BEHAVIOUR OF TIMBER PILES SUBJECT TO LARGE LATERAL DISPLACEMENT - LABORATORY AND FIELD TESTS

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ABSTRACT

In this study, full size Douglas Fir timber piles were tested both in the laboratory and in the field to assess their ability to withstand large lateral deformations which may be caused by liquefaction of the surrounding soil during an earthquake. Twenty-eight timber piles were tested in the laboratory to investigate the variability of their strength and stiffness and the feasibility of carrying out the field lateral loading test. Based on the results of the laboratory tests, three timber piles were tested in the field to model the actual foundation conditions. A concrete pile cap was used to apply a constant vertical load of 89 kN (10 tons) to the timber pile, simulating the design load for the transmission tower foundations. The piles were then subjected to horizontal displacements of increasing amplitude up a maximum of 1 m. It was found that all three test piles yielded at a horizontal displacement of the pile cap of about 0.5 m but were able to support the vertical load even after the horizontal displacement was increased to about 1.0 m. The results indicate that timber piles are more ductile than previously considered and are able to carry the design vertical compressive load after yielding. This may explain the observations of the small number of reported cases of transmission tower failures during an earthquake.

INTRODUCTION

The Fraser Delta, in which large areas are covered by surficial soils consisting of loose, saturated and unconsolidated sands and silts, is now recognised as one of the high seismic risk regions in North America. During seismic shaking, much of these loose sands and silty sands are predicted to liquefy giving rise to large horizontal ground surface movements, in the order of one or more meters (Byrne and Anderson, 1990; Task Force on Earthquake Design in the Fraser Delta, 1991). Within these areas, B.C. Hydro has numerous transmission towers, substations and other utility equipment supported on timber-piled foundations. Conventional methods of lateral pile analysis predict that the timber piles would fail when subject to these large horizontal ground movements. However reported seismic performance of transmission tower foundation in the other parts of the world suggests that damage to transmission towers due to failure of piled foundation has generally been light. In an attempt to resolve this dichotomy between design analysis and field observation, full size Douglas Fir timber piles were tested both in the laboratory and in the field to assess their ability of the timber piles to withstand large lateral deformations which may be caused by liquefaction of the surrounding soil during an earthquake.

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It is recognized that there are three key items affecting the assessment of the ability of timber piles to carry their vertical load while undergoing large lateral displacements such as those induced by soil liquefaction: 1) the magnitude of the lateral displacement, 2) the bending response of timbers piles and their ability to carry axial load after 'failing' in bending, and 3) the support provided both by the soil and the concrete pile caps. The work described here aimed at assessing items 2) and 3) and was divided into two stages. Stage 1 is the laboratory testing portion of the research work in which the properties of the timber pile, for example: moisture contents, treatment method and moment-curvature response to lateral loading were investigated. Effect of installing instrumentation on the pile was also investigated in this stage. In stage 2, the field testing portion of the research work, three single full size piled foundations were constructed and tested.

Twenty-eight size 300 (that is, the diameter of the pile head is about 300 mm) Douglas Fir piles were tested in the laboratory and three size 350 Douglas Fir piles were tested in the field. The field piles, which were installed and loaded to simulate the actual transmission tower pile foundations, were then subjected to horizontal displacements of increasing amplitude up a maximum of 1 m using a hydraulic piston.

General description of the laboratory and field tests and the overall results obtained are presented in this paper. Detailed report of the tests and further analysis of the test results will be presented elsewhere.

LABORATORY TESTING OF TIMBER PILES

The laboratory program was aimed at assessing the moment-curvature and bending failure mechanism under simple fixity conditions and a range of moisture contents and treatment conditions. One test was also carried out to assess the effect of the support provided by the concrete pile cap. A total of 28 size 300 Douglas Fir timber piles, all cut to 8 m lengths, were tested in the laboratory. Even though these piles were all graded as size 300, their actual butt or maximum diameter ranged from 272 to 360 mm (10.7 to 14.2 in) and tip or minimum diameter from 204 to 312 mm (8 to 12.3 in).

The different conditions at which these timber piles were tested are as follows:

(1) Sixteen piles in the wet condition - It was assumed that the piles used in areas where liquefaction is a possibility, will mostly be in the wet conditions.

(2) Four piles in the semi-dry condition - These were tested to investigate the effect of moisture content on the pile properties.

(3) Four piles containing a groove with an inclinometer casing epoxyed in the groove - These were tested to investigate the effect of attaching instrumentation to the timber pile required in the field test situation.

(4) Four piles which had been creosoted and in service for about 3-5 years - These were tested to investigate the effect of creosoting process and age on the pile properties.

Fig. 1b shows the laboratory test setup for the lateral load testing of the piles. This is in fact a simple beam testing setup with an added capability of applying a constant axial load during the lateral load test. Laboratory test setup directly replicating the field loading conditions was not selected due to the difficulty in maintaining a constant axial (vertical) load during lateral displacement of the pile top. Fig. 1b shows how the simple beam testing setup models the actual field loading conditions shown in Fig. 1a. The location of the transverse load application point was selected so that the required equivalent maximum displacement of 1 m at the pile cap can be achieved by a much smaller displacement, about 0.38 m, at the load point. In this case, the location of the hydraulic piston for the axial load can be fixed relative to the axis of the undeformed pile. Photographs of the actual laboratory setup is shown in Fig. 2.

For each test, the transverse load was applied in a displacement-controlled manner so that the axial capacity of the pile can be studied even after the pile yielded in the transverse loading direction. To simulate the cyclic ground motion caused by soil liquefaction, cyclic transverse displacement loading was applied before the piles were finally loaded monotonically to failure. The axial force loading was maintained at a constant value throughout the test to simulate the design vertical load.

Both the axial and transverse loads were measured using electrical load cells. The axial displacement as well as transverse displacement at 9 locations along the length of the pile were measured using electrical potentiometers. The readings from these measuring devices were taken at a rate of 2 per second throughout the test using a computer controlled data acquisition system.

A typical transverse load response presented on Fig. 3 shows that the initial cyclic loads did not cause any substantial degradation in the modulus of elasticity (E) of the pile tested. It was observed that during the final monotonic loading phase (in the transverse direction), the pile was able to sustain substantial additional displacements beyond the maximum (peak) load. For example, the peak load response occurred at 240 mm deflection but final failure of the pile (unable to hold axial load) occurred at almost 400 mm deflection.

Moisture Content, Strength and Stiffness of the Timber Piles

The moisture content of the timber piles tested under different conditions described above was found to vary from 22 to 44 %, see Fig. 4a. These values were classified into 2 groups: a) dry group, with a mean of 22.6 % and a Coefficient of Variation (CoV) of 25 %, and b) wet group, with a mean of 33.9 % and a CoV of 9.2 %.

The bending strength of the timber piles is expressed in terms of the modulus of rupture (MOR), which is the calculated extreme fibre stress using the elastic beam bending formula and bending moment at yield. It should be pointed out that as the stress distribution in the yielding timber pile is not linear, the calculated MOR does not correspond to the real fibre stress. However, this strength parameter (MOR) is still very useful in the determination of allowable stresses for design, and in comparing different timber materials. The lateral stiffness of the timber piles is expressed in terms of the modulus of elasticity (E) and is calculated using elastic beam bending formulas and the value of the slope of the elastic portion of the moment-curvature relationship. Fig. 4b and 4c show the calculated MOR and E based on the laboratory measured moment-curvature response of the wet group and the dry group of timber piles. Due to the large scattering of data within each group of piles, cumulative frequency plots are used in these comparison.

The small differences in MOR and E between the dry group and the wet group of timber piles is consistent with the concept that the strength properties of wood products are not affected by moisture content changes above the fibre saturation point (25-28 % for Douglas Fir). Consequently, the test results for all 28 piles were treated as though they were obtained from the same population of piles. The median (50 percentile) values of MOR and E obtained in the present test program are compared with the specified strength and modulus of elasticity for round Douglas Fir piles recommended by the Canadian Standards Association (CSA) CAN/CSA-086.1-M89 in Table 1.

Table 1

	Median Value (Lab Test)	CSA
Modulus of Rupture (MPa)	39.0	20.1
Modulus of Elasticity (GPa)	10.0	11.0

It may be seen that the modulus of elasticity values are in close agreement, while the modulus of rupture values from the test are twice the CSA values.

Effect of Instrumentation Procedures and Age

Out of the 28 tested timber piles there are 4 piles containing a groove with an inclinometer casing epoxyed in the groove and 4 piles which had been creosoted and in service for about 3-5 years. The results from the bending tests indicated that there are no statistically significant differences within the group of 28 piles.

Moment-Curvature Relationship

For the calculation of bending response of timber piles subject to large transverse deflection, it is more convenient to express the results obtained in this study in terms of moment-curvature relationships. For each test the moment and curvature (defined as 1/R, where R is the radius of curvature) at the failed section were calculated independently based on the applied load and the measured deflections. To account for the different pile diameters the calculated moments were then adjusted to those corresponding to a pile diameter of 270 mm using the ratio of the section moduli. These moment-curvature data corresponding to the 270 mm diameter pile were further analyzed statistically. Due to the large scatter of the results, frequency distributions were formed for the 'adjusted' moment values obtained from each pile at curvature values of 0.01, 0.02... to 0.07 (1/m). The quantiles at the 10th, 25th, 50th, 75th and 90th percentiles of the distributions were found and curves drawn through the quantiles as shown in Fig. 5. The 50th percentile curve gives an impression of the moment-curvature relationship at the median. This curve is reasonably well defined up to .07 (1/m). The other quantiles are less well defined and therefore stopped at lower values of curvature. When required, these data can be used in probabilistic design-analysis of actual timber structures.

Displacement and Curvature of Piles Tested

All piles tested in this study were able to withstand curvature of about 0.06 m^{-1}. The transverse pile displacement at the loading point for various loading conditions are shown in Fig. 6a. These conditions correspond to the elastic limit, maximum transverse load and final failure of the pile.

The piles reached the limit of linear elasticity, the maximum transverse load and the final failure at median values of deflection of 140, 215 and 275 mm respectively. In other words the deflection at final failure is about 30 % larger than that at maximum transverse load and about 100 % larger than that at the linear elasticity limit. Scatter in the measured deflections for final failure is also larger than that for the elasticity limit. Based on the laboratory data obtained in this program, it is reasonable to include plastic deformation (past yield) in the ultimate design of timber piles to resist lateral loading.

Based on the measured load-deflection behaviour shown in Fig. 6a and the kinematic relationship between the measured deflection at the load point and the equivalent pile head movement, it was estimated that field test results would likely be favourable. Consequently, stage 2 of the research, namely the field testing phase, was carried out.

FIELD TESTING OF TIMBER PILES

The field test program was aimed at investigating the effects of actual field conditions on the response behaviour of the timber piles subjected to large horizontal displacements. Three Douglas Fir timber piles, size 350 and about 10 m long, were tested. The key elements of the test setup is shown in Fig. 7. Each of the test piles was driven 9 m into the ground. A concrete pile cap was constructed over the test pile to simulate the actual piled foundation and to facilitate the application of the horizontal displacement and the design vertical load of 89 kN (10 ton). To simulate the condition of a liquefied soil layer, a pit about 4 m square in plan centred at the test pile was excavated to a depth of 4 m below the bottom face of the concrete pile cap and filled with bentonite slurry (6 % by weight). The rotational constraint of a rigid pile cap was obtained in the test setup by preventing rotation during horizontal loading. This was achieved through the use of a guide on the reaction pile to restrict the motion of the load frame to a horizontal displacement only.

Test Site Location and Setup

Field testing of the timber piles was carried out at the UBC Soil Mechanics test site located near MacDonald Beach, Sea Island. This site was selected due to the similarity of its soil conditions with those of the river crossing tower sites.

A total of six timber test piles were driven at the test site, all to a depth of 9 m, equally spaced along the circumference of circle approximately 12 m in diameter. A reaction pile consisting of a steel pipe pile, 600 mm diameter by about 12 m long and having a wall thickness of 12.7 mm was also driven and located in the centre of the circle. Three timber piles were selected for lateral load testing and the rest were kept as spares in case of damage and misalignment during pile driving and pile test setup.

After completion of the pile driving work, the strain gauges and inclinometer casings installed in the timber piles before driving were verified to be in working condition. Concrete pile caps, one on each selected pile, were then constructed over the test piles. In addition to being used as a cap to apply lateral load to the test pile, the pile cap was designed so that its weight exerted a downward load of 89 kN (10 tons) on each pile.

For each test, a pit about 4 m square in plan centred at the test pile was first excavated to a depth of 4 m below the bottom face of the concrete pile cap and then filled with bentonite slurry (6 % by weight). The lateral load frame was then attached to the pile cap on one end and fitted over a guide on the reaction pile on the other. A photograph of the actual field test setup is shown in Fig. 8.

Lateral loading was applied to the test pile in a 'displacement-controlled' manner, i.e., the pile cap was forced by either a 'push' or 'pull' to undergo a specified displacement amplitude and the magnitude of the required force was measured. A typical load sequence consisting of cyclic and monotonic displacement 'loads' for a test pile is shown in Fig. 9. The load was applied using a hydraulic piston pushing against the reaction pile and a cross-arm on the loading frame. The magnitude of the lateral load was measured using a 130 kN capacity load cell. Deformations of the timber pile were monitored using displacement transducers, strain gauges, survey level and electro-levels. Different frequencies of taking readings were used for different type of instrumentation.

Instrumentation for Field Testing of Timber Piles

Before being shipped to the test site and driven into the ground, instrumentation were installed in the test piles. Typically, a total of 8 strain gauges and 1 inclinometer casing were installed in each test pile. The 8 strain gauges were spaced along the pile length down to a depth of 5.5 m below the bottom face of the pile cap. The inclinometer casing was installed in a groove cut on the side of the pile and along almost the full length of the pile.

The horizontal load applied to the timber pile to achieve a predetermined displacement of the pile cap was measured using conventional load cells. As the cap was prevented from rotation during lateral translation, reactive moments were developed at the pile cap. The moment was measured using a custom made adaptor developed by Powertech. The location of the moment measuring device which was attached between the pile cap and the lateral load frame is shown in Fig. 7.

Small strain gauges that are generally used in the stress and strain measurements of metallic and plastic are not quite applicable to timber pile materials. A preliminary investigation carried out at the start of this program indicated that a special kind of strain gauge, gauge length 10 cm or larger, should be used. Moreover, a special epoxy was required in order to keep moisture (the timber pile is wet) from the gauges and wirings.

In addition to measuring the deflected shape of the timber pile using strain gauges, an inclinometer casing was embedded along almost the full length of the test piles. The intention was to use either a slope indicator or a series of electro-levels inside the casing to measure the deflected shape of the timber pile. During the lateral test, the pile cap displacement was also monitored using a displacement transducer. The measured pile cap displacement was used as a redundancy check on the measured deflection profile of the timber piles.

A series of electro-levels spaced a distance of 0.5 m was finally selected to measure the deflected profile instead of an inclinometer. The selection was made based partially on the ease of taking readings and partially on the potential risk of damaging the inclinometer when the deflections become large.

The settlement of the pile cap was measured by using a surveyor's level and taking readings from 2 scales attached to the pile cap along two vertical edges of a vertical face parallel to the direction of loading. The settlement and rotation of the pile cap were calculated by using half the sum and difference of the two readings of a set.

Readings from the load cell, the displacement transducers and the strain gauges were monitored using a computer data acquisition system. The survey level and the electro-level readings were taken at peak displacements of each half cycle of loading, at zero load magnitude and at displacements amplitudes of .6, .7, .8, .9 and 1.0 metre.

FIELD TEST RESULTS

Test Results

Fig. 10 shows the measured horizontal load, moment, pile displacement and pile cap settlement of the three timber piles tested. The values plotted in these figures correspond to those obtained at the peak value of a displacement load cycle.

Load and moment measurements obtained from the three tests were observed to increase with horizontal displacement initially. The maximum loads and moments occur when the horizontal displacement of the cap reached a value of about 0.4 to 0.6 m. With increasing displacement, the measured load and moment decreased gradually but there was no catastrophic failure of the timber pile. Although 'snapping' sounds were generally heard from the timber pile when the displacements were in the range of 0.5 to 0.7 m the loads and moments were only slightly reduced from the maximum values. At the maximum horizontal displacement of 1 m, the measured horizontal load and moment were still more than 50 % of the respective maximum values. In all three tests, the shape of the moment-displacement curve was quite similar to that of the load-displacement curve.

Based on the lateral displacement measurements, some small rotations were observed during the lateral loading due to the flexibility of the lateral load frame. The plotted vertical movement or settlement indicates that relatively small settlements occurred when the horizontal displacement of the pile cap is less than or about 0.3 to 0.5 m. At larger displacement values, the settlement of the pile cap increased quite rapidly. The maximum recorded settlements of the three piles were 80, 70, and 160 mm at horizontal displacements of about 1.0.

The deflected profiles show similar behaviour for the three test pile, Fig. 10. When the horizontal displacement of the concrete pile cap is about 0.3 m the deflected profiles are generally smooth curves. As the displacement of the pile cap reached 0.5 m, 'kinks' were formed at 2 locations: one close to the bottom of the pile cap and one at a depth of about 0.5 m below the bottom of the slurry pit. Electro-levels installed at 5.5, 6 and 6.5 m below the pile cap, or 1.5, 2 and 2.5 m below the bottom of the slurry pit, did not register any appreciable change in inclination indicating that the bending of the pile did not extend to more than 1.5 m below the bottom of the slurry pit.

After subjected to a maximum lateral displacement of 1 m, all three timber piles were still able to support the vertical load of 89 kN (10 tons). However, when support provided by the lateral load frame was removed only two piles, pile 1 and pile 2, were able to support the load without falling over. Fig. 12 shows pile 1 after it was tested to 1 m and the load frame removed. Attempts were made to extract the piles but they all broke at the lower 'hinge' when an upward force was applied. Fig. 13 shows the broken sections of the piles.

Behaviour under Load

Based on the shape of the load-displacement curve, moment-displacement curve and the deflected profiles shown in Fig. 10, it is evident that some sort of yielding at the outer fibre, either tensile breakage, buckling in compression or longitudinal shear failure, started to occur at a pile cap displacement of about 0.3 to 0.5 m. Although the load and moment decreased and 'snapping' sounds occurred when larger horizontal displacements were applied, no catastrophic failure of the timber pile was observed. The tests were carried out to the maximum displacement of 1 m when horizontal travel in the load frame was exhausted. No definite final failure point was identified in these tests as the pile was able to support the weight of the pile cap of 89 kN (10 tons) at the maximum horizontal displacement of 1 m.

Location of Maximum Curvature

For each laterally loaded test pile, there are 2 locations with relatively large curvature values. These locations - one close to the bottom of the pile cap and one at a depth of about 0.5 m below the bottom of the slurry pit, are the same in all 3 tested timber piles. For displacements less than about 0.3 m, the curvatures at the bottom and at the top were more less the same. However, at larger displacements, the difference in the two curvature values started to increase so that at the peak displacement of 1 m the two curvature values became quite different, shown in Table 2.

TABLE 2

	Pile 1	Pile 2	Pile 3
Critical Disp. (M)	0.35	0.30	0.50
Critical Curv. (1/M)	.059	.047	.111
Ratio Bot/Top curvs. at 1 m	1.5	0.5	1.7

It may be deduced that Pile 1 and Pile 3 yielded more at the bottom location while Pile 2 yielded more at the top. It is possible that the pile started to yield at about 0.3 to 0.5 m at either the top or bottom location depending on the actual relative strengths and stiffnesses at these two locations. When any one location yielded the applied load, and moment, required to cause the further horizontal displacement dropped so that the amount of yield and moment at the other location always trailed the first location to yield.

Moment-Curvature Relationships

The moment-curvature relationships were evaluated for the timber piles at the location close to the bottom of the pile cap. For purpose of comparison with the laboratory test results, these moment-curvature relationships were adjusted for a theoretical pile of 270 mm diameter and the results are shown on Fig. 11. There are roughly three branches in each of the moment-curvature curves:-

1. Initial branch - the moment increases rapidly with curvature up to the yield point,
2. Yielded branch - the moment increases very slowly with curvature, and,
3. Post Peak branch - the moment actually decreases with curvature.

From Fig. 11, the 'yield' point for piles 2 and 3 occurred at curvature value of about 0.05 m^{-1} and for pile 1 at a curvature of 0.025 m^{-1}. The moment at the yield point ranged between 72 and 85 kN-m. The peak moments were in the range 80 to 100 kN-m and occurred at curvatures of about 0.12 to 0.15 m^{-1}.

Comparing with the results of the laboratory tests from Fig. 5, it is observed that the developed moments in the field test piles are marginally, about 10 to 20 %, larger than that of the 50 percentile curve obtained in the laboratory tests. However, the field piles were able to sustain much larger curvatures than the laboratory piles. It is envisaged that the different maximum curvatures are due to the different support details. In the laboratory, the piles were held and the loads were applied through 'rigid' metal clamps or supports. These supports are close to actual point load supports. In the field, the piles were held or supported by soil at the bottom and concrete pile cap at the top. Yielding of these supports is possible, providing a more 'distributed area' support than a point support. Other factors that might have contributed to the different maximum curvature values are:

1. Error in the measurement of moment. The calibration factor of the moment measuring transducer was double checked after the field tests and was verified. The following factors are more likely.
2. Non-uniformity of timber strength and stiffness properties within a cross-section may make the procedure for normalizing the moment with respect to the pile diameter inaccurate.
4. Shear failure of the timber. It may be possible that longitudinal shear failure occurred and two structurally independent sections were formed, one to each side of the neutral axis of bending. In this way, the composite may undergo larger curvature value before final failure.

Settlements of the Pile Cap

As mentioned earlier the measured settlements of the pile caps generally increases with horizontal displacement. This is consistent with the kinematics of the cantilevered pile configuration. Based on the measured deflection profile of the test pile, the distance between the top and bottom 'plastic hinges' is about 4.5 m. At maximum horizontal deflection of 1 m, the projection of the deflected 4.5 m length on the vertical axis is about 4.39 m, or a settlement in the vertical direction of 110 mm. The measured maximum settlements of the three piles are 80, 70, and 160 mm at a maximum horizontal displacement of about 1 m, indicating that major portions of the measured settlements were caused by the kinematics of large displacements and most likely are unavoidable. These large settlements, kinematic or otherwise, may be critical when considering the overall performance of the piled foundation and the supported structure.

Stability of the Timber Piled Foundation

The results indicated that when a timber pile is subjected to increasing horizontal displacement at the pile cap the gross behaviour of the piled foundation could be broadly classified into 3 stages:

1. Displacement amplitude less than about 0.3 m.
   Within this range of displacement, the maximum curvatures are generally less than 0.03 to 0.05 m^{-1}. Some nonlinear stress-strain sets in but the degradation of the lateral stiffness of the pile is small, see Fig. 11. Maximum settlement measured at this displacement is 30 mm with an average for the 3 piles of 10 mm, i.e. the settlement is small. The risk of degradation in the pile capacity is expected to be low.
2. Displacement amplitude larger than 0.3 m and less than about 0.5 m.
   Within this range of displacement, the maximum curvatures are generally less than 0.10 to 0.13 m^{-1}. The lateral stiffness of the timber pile degraded significantly, the incremental stiffness becomes so small that it is almost zero. Maximum settlement measured at this displacement is 40 mm with an average for the 3 piles of 25 mm, i.e. the settlement is becoming significant. Although the capacity of the embedded portion of the pile may not be weakened, the integrity of the timber pile itself is questionable.
3. Displacement amplitude larger than 0.5 m and less than about 1.0 m.
   Within this range of displacement, the maximum curvatures are about 0.20 m^{-1} or more. The incremental lateral stiffness becomes negative (the corresponding loads and moments at these larger displacements are actually becoming smaller). This suggests some breakage of the timber pile occurred at the two key locations. Maximum settlement measured at this displacement is 160 mm with an average for the 3 piles of 103 mm, i.e. the settlement is significant. Although the vertical downward capacity of the embedded portion of the pile may not be weakened, the integrity of the timber pile is questionable and the uplift capacity of the pile cannot be relied on.

It is important to point out that the specific numerical results obtained in the present field test program applies to situations where the site conditions are similar to that of the test setup described earlier. Extrapolation of the results to other field conditions will require analyses using the fundamental material properties obtained here together with appropriate soil properties obtained for the specific site under consideration.

CONCLUSIONS

Conclusions based on the laboratory tests

1) The moisture content of the 28 timber piles tested varied from 22 to 44 % and the measured strength and stiffness values were not affected noticeably by this variation. This observation is consistent with the concept that the strength properties of wood products are not affected by moisture content changes above the fibre saturation point (25-28 % for Douglas Fir). The test results for all 28 piles were treated as though they were obtained from the same population of piles.

2) The median modulus of elasticity value is about the same as that given by the Canadian

Standards Association (CSA). The median modulus of rupture value is about 39 MPa and is about twice the bending strength recommended by the CSA.

3) Moment-curvature data obtained for the 28 piles tested show a very large scatter, typical of timber products. A family of curves were used to present the calculated moment-curvature data corresponding to different percentile levels, see Fig. 5. These data can be used in probabilistic design-analysis of actual timber structures.

4) The deflections at final failure is about 30 % larger than that at maximum transverse load and about 100 % larger than that at the linear elasticity limit. It is reasonable to include plastic deformation (past yield) in the ultimate design of timber piles to resist lateral loading when the loading is prescribed displacement.

5) Out of the 28 tested timber piles there are 4 piles containing a groove with an inclinometer casing epoxyed in the groove and 4 piles which had been creosoted and in service for about 3-5 years. The results from the bending tests indicated that no statistically significant differences were observed.

6) Based on the laboratory test data, it was estimated that the Douglas Fir timber pile loaded under the field loading situation could 'survive' up to 1 m horizontal displacement.

<u>Conclusions based on the field tests</u>

7) Three field tests were performed. All 3 tests were carried out to the maximum displacement of 1 m when the horizontal travel in the load frame was exhausted. No definite final failure point was identified in these tests as the pile was able to support the weight of the pile cap of 89 kN (10 tons) at the maximum horizontal displacement of 1 m. Although the moment-curvature relationship indicates that the pile yielded in bending, the residual structural capacity of the timber pile was able to support the vertical loads of greater than 89 kN (10 tons).

It should be pointed out that the numerical values given in the following conclusions which are based on the results of field testing are applicable to situations were the depth of liquefaction and the loading conditions are similar to those under which the tests were carried out. Extrapolation to other situations requires care, judgement and further analysis of the test data reported here.

8) For each laterally loaded test pile, there are 2 locations with relatively large curvature values. These locations - one close to the bottom of the concrete pile cap and one at a depth of about 0.5 m below the bottom of the slurry pit, are approximately the same in all 3 tests.

9) The moments developed in the field test piles are 10 to 20 % larger than those in the laboratory piles but within the scatter of the laboratory test results. The field test piles were able to sustain much larger curvature before final failure, about 3 to 4 times that of the laboratory tests.

10) The large settlements of the pile cap measured during the lateral loading are due to the kinematics of 'rigid' body rotation rather than yielding, punching and uplift. However, such settlements are still important when considering the overall performance of the pile foundation.

11) The chance of the timber pile surviving a large horizontal displacement is high but the integrity of the piled foundation depends on the actual magnitude of the displacement:
    a) Less than 0.3 m. Chances are very good that the piles and the piled foundation remains intact.
    b) More than 0.3 but less than 0.5 m. Chances are that the piled foundation suffers some settlements probably less than 25 mm but the integrity of the timber piles is questionable.
    c) More than 0.5 but less than 1.0 m. Even though the piled foundation 'survived' the displacement, large (mostly kinematic) settlement, 100 mm, may occur. Damage occurs to the piles and uplift of the piles cannot be relied on. Some form of remediation to the piled foundation is needed afterwards.

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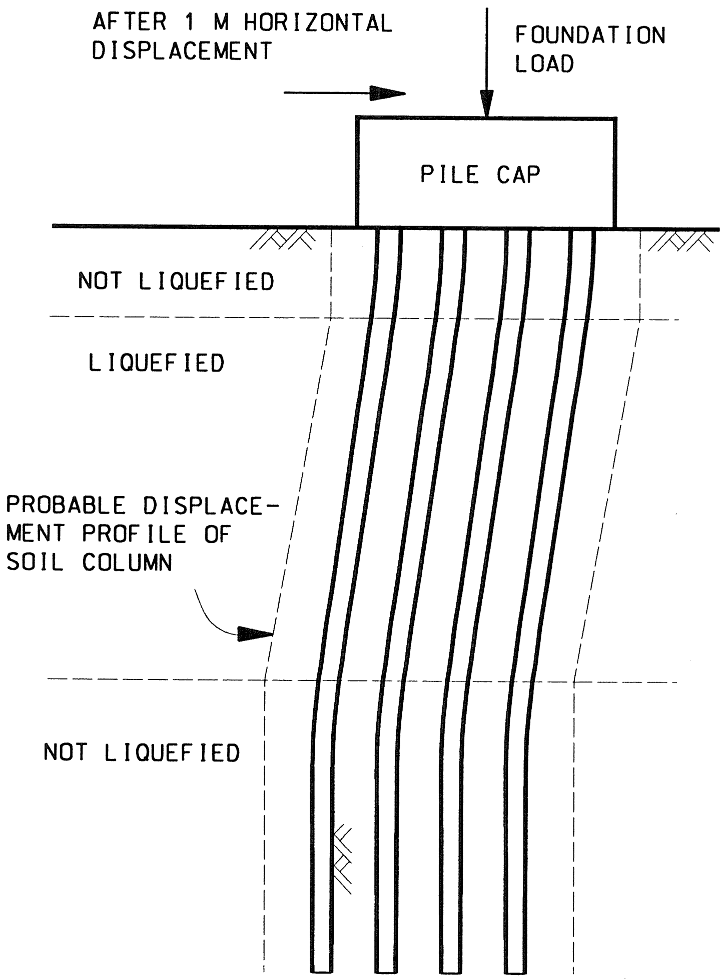
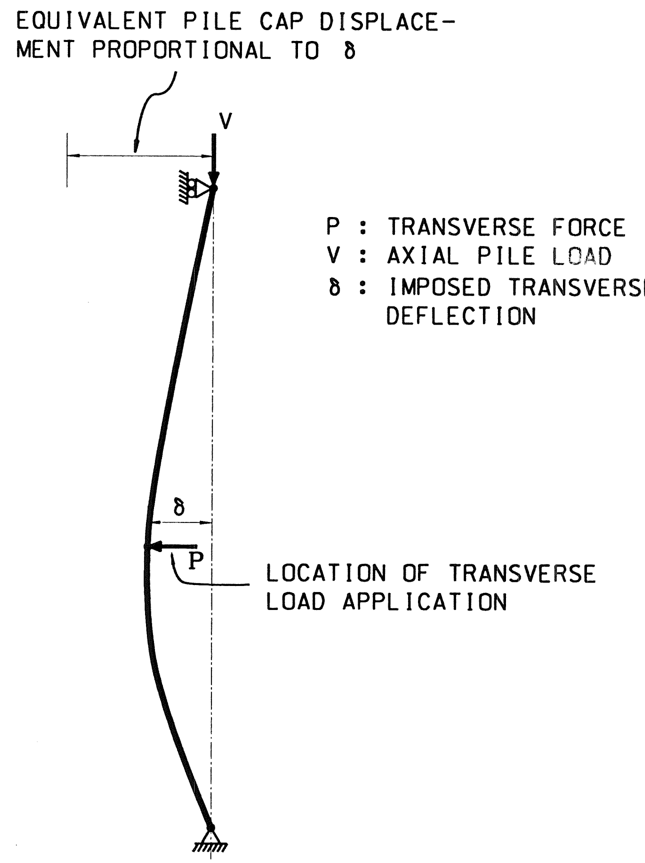


(a) IDEALIZED PILE DEFORMATION



(b) SIMPLE BEAM BENDING

FIG. 1 MODELLING PILE DEFORMATION IN LABORATORY TEST

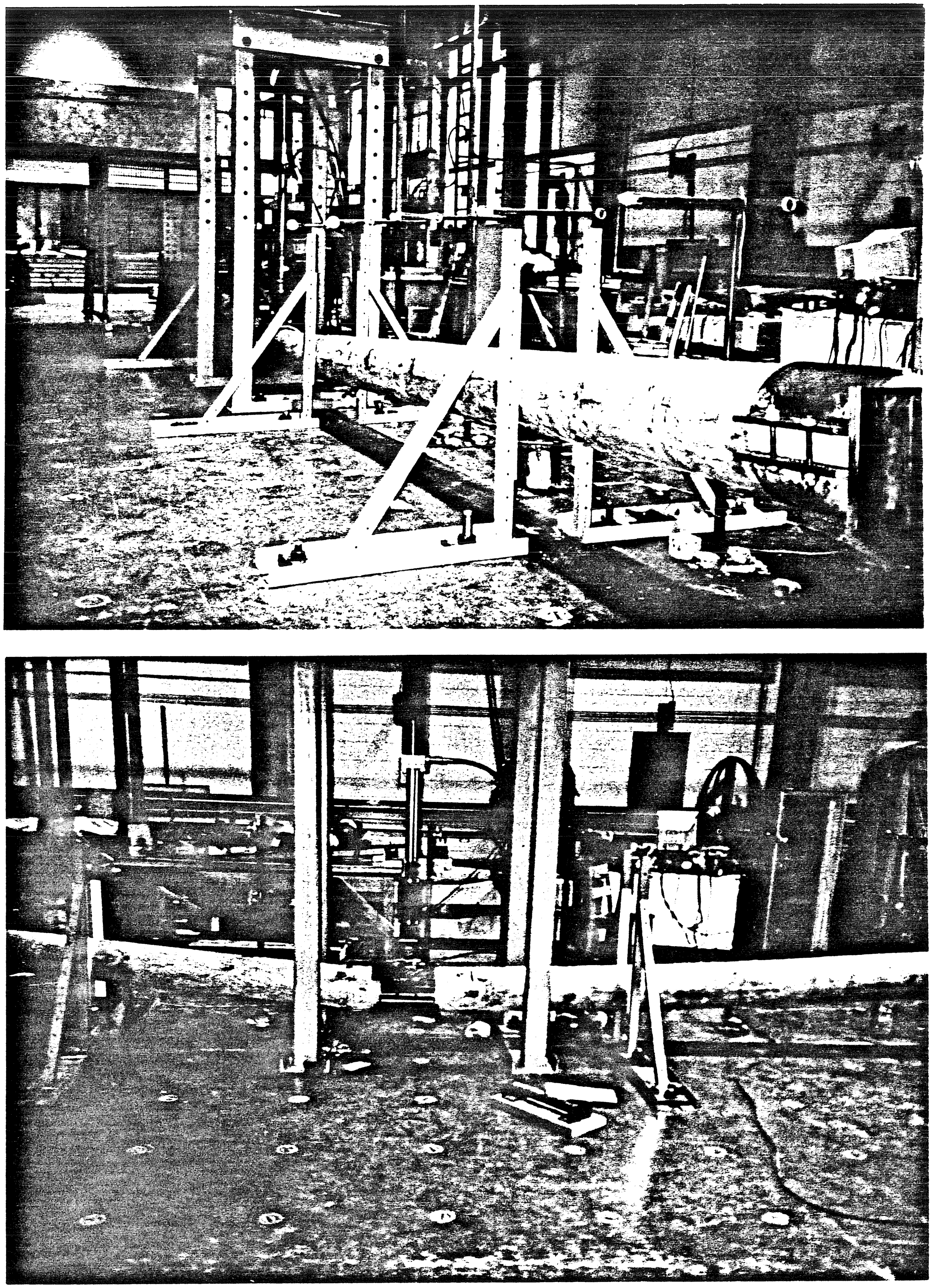


FIG. 2 PHOTOGRAPHS OF LABORATORY TEST SETUP

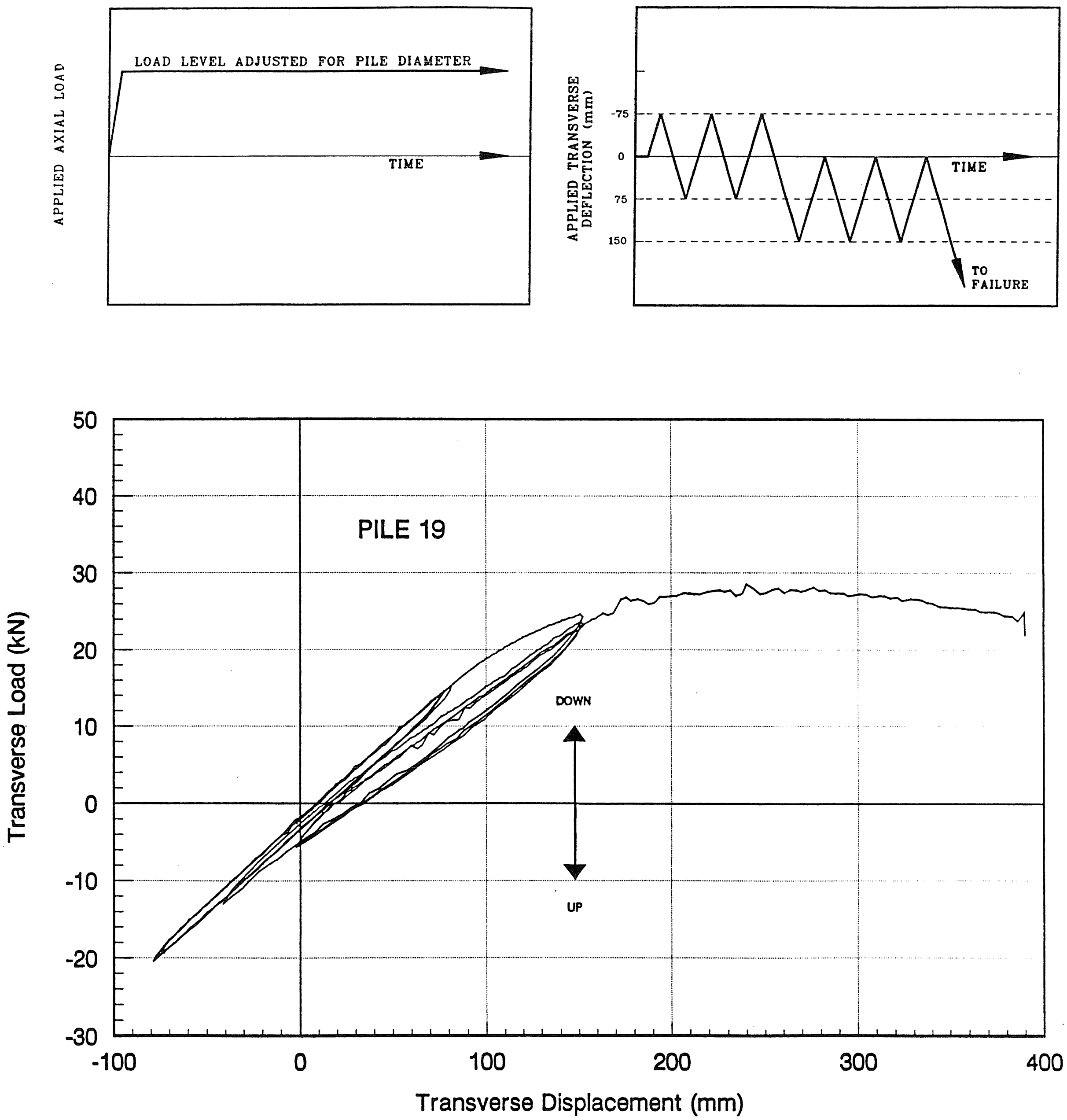


FIG. 3 TYPICAL LOAD-DEFLECTION RESPONSE OF TIMBER PILES (LABORATORY TESTS)

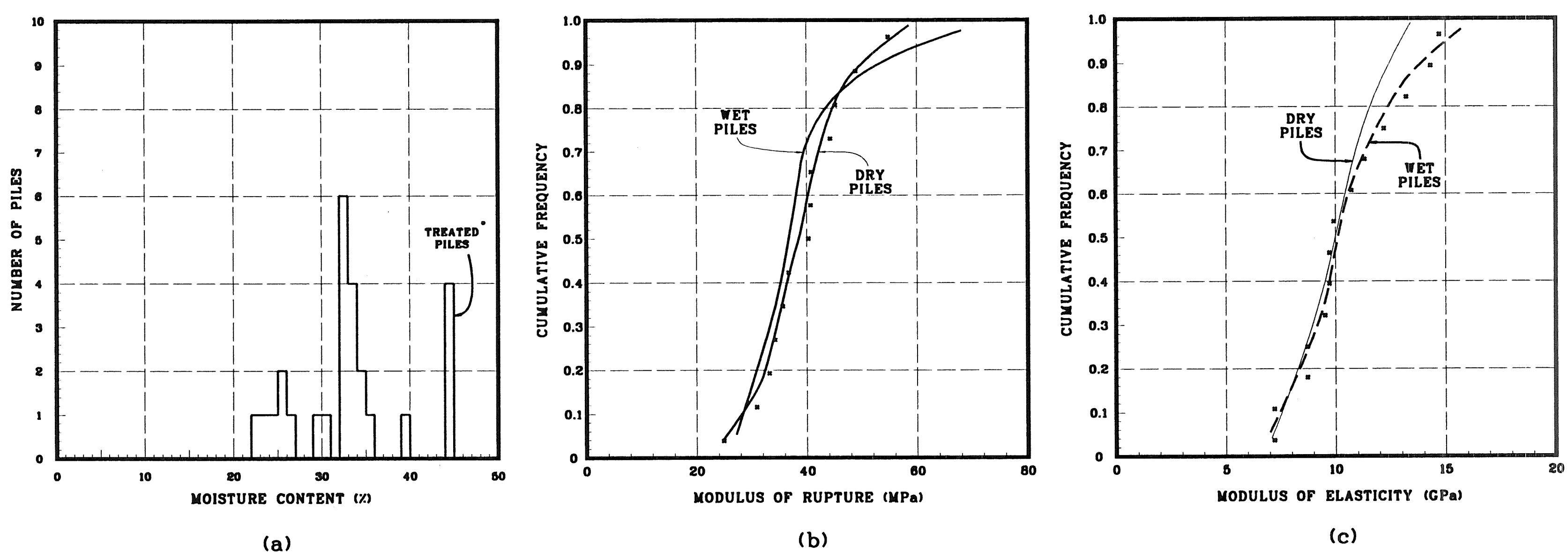


FIG. 4 LABORATORY TEST PILES : MEASURED MOISTURE CONTENT, MODULUS OF RUPTURE AND ELASTICITY

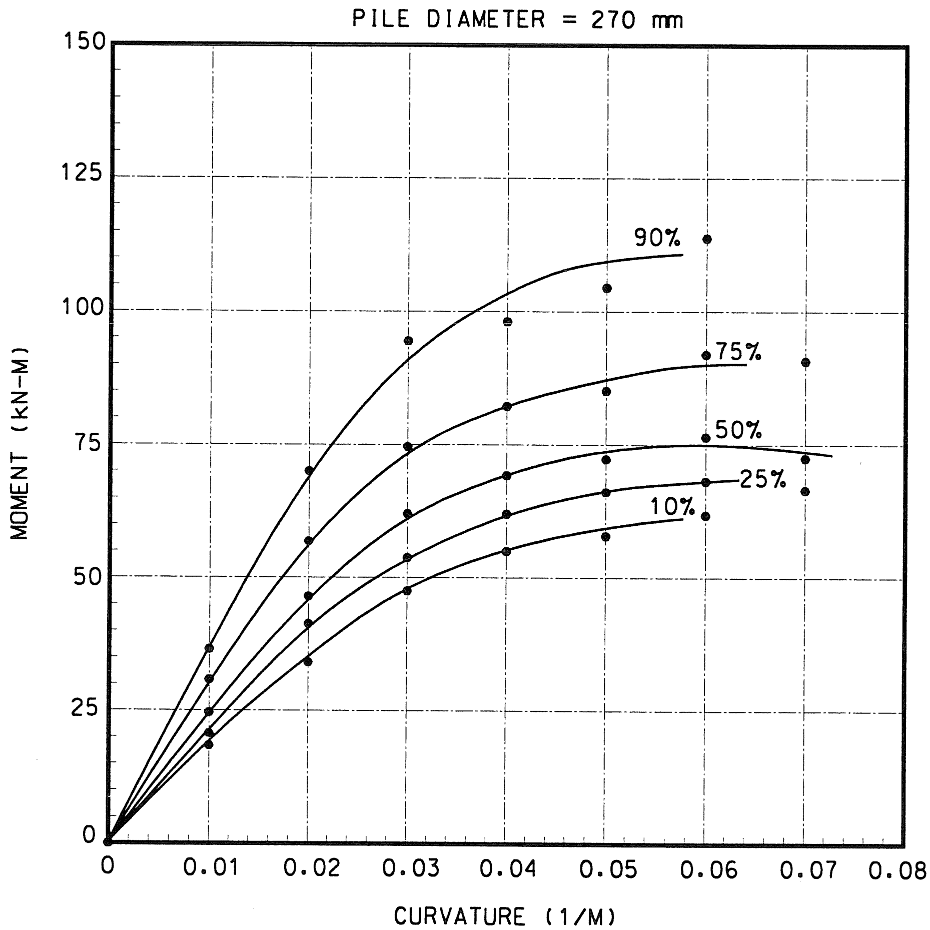


FIG. 5 MOMENT-CURVATURE CURVES ADJUSTED TO 270 mm PILE DIAMETER (LABORATORY TESTS)

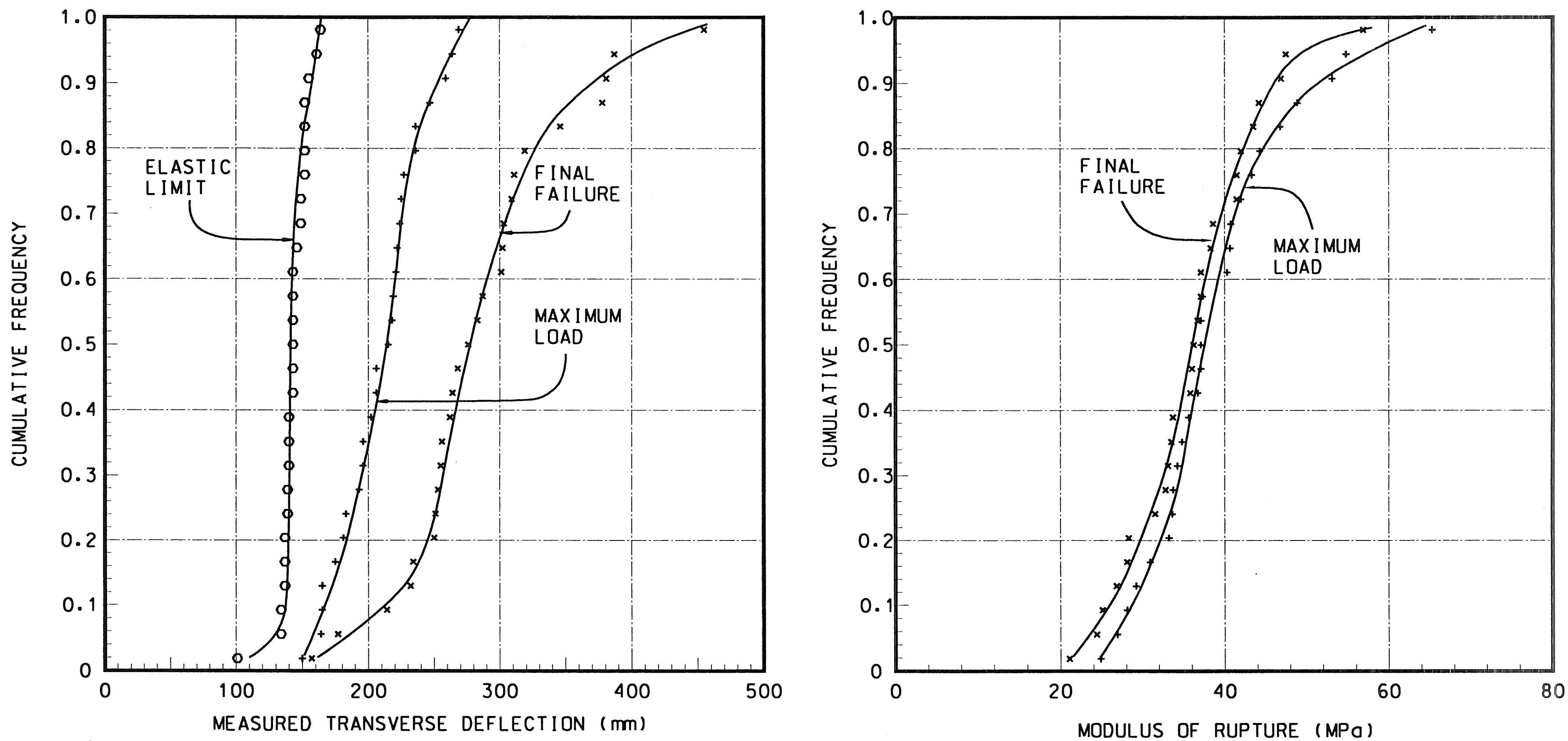


FIG. 6 LABORATORY TEST PILES : MEASURED DEFLECTIONS AND MODULUS OF RUPTURE

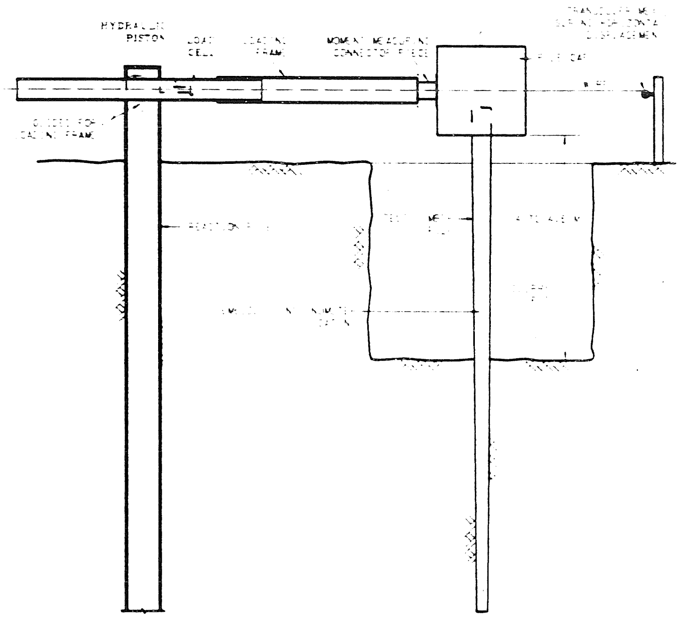


FIG. 7 FIELD TESTING OF TIMBER PILE

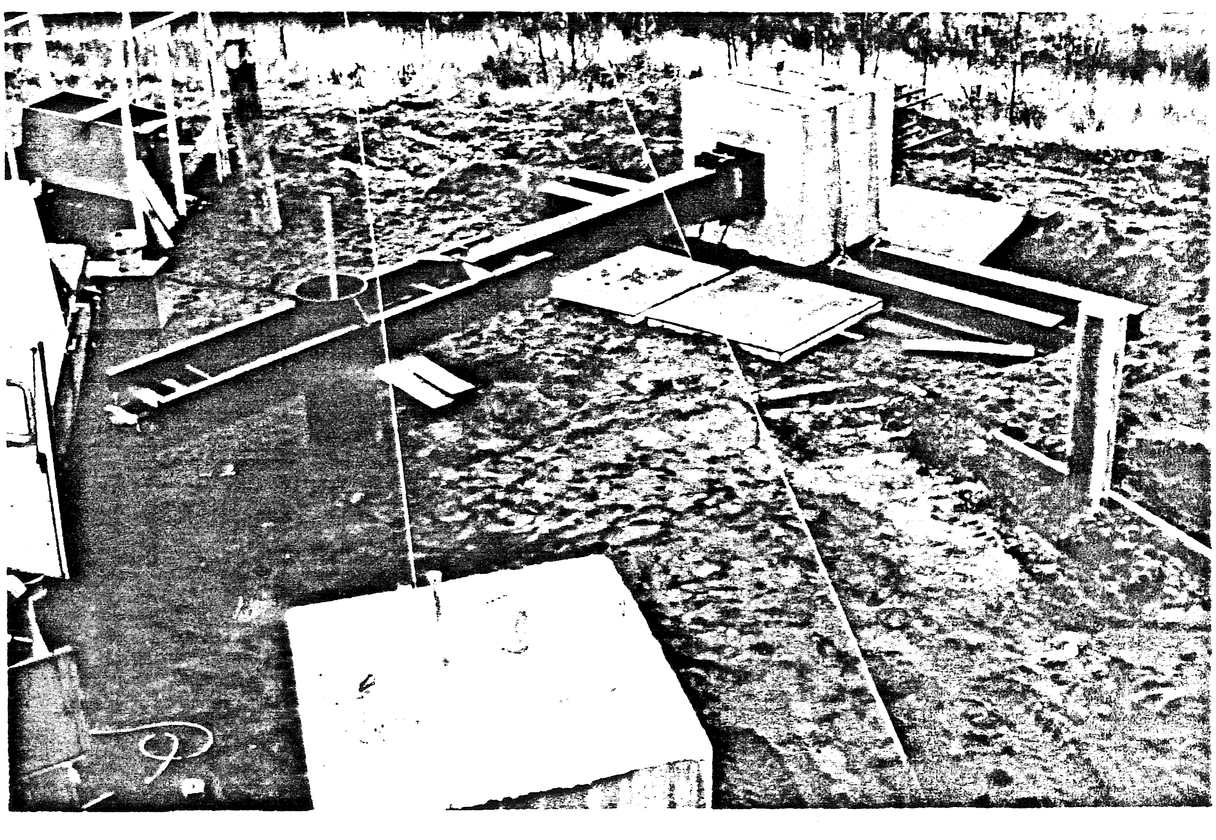


FIG. 8 PHOTOGRAPHS OF FIELD TEST SETUP

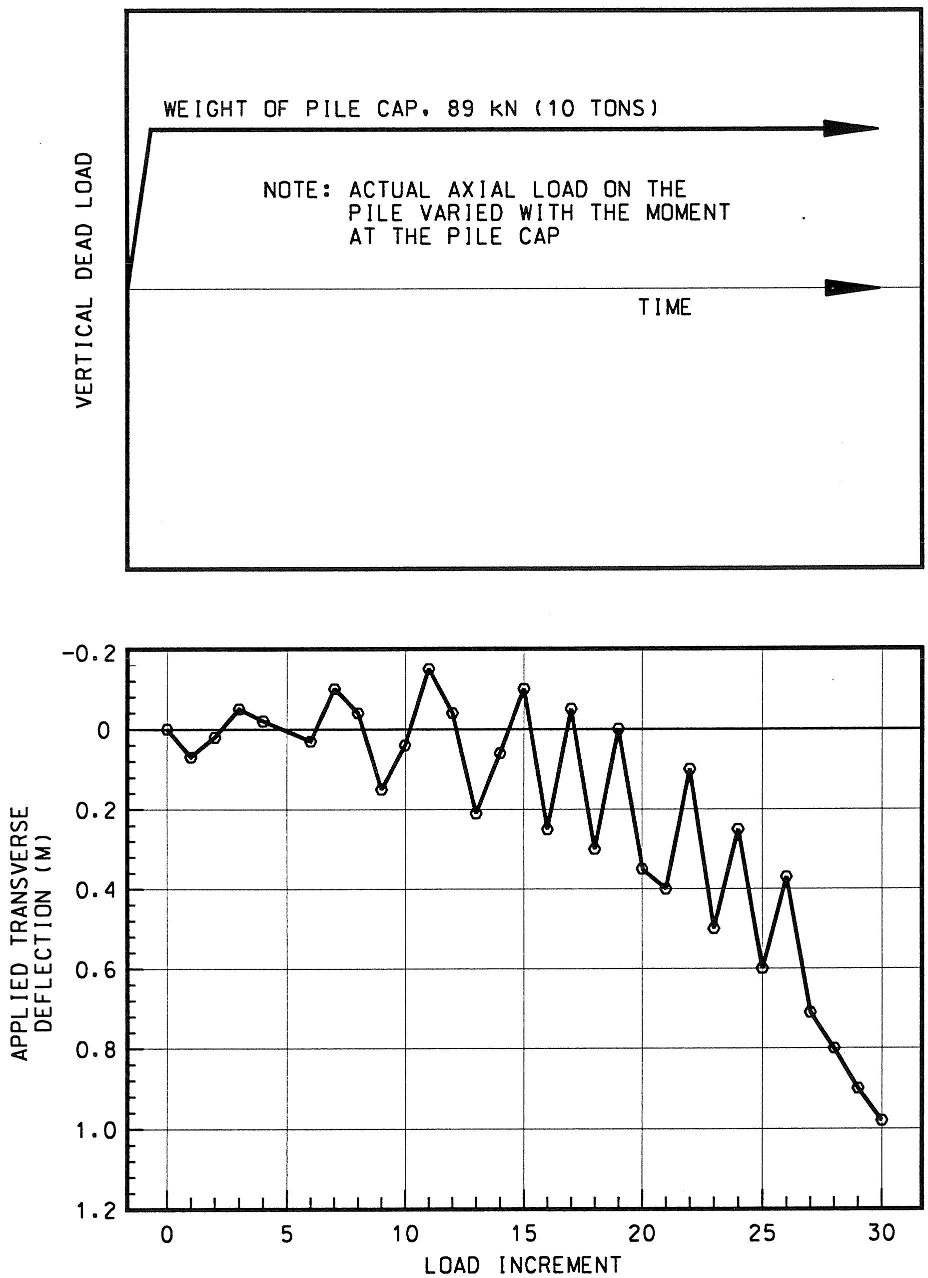


FIG. 9 FIELD TEST LOADING SEQUENCE

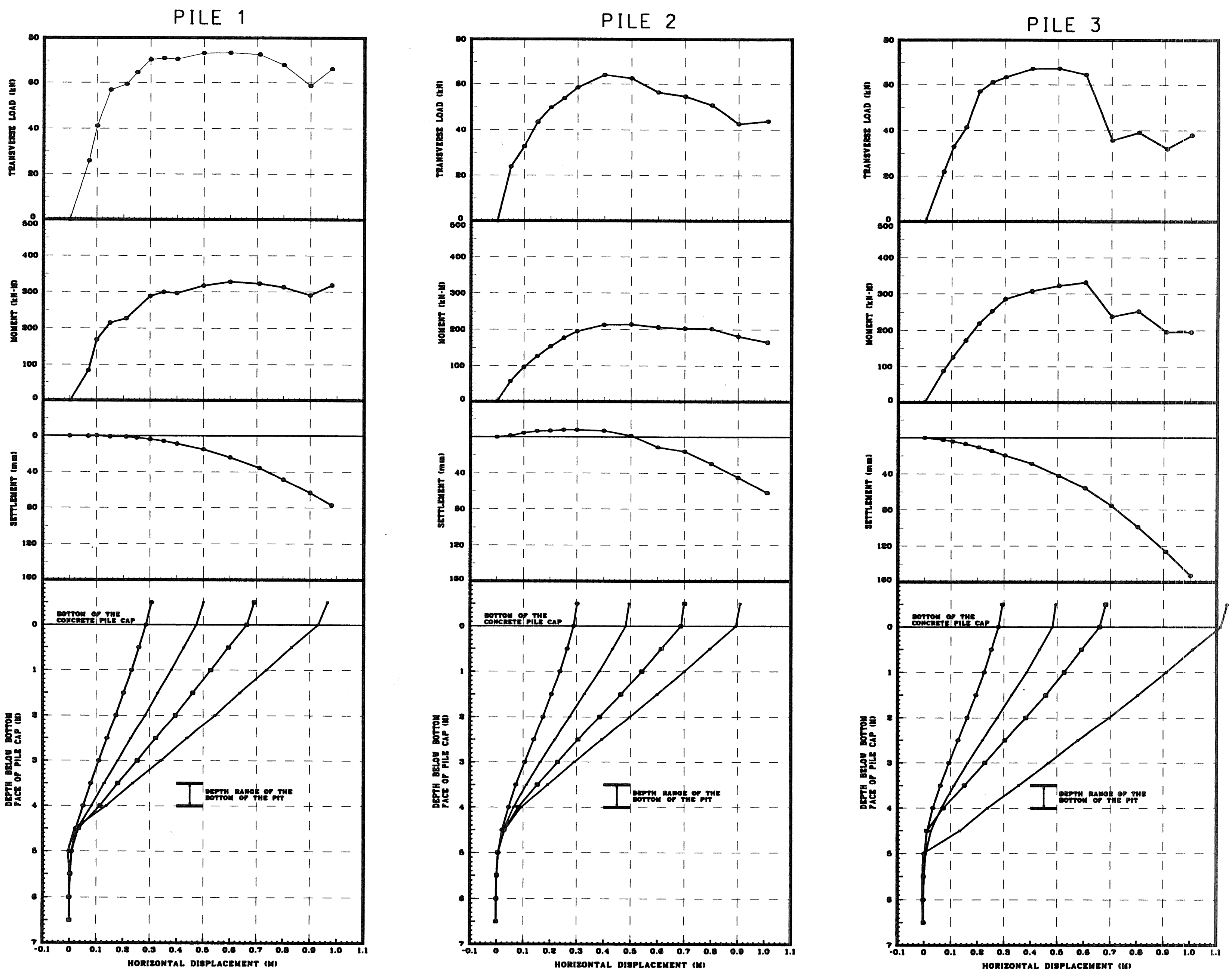


FIG. 10 FIELD TEST PILES : MEASURED LOAD, MOMENT, SETTLEMENT AND DEFLECTION PROFILES

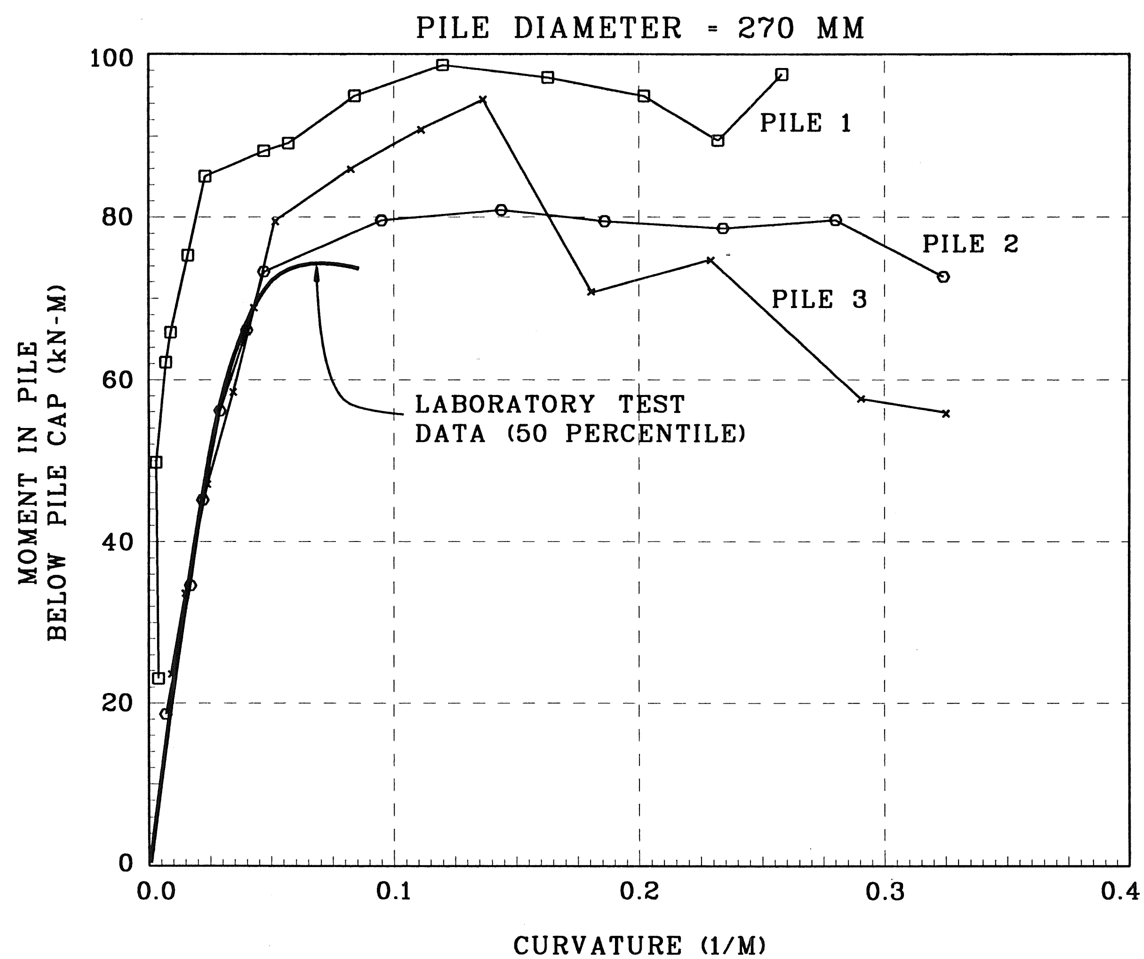


FIG. 11 MOMENT-CURVATURE RELATIONSHIP ADJUSTED TO 270 mm DIAMETER PILE

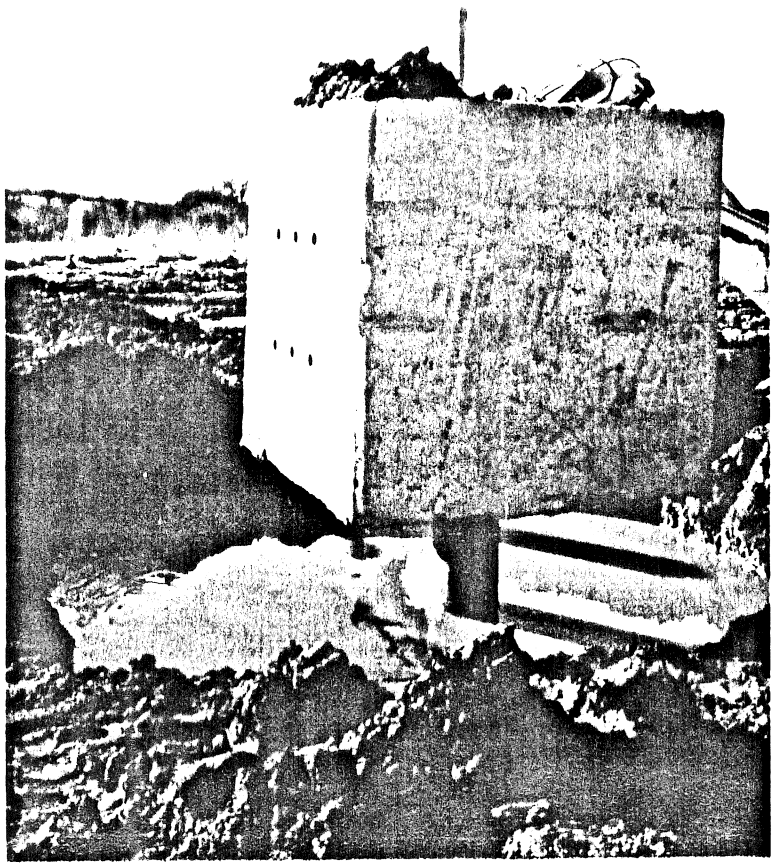


FIG. 12 PHOTOGRAPHS OF THE FIELD TEST PILE AFTER 1 M OF PILE CAP DISPLACEMENT

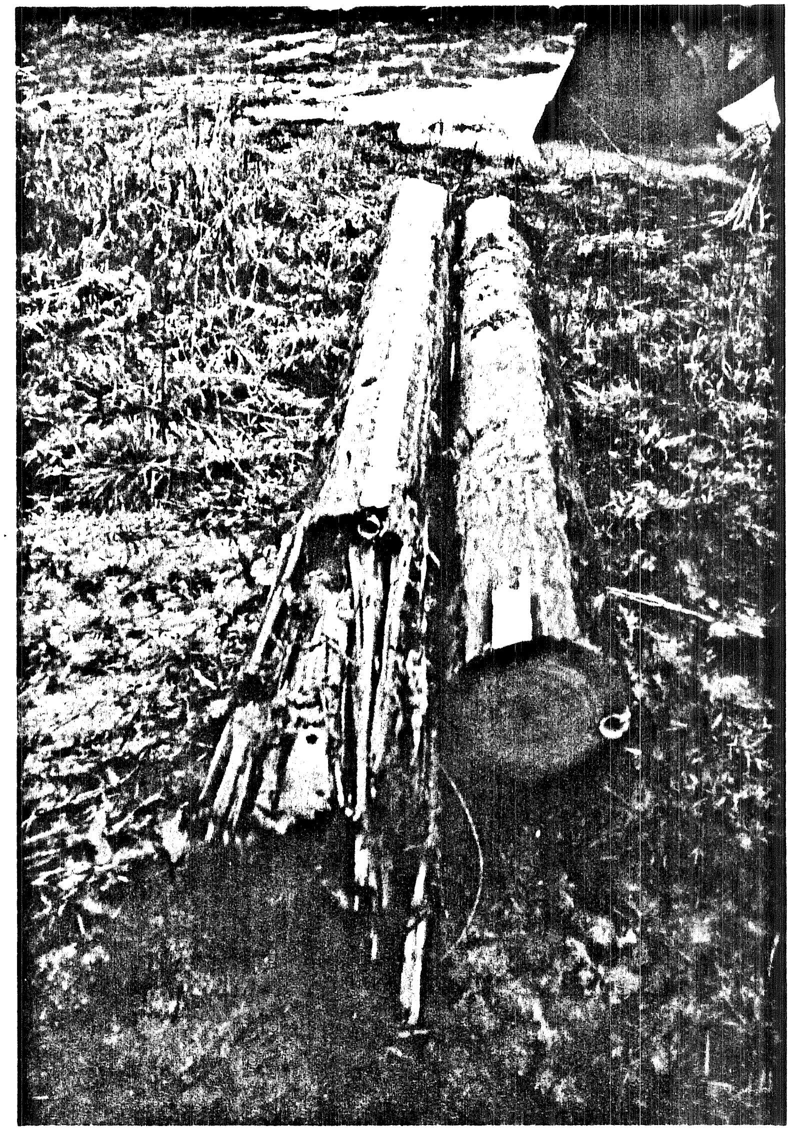


FIG. 13 'BROKEN' SECTION OF FIELD TESTED PILE