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Technical Note

Feasibility Studies On Pile Integrity Testing Through AEM

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Introduction

Proper pile installation is as important as rational pile design in order to obtain cost effective and safe end product. To ensure good quality piles, there should be good communication between the design and field engineers and there is need for evolving appropriate integrity testing methods. Since the static pile load tests are time consuming and costly, non-destructive methods of testing to ensure pile integrity have increasingly become common place during the past two decades. Non-destructive testing techniques can be effectively used to detect irregularities in the form of necking, honeycombing, defects in the pile, toes and pile joints. In many cases, the static load tests were not performed in sufficient numbers due to time and cost limitations. In some cases, such as offshore oil installation and marine structures, large loads are involved. In conditions where soil profile changes are sudden or in the absence of compatible driving system for driven piles, adequate programme to confirm the static capacity is not often rightly pursued and developed. To meet this void, non-destructive method of testing has become increasingly common place during the past two decades as both measuring equipments and techniques of analysis have been developed and improved. The non-destructive testing method is a quick, reliable, inexpensive, realistic, quality control tool and is used as an efficient monitoring method in large number of pile projects.

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Non-destructive Testing Method

Types of Non-destructive Tests

1. Dynamic high energy testing of driven piles
2. Dynamic low energy method of pile integrity tests for all types of piles
3. Miscellaneous non-destructive pile integrity tests

Dynamic High Energy Test

In this test, a large mass is allowed to strike the pile head and the acceleration and velocity of the propagated wave is measured. Each blow is analysed by special software. The one dimensional stress wave propagation approach applicable to pile driving has been used to predict the pile capacity and stress level, during driving.

Dynamic Low Energy Method of Pile Integrity Test

In the category of low energy method of pile integrity test the following methods may be mentioned :

1. Sonic echo method (seismic test)
2. Vibration method (dynamic response test)
3. Sonic coring method (acoustic test)

Sonic echo method is a low strain non-destructive testing method useful for both cast-in-situ and precast concrete piles. The principle of the method as explained by Middendrop et al. (1983) and Bhandari et al. (1989) is time domain reflectometry, wherein the pile acts as a one dimensional medium in which a wave is propagated. In vibration method by means of a mechanical or electric vibrator a constant amplitude stress wave at the pile top is applied. A velocity transducer placed at the top of the pile measures the impedance of the pile as a relationship between the applied frequency and velocity. Kinks in the velocity/(frequency) of mechanical admittance of the effective length of the pile and variation in the output will indicate various defects of the pile. Sonic coring method involves the tracing of sonic pulses through concrete to find the defects in the concrete.

Miscellaneous Methods

There are many other methods less popular than those already described used for pile integrity. They are coring method, electrical resistance method, prestressing method, radiation method, etc. Another non-destructive testing technique which has not so far found its application in pile integrity tests is acoustic emission monitoring method.

Acoustic Emission Monitoring Technique (AEM)

Principle

The phenomenon of transient elastic wave generation due to a rapid release of strain energy caused by a structural alteration in a solid material is known as stress wave emission or acoustic emission. Generally the structural alterations are, as a result of either internally or externally applied mechanical or thermal stresses. As explained in NTIS report (1976), external loading on a test specimen produces plastic flow, slippage of adjacent particles, crushing of particulate matter, micro-cracking, sliding friction, rolling friction, degradation of particle asperities and these actions result in the release of energy. Depending on the source of mechanism, acoustic emission signals may occur with frequencies ranging from several Hertz upto tens of Mega Hertz. The acoustic emission signals are classified as two types : burst and continuous. The burst type emission resembles a damped sinusoid, while the continuous type emission appears to consist of an overlapping sequence of individual bursts. The importance of acoustic emission monitoring lies in the fact that proper detection and analysis of acoustic emission signals can permit remote identification of source mechanisms and the associated structural alteration of solid materials. This information in turn can augment understanding of material behaviour and can be used as a quality control method during material processing and fabrication and as a non-destructive evaluation technique for assessing the structural integrity of materials under service conditions.

Detection and Signal Analysis System

The most simple type of acoustic emission detection system commonly used consists of a piezoelectric transducer directly attached to the work piece with an acoustical impedance matching coupling medium. The voltage output from the transducer is fed directly into a preamplifier, which is located as close to the transducer as possible. The preamplifier output signal is then passed to a signal analysis system which produces an analog or digital signal, everytime the amplified acoustic emission voltage signal exceeds selected discriminator threshold level. The most frequent method for evaluating structural damage by acoustic emission monitoring is to count the signal emitted during deformation of the material and to plot the result as count rate or total count as a function of some measure of the deformation such as pressure, stress, strain or number of fatigue cycles. Other methods used to process acoustic emission signals are to record the mean square voltage, which is a measure of the energy content and the root mean square voltage which is a measure of the signal displacement amplitude.

Non-destructive Testing Application of AEM

Hardly (1972) adopted the acoustic emission technique to determine the safety of overpressurizing underground gas storage facilities. Mearns and Hoover (1973) have continued a long term project of monitoring the stability of rock highway slopes initiated by Goodman and Blake (1966). Liptai and Hutton (1972) describe the use of the technique to inspect the safety of large crane rails, wooden roof trusses, bridges and the compression effects of tendons in prestressed concrete beams. In their recent state-of-the-art review, Galambos and Mcgogney (1975) include acoustic emission monitoring as a possible non-destructive method for bridge inspection. Koerner et al. (1976) have studied the behaviour of the granular soils using acoustic emission monitoring technique. Feasibility studies have been initiated at Anna University to examine the adaptability of AEM technique in pile integrity testing. The studies include integrity testing of model piles and prototype piles both at laboratory and field level and the details are furnished below :

Laboratory and Field Tests

laboratory Studies on Concrete Cube Samples

Concrete cube samples conforming to Indian Standard Specification of mix M10, M15 and M20 and of size 100 mm × 100 mm × 100 mm, 150 mm × 150 mm × 150 mm and 200 mm × 200 mm × 200 mm and cylindrical samples of 100 mm diameter and 200 mm long with waveguides in the form of 6 mm dia. bar protruding outside the samples from the centre of the specimen were prepared. The specimens were cured for 21 days and then tested in the universal testing machine. During loading, the transducer was attached to the wave-guide which in turn was connected to a Geo-monitor. All the samples were tested by adopting constant rate of loading till failure with continuous monitoring of acoustic emissions. At the end of the test, the acoustic emission recorded by the recorder were counted for each one of the load increments. The influence of the type of concrete mix and size and shape of the concrete cubes on the acoustic emissions so obtained from the test results are presented in Figs. 1 to 4.

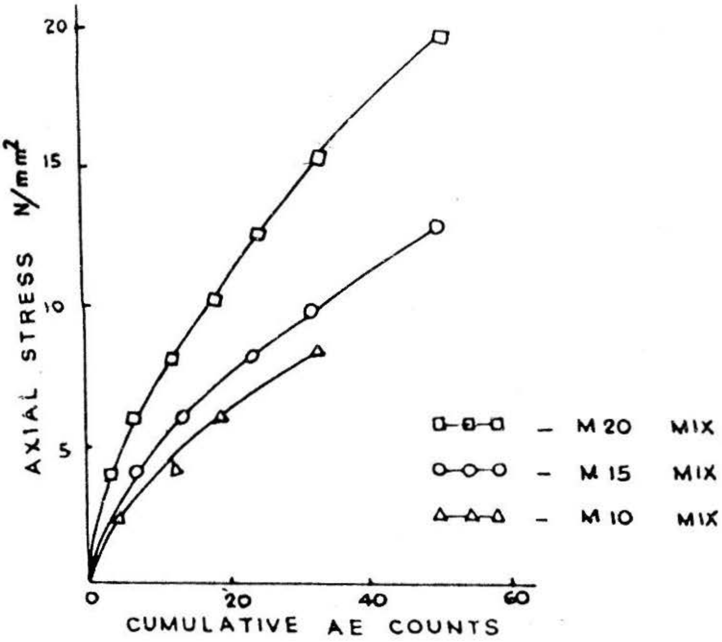

FIGURE 1 : Influence of Concrete Mix on Cumulative AE Counts (100 mm Size Concrete Cube)

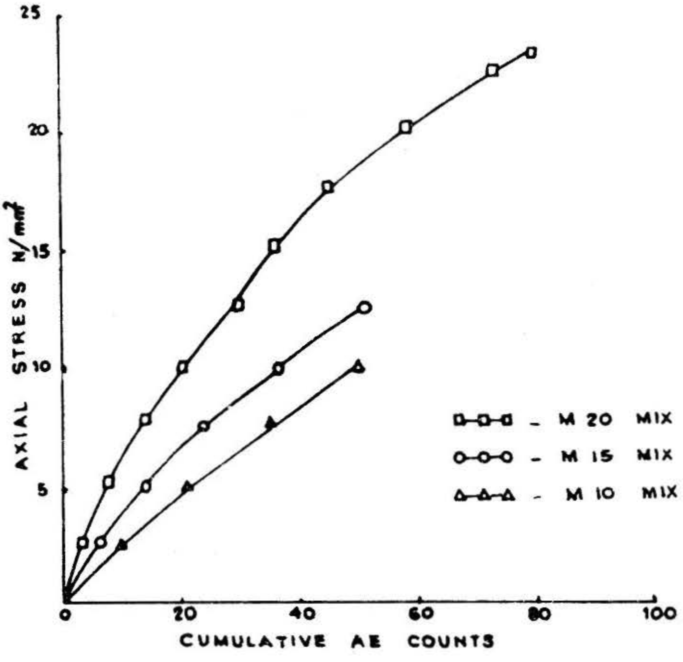

FIGURE 2 : Influence of Concrete Mix on Cumulative AE Counts (200 mm Size Concrete Cube)

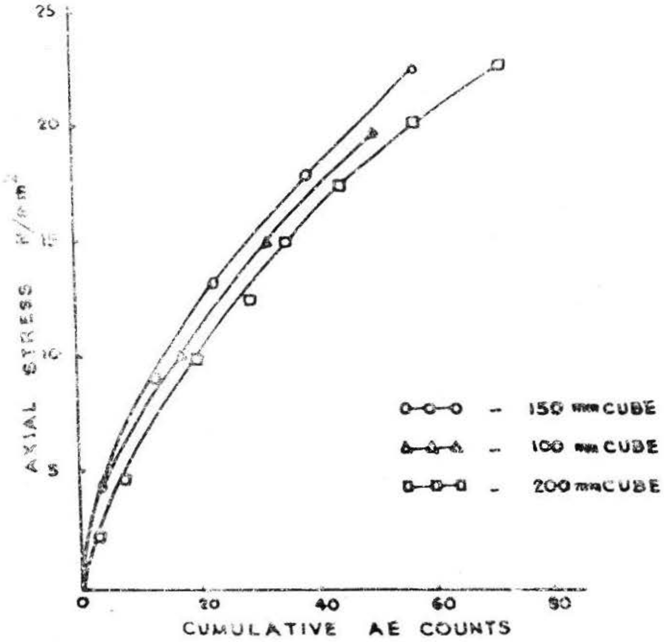

FIGURE 3 : Size Effect on Cumulative AE Counts (M20 Mix)

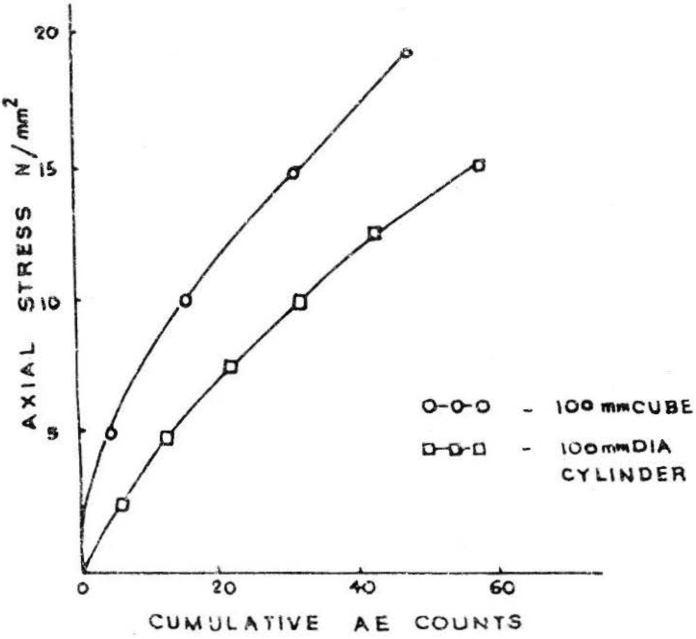

FIGURE 4 : Shape Effect on Cumulative AE Counts (M20 Mix)

Laboratory Studies on Model Piles

Four model piles of size 150 mm × 150 mm × 1200 mm were casted using M20 concrete with 4, 8 mm diameter longitudinal bars and 8 mm diameter mild steel stirrups at 300 mm c/c. Of the four piles, the first pile was cast without any defect. The second pile was cast with a central region of honeycomb defect and the third pile was cast with a central region of necking of 100 mm × 100 mm. During casting of these three piles, a central hole was made in each pile for the introduction of transducer and in addition a waveguide was introduced at the centre of each pile so that another transducer can be attached to monitor the acoustic emission. The fourth pile was made without any defect and without any central hole. In this pile, apart from main pile reinforcement, two additional mild steel bars were used to act as waveguides. One of the waveguides was taken to the full length of the pile and another waveguide was terminated at one third length of the pile, so that the feasibility for monitoring the acoustic emission during loading can be examined by adopting reinforcements as waveguides. After curing, the piles were loaded as point bearing piles embedded in a sand bed. Before the commencement of the load test on each one of the pile, a transducer was lowered through the central hole filled with water and another transducer was attached to the waveguide and these transducers were connected to the Geo-monitor. The details of the piles tested and the test set-up are presented in Figs. 5 to 7. The loads were applied at suitable intervals and the acoustic emission were monitored continuously. The relationship between cumulative counts of acoustic emission and applied axial stress obtained from test results is shown in Fig. 8. While loading the

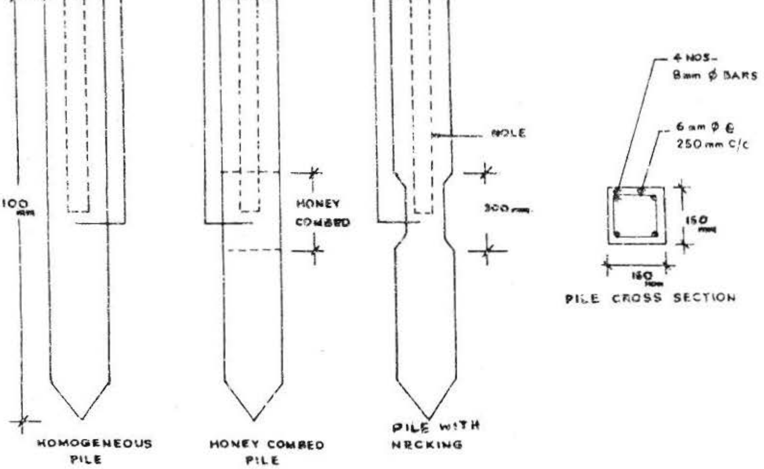

FIGURE 5 : Details of Model Piles

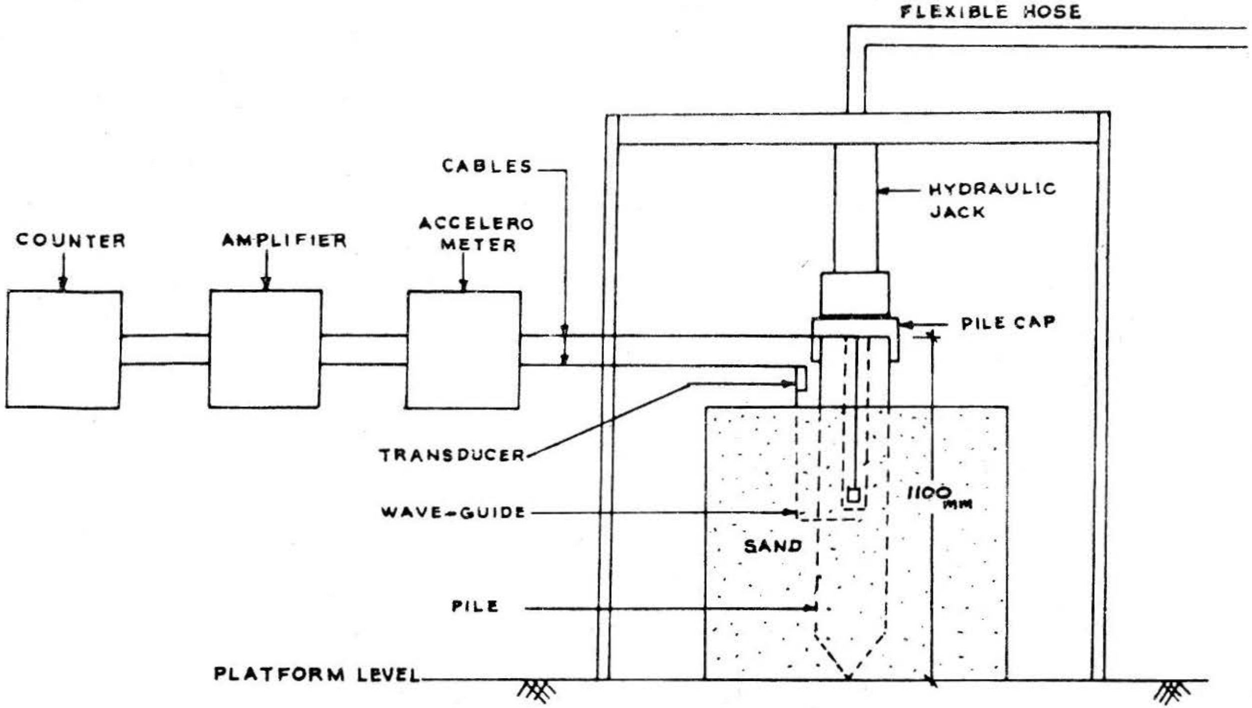

FIGURE 6 : Experimental Set-up (Model Pile Load Test)

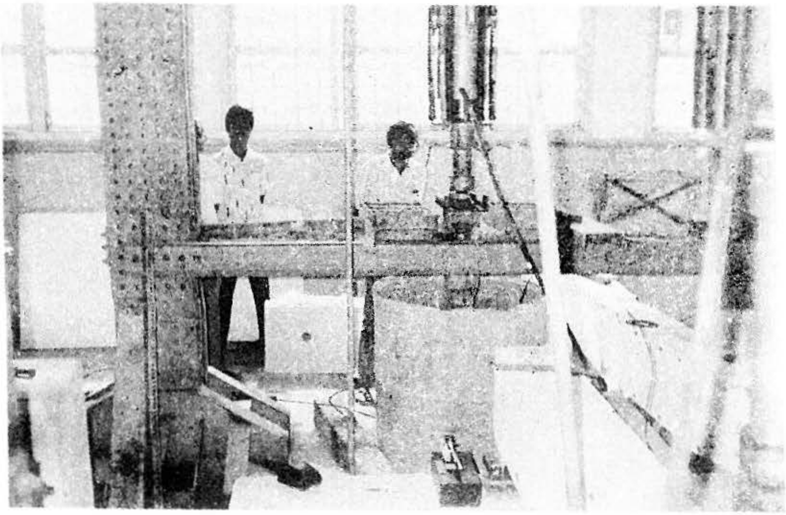

FIGURE 7 : Experimental Set-up (Model Pile Load Test)

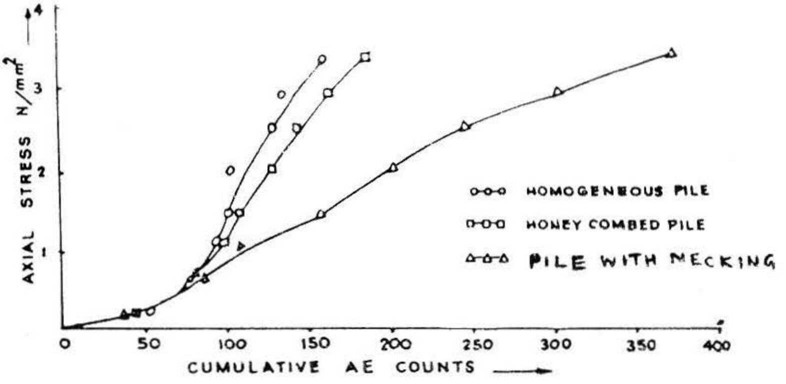

FIGURE 8 : Axial Stress Vs. Cumulative AE Counts (Model Piles)

fourth pile, one transducer was attached to the waveguide running for the entire length of the pile and the second transducer was attached to the waveguide which was taken out from the 1/3rd pile depth. the relationship between applied axial stress and cumulative acoustic emission counts obtained in the test is shown in Fig. 9 together with those for the seventh cycle of loading.

Field Studies on Prototype Pile

to study the feasibility of adopting the acoustic emission monitoring technique in field studies, a prototype bored cast-in-situ pile 400 mm

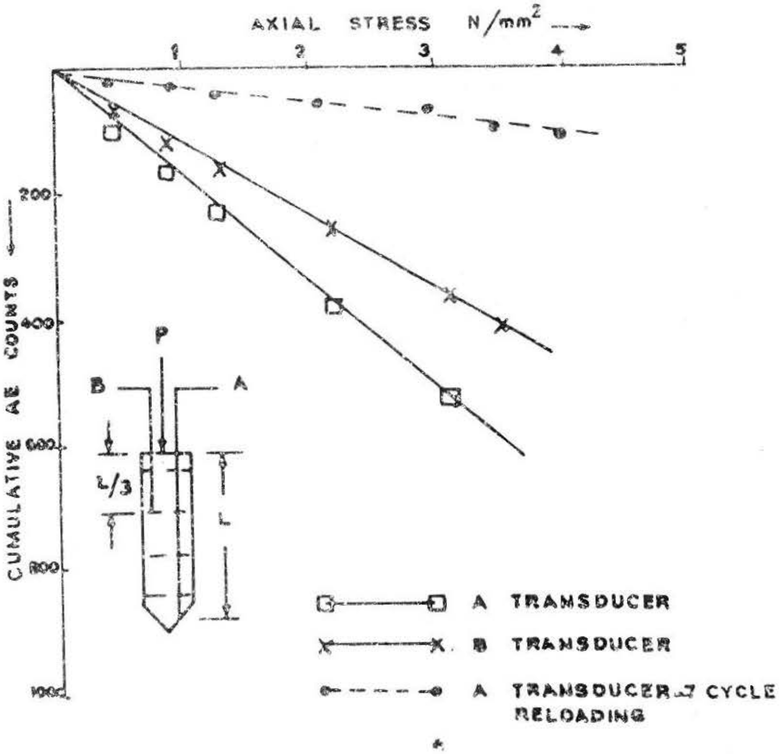

FIGURE 9 : Axial Stress Vs. Cumulative AE Counts (Model Pile)

diameter and 14100 mm length was cast with M20 concrete at a site in Athipattu in North Madras neighbourhood. The soil profile at Athipattu is shown in Fig. 10. During concreting, the borehole was supported with bentonite slurry and main reinforcement of 6, 12 mm diameter steel bars with circular stirrups of 6 mm diameter mild steel rods at 150 mm c/c were used. In addition, 2 additional 6 mm diameter mild steel rods were also introduced and terminated at depths of 5000 mm and 10000 mm to serve as waveguides. After 28 days of curing, the pile was loaded as per the specification of IS 2911 Part-IV (1979). During loading, the transducers were connected to the waveguides. For each load increment, the acoustic emissions were recorded continuously. The load test arrangements are shown in Figs. 11 and 12. Typical plots of acoustic emission obtained in the field are shown in Figs. 13 and 14.

Interpretation and Discussion of Test Results

Influence of Concrete Mix on Acoustic Emission Counts

Figures 1 and 2 show that as the concrete mix changes from M20 to

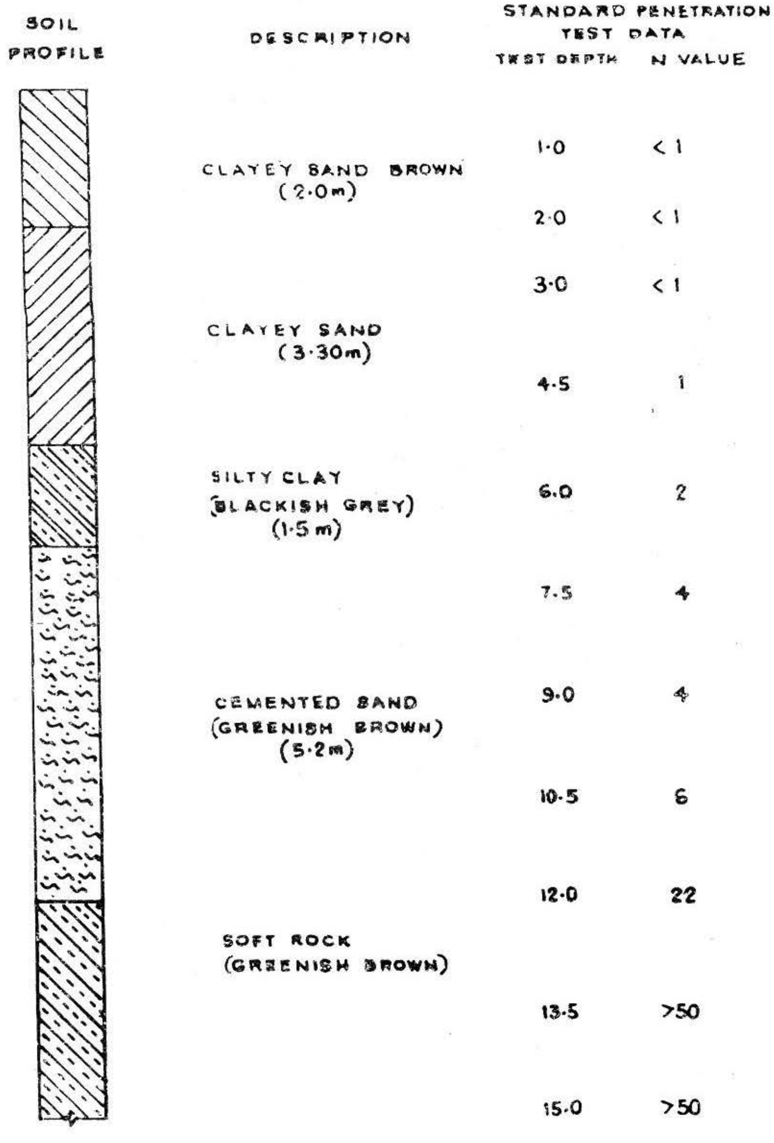

FIGURE 10 : Soil Profile (Athipattu Site))

M10, and for identical axial stress, the acoustic emission counts have increased irrespective of the size of the cube samples tested. In a brittle material like concrete the frequency of acoustic emission depends to a large extent on the frequency of micro-cracks developed and number of locations where sliding and rolling have occurred in the matrix under the influence of axial stress. As the strength of the concrete mix decreases from M20 to M10, under the influence of identical axial stress, intensity of micro-cracking

FIGURE 11 : Prototype Test Arrangement

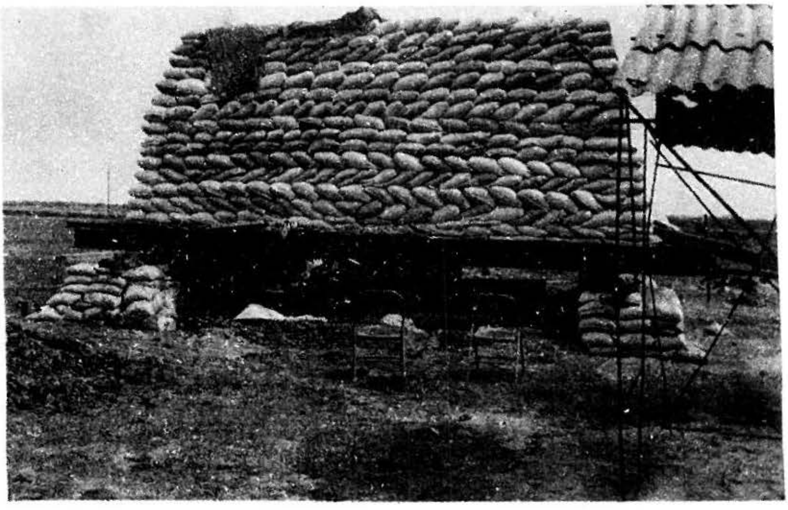

FIGURE 12 : Prototype Test Arrangement

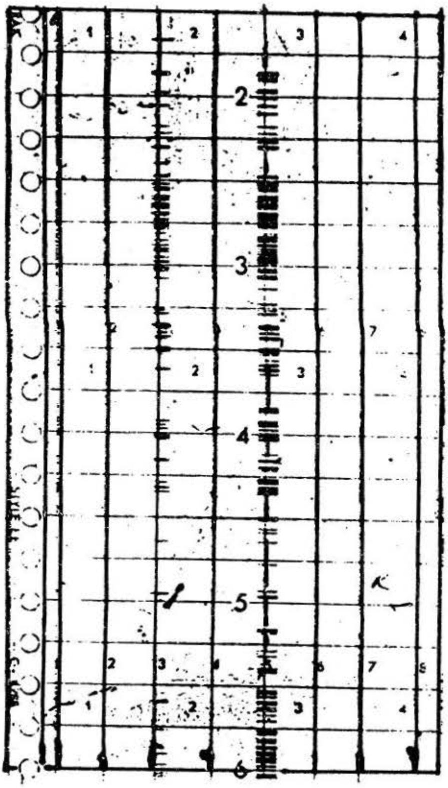

FIGURE 13 : Typical Plot of Monitored Acoustic Emission (Athipattu Site)

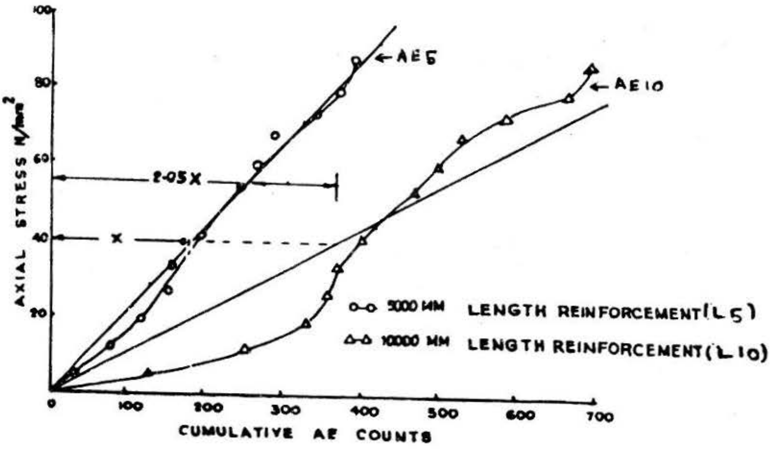

FIGURE 14 : Axial Stress Vs. Cumulative AE Cunts (Athipattu Site)

has increased in M10 mix when compared to that of M20 mix and this has contributed to increased cumulative acoustic emission counts observed in the experiments for M10 mix. The same observation is found equally true in the case of cylindrical concrete samples tested.

Influence of Size of Concrete Samples

Figure 3 shows for M20 mix the cumulative acoustic emission counts picked up at the centre of the cubes under identical axial stress are fairly independent of the size of the sample tested which has been found to be true for other mixes as well. It is to be noted that in these cases acoustic emission counts were monitored at one single spot of the specimens.

Influence of Shape of Concrete Samples

Figure 4 shows that under identical axial stress and for M20 concrete, 100 mm diameter cylindrical concrete samples have recorded more acoustic emission counts that the cubical sample. Due to frictional resistance the development of end restraint in cubical concrete specimens is likely to be more pronounced than in the case of cylindrical concrete samples and this has retarded the occurrence of micro-cracks and hence the acoustic emissions in the case of cubical concrete specimen. Strength of cylindrical concrete specimens are lower than that of cubical concrete specimens of same composition and hence the recorded acoustic emissions are more under identical axial stress, in the case of cylindrical samples.

Effect of Honeycombing and Necking

From Fig. 8 it is seen that under identical axial stress applied at the top of the pile the cumulative acoustic emission counts have become large in the case of model pile with necking than in the other two cases. The cumulative acoustic emissions are the least under identical axial stress in the homogenous pile of good quality. the occurrence of comparatively more acoustic emission counts in the case of pile with honeycombed concrete at the middle part of the pile is due to poor quality of concrete with lower strength which is corroborated by the test results reported earlier on the cube sample. In the case of piles with necking, even though the quality of concrete is good and identical with that of homogenous pile, because of increased axial stress under identical axial load in the region of necking, more acoustic emission counts have been recorded than in the case of homogenous pile. The ratio between the observed acoustic emission counts in the pile with normal area of cross section and that with reduced area of cross section in the region of necking, under identical axial stress applied at the ends (or axial loads), has been observed to be inversely proportional to the ratio of area of cross section of normal pile and that of reduced necking area of cross section.

These findings show that the acoustic emission monitoring method can be profitably extended in the integrity testing of prototype piles in the field provided suitable procedures are evolved to introduce the waveguides in the prototype pile during casting of the pile so that the transducers can be attached and acoustic emission counts can be monitored using low intensity static loading which can be done without elaborate loading arrangement and costly kentledge as in the case of conventional prototype load tests.

Acoustic Emission Monitoring through Pile Reinforcements

Figure 9 shows the acoustic emission counts measured through reinforcements run through the entire length of the model pile are 1.4 to 1.5 times higher than that measures through the reinforcement run through 1/3 length of the pile, under identical axial stress. When a pile is stressed, acoustic emissions are generated throughout its length and the number of emissions may depend on the strength of concrete, stress intensity and length of the pile. These factors to certain extent can be reflected in the strain energy as follows :

$$\text{Strain Energy} = P^2\ L/2\ AE$$

where,
P = applied load,
L = length of the specimen along which the acoustic emissions are measured,
A = area of cross section, and
E = elastic modulus of the specimen.

Hence other factors being constant, the acoustic emission counts measured through full length reinforcement should be three times larger than that corresponding to reinforcement run through 1/3 length of the pile, provided the pile is point bearing and the influence of strains due to flexure are neglected. However, measured acoustic emission counts have fallen short of this ratio. Since the acoustic emissions may depend on the propagation of micro-cracks and elliptical flaws, better appreciation of this observed phenomenon may have to be attempted in terms of fracture mechanics. Figure 9 also indicates that the measured acoustic emission counts under identical axial stress for the seventh cycle of loading are 1/6th of the corresponding emissions monitored during the first cycle of loading. This effect, familiarly known as Kaiser effect, was also observed during the second and subsequent cycles of loading. Figures 8 and 9 also show that there is no correlation between the acoustic emission counts observed at a single spot (Fig. 8), and the acoustic emission counts measured through a reinforcement run throughout the length of the pile (Fig. 9), even though the strength of concrete, the axial stress and area of cross section are identical.

Feasibility of Acoustic Emission Monitoring in Prototype Pile through Steel Reinforcement

Figure 10 shows that the soil profile at Athipattu site consists of a clayey sand layer upto 5300 mm below ground level followed by a thin silty clay layer of 1500 mm thick which is underlain by a cemented sand layer of 5200 mm depth. the cemented sand layer is overlying a soft rock at 12000 mm depth below ground level. The standard penetration test data indicates upto 12000 mm depth, the soil layers are either very soft or very loose with N values ranging from 1 to 6. Hence it is reasonable to assume that the prototype bored cast-in-situ pile of 400 mm diameter cast at Athipattu site can only function as point bearing pile with very little contribution from skin friction of the surrounding soil upto 12000 mm depth. Load test results have indicated an ultimate failure load of 816.8 kN as against a design load of 440 kN. Figure 14 shows the axial stress vs. cumulative acoustic emission counts recorded during prototype load test through the steel reinforcement waveguides which were terminated at 5000 mm and 10000 mm depths of the pile. Figure 14 indicates that the acoustic emissions monitored through 5000 mm length reinforcement of prototype pile are much less than that monitored through 10000 mm length reinforcement.

For satisfactory interpretation of acoustic emission data monitored in a prototype pile, appropriate theoretical reasoning has to be evolved through energy principles or fracture mechanics, interrelating the acoustic emission counts with various factors as strength of concrete, portion of the applied load shared by the pile through its length as skin friction. The development of more refined instrumentation which can isolate and eliminate other extraneous emissions caused by traffic, wind and other construction activities is also essential. Fabrication of a load frame which can be installed for application of a small fraction of design load quickly and easily, coupled with the development of appropriate specification for pile integrity testing through acoustic emission monitoring may lead to a viable economical alternative to costly time consuming pile load tests to ensure the installation of good quality bored cast-in-situ piles. Since additional field tests are required to evolve a proper analytical reasoning and rational method of interpreting the acoustic emission test data obtained on prototype piles, serious attempt has not been made to interpret the field data presented here. During prototype pile load test, it was observed that the transducers were very sensitive to pick up additional noise emissions caused by wind velocities and other constructional activities. hence the data represented above are likely to have been influenced to some extent by these external factors. However, the limited test data presented here indicates the feasibility of using the pile reinforcements for monitoring the acoustic emissions occurring throughout the length of the pile during loading. One question that may engage the attention of future research workers in this field is, "Can this data be used to separate skin friction and point resistance mobilised in a pile during loading ?" Further research efforts in these directions mentioned above are likely to present a rewarding experience to the research workers who are fascinated towards the non-destructive integrity testing techniques of piles through AEM.

Conclusions

From the foregoing interpretation, following conclusions are arrived at :

(i) Observed acoustic emission under compression testing are influenced to a great extent by the strength of concrete, the intensity of axial stress and to a lesser extent by the shape of the concrete specimen.

(ii) Size of the concrete specimen has only marginal influence on the acoustic emissions under identical condition of static loading, shape, strength of samples and method of monitoring.

(iii) Laboratory load test results on model piles indicate the feasibility for the potential use of acoustic monitoring as a non-destructive integrity testing of concrete piles, for detecting honeycombing and necking.

(iv) The interpretation of measured acoustic emission counts obtained from prototype and mode pile integrity tests through pile reinforcement with appropriate correlations based on strain energy principle is found to be very complex. Hence there is a need for evolving better well defined analytical mechanism based on fracture mechanics, for satisfactory exploitation of acoustic emission techniques in prototype pile integrity tests.

Acknowledgement

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Notations

P = Applied load
L = Length of specimen
A = Area of cross section
E = Elastic modulus of the specimen
(AE)10 = Acoustic emission for 10 m length of pile
(AE)5 = Acoustic emission for 5 m length of pile
L5, L10 = Length of pile from G.L.