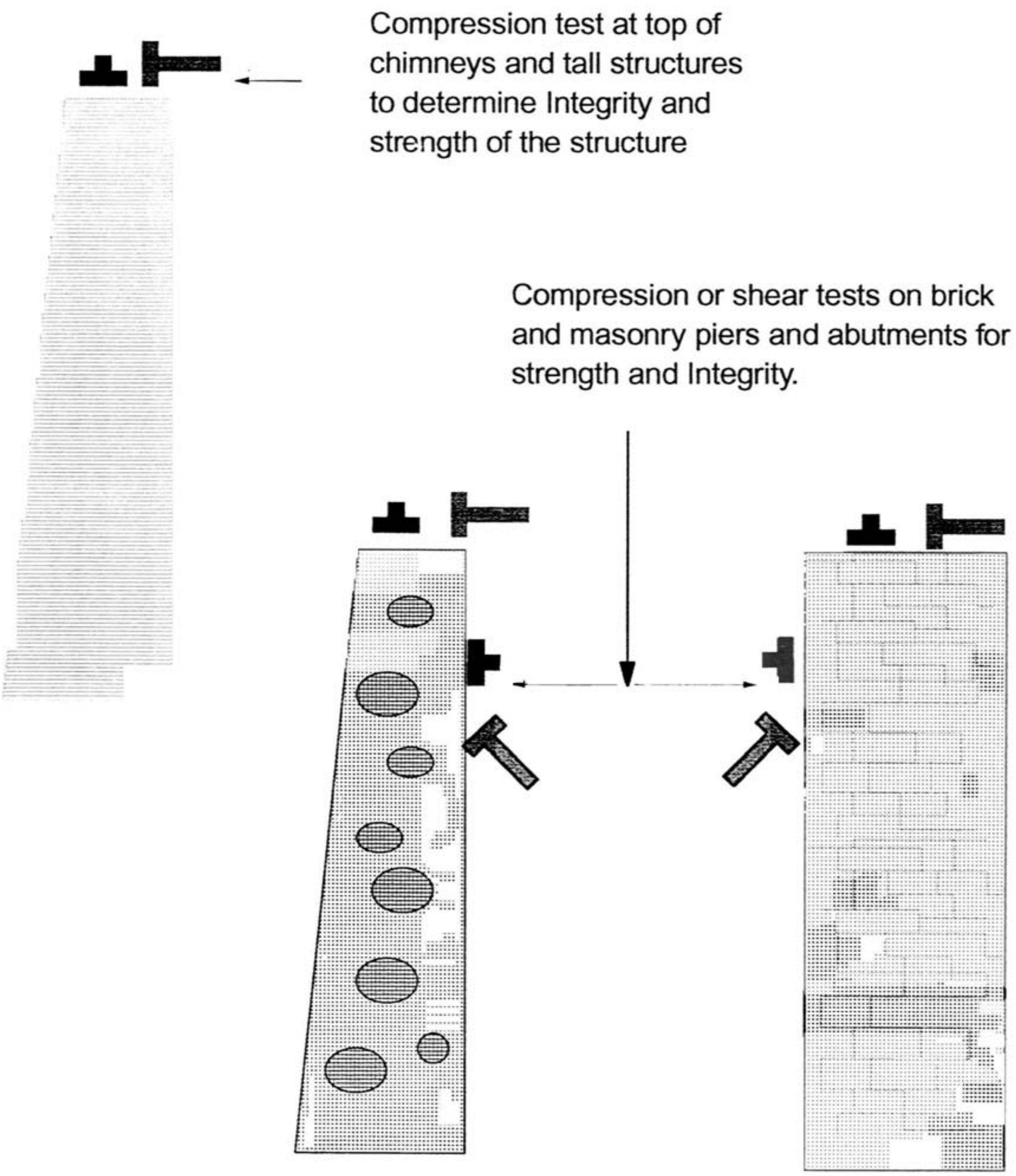
CHAINAGE: 88 + 00

Location	Load (Tonnes)	Model	Remarks
A	5.92	Necked	1+m wet clay
B	7.83	Slight necking	1+m wet clay
C	5.48	Necked	1+m wet clay
D	8.14	Necked	1+m wet clay
E			

Fig 4

Shock testing of structures

Insitu Testing of Elements

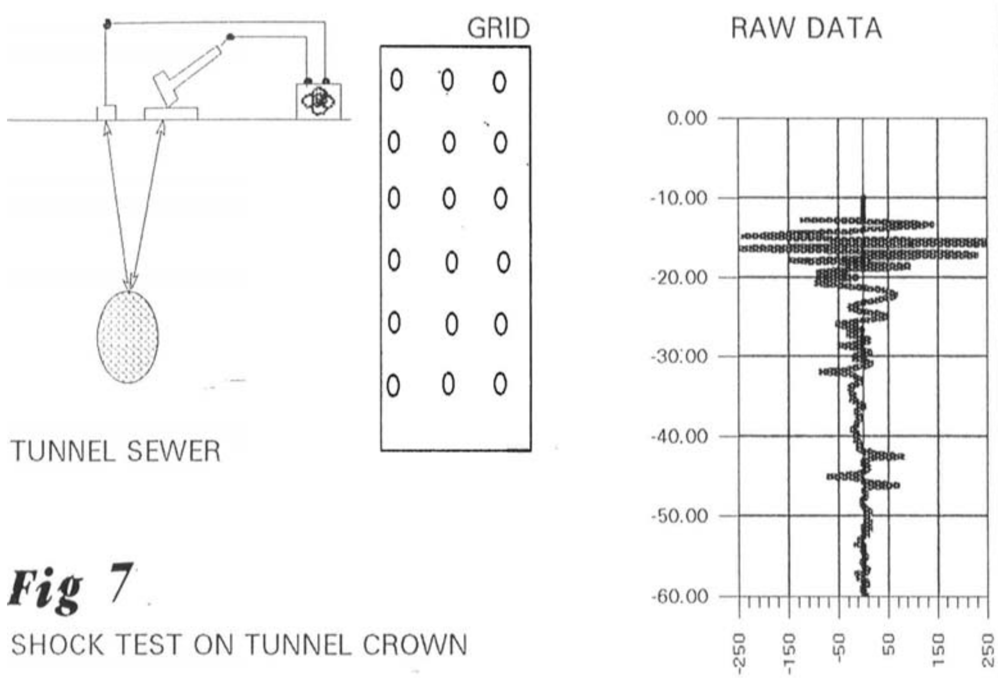


Compression test at top of chimneys and tall structures to determine Integrity and strength of the structure

Compression or shear tests on brick and masonry piers and abutments for strength and Integrity.

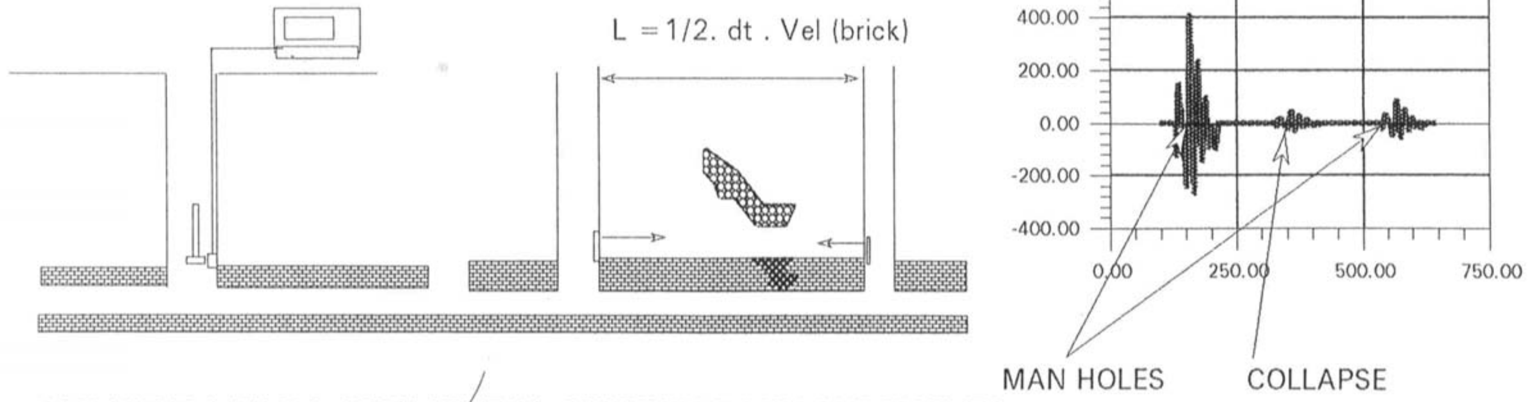
FIG. 5: TESTING OF MASONRY OR BRICKWORK STRUCTURES

Fig 6 ZERO OFFSET TECHNIQUE



TIME msec.	1/ 2 msec.	VELOCITY m/s.	THK (m.)	DEPTH (m.)	SOIL PROFILE
0.00	0.00	300.00	2.25	0.00	CLAY
15.00	7.50	1000.00	5.00	5.00	IV ROCK
25.00	5.00	2250.00	5.63	10.63	III ROCK
30.00	2.50	450.00	0.45	11.08	VOID
32.00	1.00	3500.00	14.00	25.08	II ROCK
40.00	4.00	200.00	0.00	25.08	TUNNEL
48.00					

Fig 7 SHOCK TEST ON TUNNEL CROWN



ANALYSIS YEILDS STRUCTURAL STIFFNESS MEASUREMENTS ON TUNNEL FABRIC

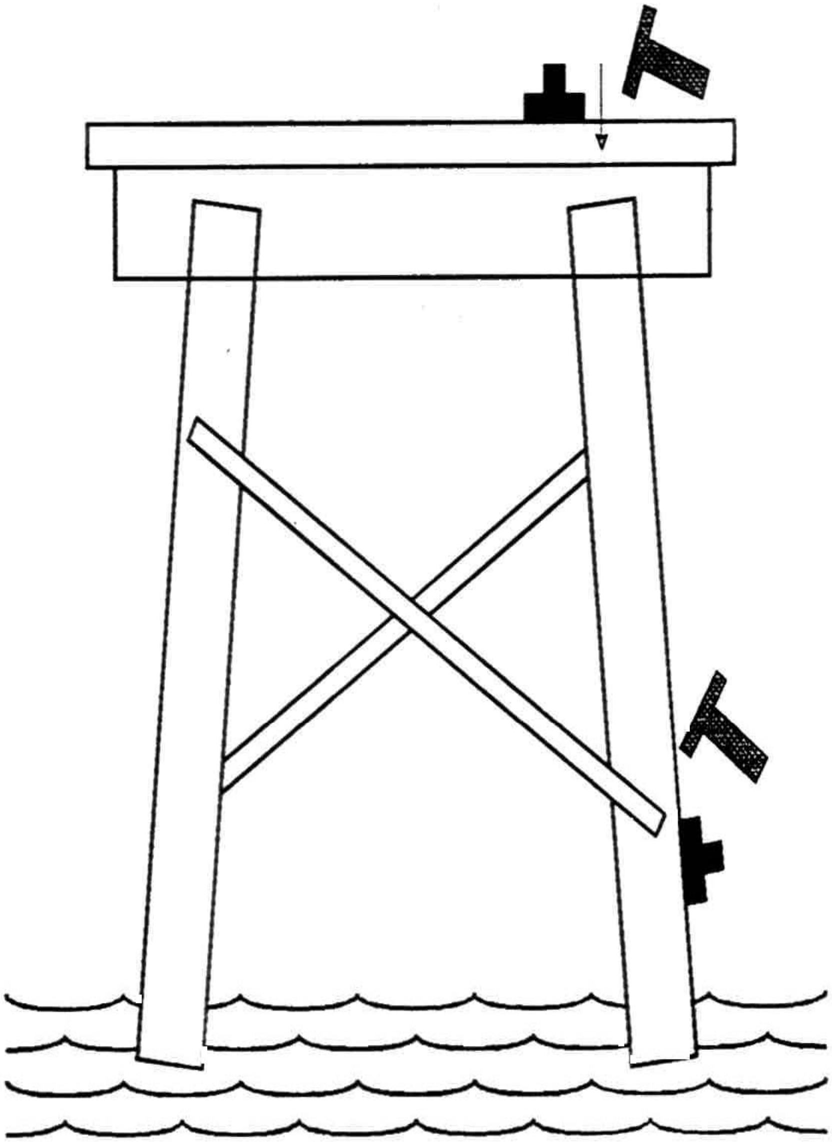


FIG. 8: TESTING OF INSITU TIMBER PILES