Driving Stresses in Concrete Piles

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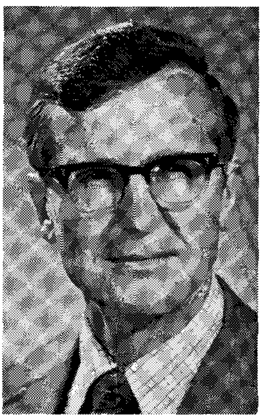
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During the summer of 1973 extensive measurements were made during the driving of piles for a bridge in Dade County, Florida. These measurements raise serious questions regarding the validity of the ram-pile weight ratio as an index for specification of pile driving hammers if a diesel hammer is used.

During the past several years a research project on pile driving has been underway at Case Western Reserve University sponsored by the Ohio Department of Transportation and the Federal Highway Administration. Some financial support has been obtained from several other state highway departments and a few private organizations including the Prestressed Concrete Institute.

The primary purpose of this project has been to develop means for determining static pile capacity from dynamic measurements made at the pile top. Considerable success has been achieved and the resulting approach known as the Case Method is now being implemented with increasing frequency in pile design and construction control.

Synopsis

Dynamic tests were performed in Miami, Florida, on three 18-in. square, 60-ft long prestressed concrete piles. Each pile was driven with a different size open end diesel hammer. Strains during driving were measured at the midlength of the pile and at the pile top. Set rebound and ram stroke were also measured. Since some current specifications include pile-ram weight ratios for the purpose of limiting driving stresses in concrete piles, this test was useful to investigate how successful the code restrictions were in limiting potentially damaging stresses due to various size hammers. Measured tensile and compressive stresses were compared with hammer size, pile net displacements, ram stroke, and hammer throttle setting to determine conditions which were most likely to produce damaging tensile or compressive stresses. It was found that pile-ram weight ratio is an unsatisfactory parameter for controlling hammer selection for open end diesel hammers. In fact, the use of this ratio can lead to excessive pile stresses. Finally, alternate procedures for selecting driving equipment are presented.

Summary of Previous Work

A complete discussion of this research project, covering a 10-year period, is beyond the scope of this paper.[1-4] However, it will be reviewed briefly so that the Miami tests can be placed in context.

The Case Piling Research Project has comprised five phases of activity.

First phase

The first and most important part of the work has been the development of instrumentation for making dynamic measurements at the pile top during driving.

Since most of the measurement ex-

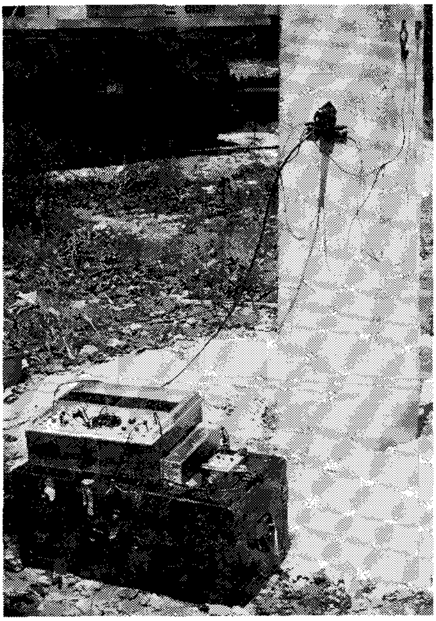

Fig. 1. Data acquisition system attached to a concrete pile.

perience has been obtained during ongoing construction projects, a primary consideration in the development of the equipment was that it be rugged and useable in the rather difficult conditions common on pile driving jobs.

The resulting system is air portable and has been used throughout most of the United States as well as in Canada, Mexico, and Europe.

The field data acquisition system is shown in Fig. 1 attached to a prestressed concrete pile during the Dade County tests. It consists of a strain transducer, the diamond-shaped device shown in the extreme upper right in Fig. 1.

These devices are bolted to opposite sides of the pile. They measure the deformation over a 3-in. gage length and have been calibrated both statically and dynamically with measurements taken from strain gages directly attached to the pile.

The other transducer next to the strain transducer in Fig. 1 is a piezoelectric accelerometer. These devices are also attached on opposite sides of the pile. For concrete piles the transducers are attached with expansion bolts set in holes drilled in the pile surface. This system has now been well proven by many tests on concrete piles.

The ouptut from the transducers is carried through a single cable to a portable analog tape recorder and associated signal conditioning. After returning to the laboratory the tape recorded data is automatically converted to digital form using a minicomputer controlling an analog-to-digital converter.

The data can then be stored on digital magnetic tape and can be automatically plotted and processed. A sample of such plotted data is shown in Fig. 2 This system makes it possible to record and process hundreds of hammer blows.

Second phase

The second phase of the research program was the development of a means of reliably predicting pile capacity from the above dynamic measurements. This goal was the original motivation for the project and a series of prediction methods have evolved where successive methods have represented improvements and refinements.

This approach, known as the Case Method, has been correlated with over 70 piles which were also statically tested to failure and has recently also been proven analytically.[4] The Case Method computations involve the measured force and acceleration records and are computationally very simple.

Third phase

A third phase of the project has been the development of computational devices to perform the Case Method computation in the field in real time and immediately display the results.

The current equipment will not only

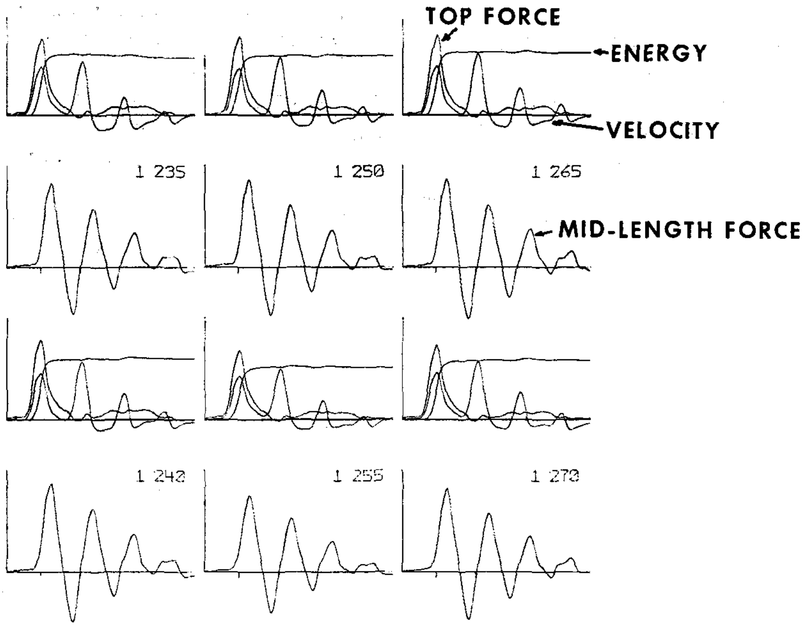

Fig. 2. Example of automatically processed data.

perform this task but also calculate the energy delivered to the pile and display extreme values of force, velocity, and acceleration generated during impact. Thus, the system could be used in the field to modify the driving system based on measurements of actually generated stresses.

This equipment has been acquired by state departments of transportation, the Federal Highway Administration and private foundation consultants for routine use in pile design and construction control.

Fourth phase

The fourth phase of the piling research program has been the study of dynamic pile analysis. An analysis procedure has been developed which uses the measured force and acceleration as input and determines the soil resistance forces and their distribution.

A computer program, known as CAPWAP, performs a wave equation type analysis on the pile using the measured acceleration as input. The resistance forces are adjusted iteratively until the pile top force computed from the input acceleration matches the measured force. An application of this program is described in this paper.

Fifth phase

The fifth phase of the research activity has been the study of hammer performance characteristics. This has particularly involved diesel hammers and one such study is presented here.

Most of the research activity has been sponsored by the Ohio Department of Transportation. In order that the available measurements be broadened beyond pile and soil types available in Ohio, tests were sponsored by other highway departments. As part of that research program three sites were scheduled for testing by the Florida Department of Transportation.[5-7]

At about the time of these tests a change was made in the pile driving specification used by the Florida DOT which would have required that the pile-to-ram weight ratio not exceed approximately four. This type of limitation is common in pile driving specifications.

The requirement is based on the fact that in the simple impact of a mass on a slender rod the length of the induced stress wave is determined by this ratio. Heavier rams cause longer stress waves.

On the other hand, the induced stress (at least until after reflection from the tip, neglecting small side friction forces) is directly proportional to the ram impact velocity.

In the case where a light ram is used, inducing a short stress wave, the compression wave is reflected as a tension wave back on the oncoming compression wave, during the easy driving portion when there is little tip resistance.

If the compression wave is short, then the net tension can be sufficiently large to exceed both the prestress force and the tensile strength of the concrete. The traditional solution to this problem has been to use heavy rams with the resulting long stress waves so that tension stresses are limited.

This approach was supported by studies conducted at Texas A and M University using a wave equation computer simulation of the pile driving system. This computer program, reported in 1963,[9] and other similar ones have found increasing use in pile driving.

However, the program was developed to model air-steam hammers and did not include either the thermodynamic or mechanical characteristics of the diesel hammer. There is a great difference between a pile driving system and the idealized rigid mass impacting the elastic rod.

Contractors using light, high impact velocity diesel hammers have claimed considerable success in driving concrete piles, and at the time of the Florida specification change, they voiced some concern. Since the contractor on the Dade County test site was planning to use a diesel hammer it was possible to expand the scope of the tests to make measurements to check the actual stresses generated.

Field Tests

Extensive soils data at the site were obtained and made available by the Florida Department of Transportation. In general, the soils could be described as a mixture of limerock and sand. Split spoon blow counts showed considerable variability as could be expected from these soils. The site was ideal for evaluating induced tension stresses since the pile could be expected to break through hard layers during driving.

For the purpose of the hammer tests, three piles were driven. They were all 18 x 18-in solid sections 60 ft long. All aspects of the driving systems were identical except the hammers.

Three DELMAG hammers were used; the D-30, the D-22, and the D-12. These three machines gave a range of pile-ram weight ratios from 2.97 to 7.18. Dtails of the hammers are given in Table 1 and the piles in Table 2.

The DELMAG hammers are classified as open end diesels; that is, the ram is free to float in the cylinder and the stroke will vary depending on the driving conditions and, for the D-30, on the throttle setting.

The following measurements were made for every hammer blow on each of the three piles:

1. Strain at the pile top was recorded on magnetic tape.

2. Acceleration at the pile top was recorded on magnetic tape.

3. Strain at pile midlength was also

Table 1. Miami hammer information.

Performance data	D12	D22	D30
Ram weight (piston), lb	2,750	4,850	6,600
Impact block weight, lb	810	1,600	1,600
Energy per blow, ft per lb	22,500	39,700	23,870-54,200
Number of blows per minute (rated)	42-60	42-60	39-60

Note: Pile Helmet—MKT, 24 in.-sq, with an 18-in. filler. Total assembly was 2650 lb. No cushion was in helmet assembly.

recorded until that point on the pile passed below the ground surface requiring the removal of the transducers.

4. Set-rebound was measured at the ground surface on a piece of paper attached to the pile by drawing a pencil across a straight edge supported on the ground. This gave a good measure of both dynamic displacement and final set for each blow. An example of such a measurement is shown in Fig. 3.

5. Ram stroke was measured for each hammer blow by visually observing the ram top against a measuring rod attached to the hammer cylinder and recording each stroke on an audio cassette recorder.

In excess of 2500 hammer blows were recorded.

Laboratory Processing

After returning to the laboratory at Case Western Reserve University, all tape recorded hammer blow data were converted to digital form and stored on magnetic tape. It was then possible to associate the strain and acceleration records for a given blow with the measured hammer stroke and the set-rebound record. The acceleration record was integrated to obtain velocity and integrated a second time to displacement. This displacement value could then be compared with the one obtained from the set-rebound record.

Strains were converted to force using the pile area and material dynamic

Table 2. Basic Miami pile information.

Parameter	Test Pile #1	Test Pile #2	Test Pile #3
Length (total), ft	60.0	60.0	60.0
Length below gages	58.5	58.5	58.5
b, in.	18	18	18
Area, sq in.	324	324	324
Weight, kips	19.62	19.81	19.74
Hammer	D30	D22	D12 & D30
Cushion	3-in. pine	3-in. pine	3-in. pine
Test dates			
Dynamic test	7-11-73	7-12-73	7-12-73
Date cast	7-3-73	N.A.	7-3-73
E, ksi	4425	4473	4586
c, ft per sec	11,695	11,740	11,907

Notes:
E = modulus of elasticity
c = wave speed in concrete

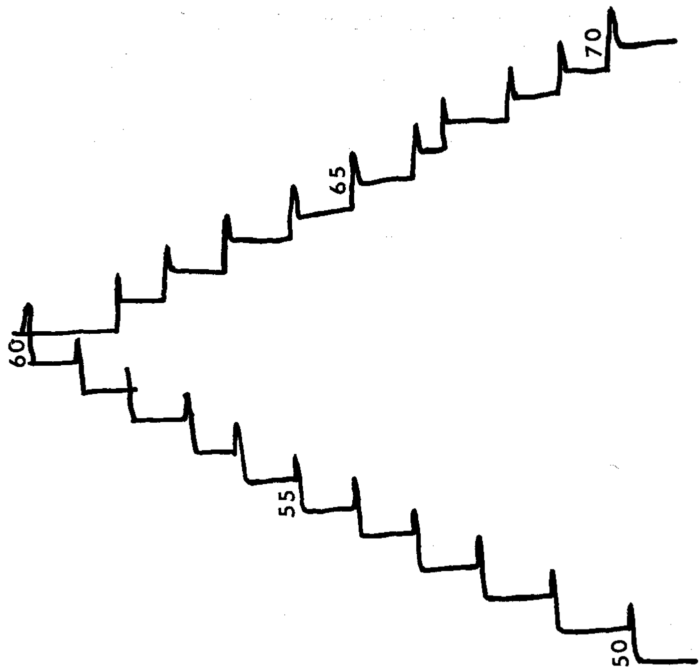

Fig. 3. Sample set-rebound measurements.

modulus as determined from a field measurement of the wave speed. Also the known proportionality between force and velocity was checked automatically.

Selected hammer blows were then automatically plotted on a digital drum plotter. Due to the time involved it was not feasible to plot each record and a careful visual examination of all 2500 blows would have been impractical.

Important parameters were determined and printed for each hammer blow. They included maximum acceleration, maximum velocity, maximum displacement, maximum energy delivered to the pile (ENTHRU), final energy (that portion of the energy delivered to the pile which does not go back to the driving system as rebound), maximum measured compression stress, maximum measured tension stress, and the Case Method of static capacity.

Test Results

Test Pile No. 1 was 60 ft long and was driven with the D-30 hammer. Driving and testing started after the pile had been set in a predrilled hole about 7 ft deep.

A total of 572 hammer blows were recorded and analyzed. These data were recorded in six sets in order to divide the data into blocks to simplify processing.

Unfortunately, the electronically recorded data from Set 6 produced meaningless results apparently due to compression failure at the pile top so the last 45 blows were lost. However, the ram stroke and set-rebound data were available from this set. A strain transducer was located at the pile mid-length during the first three sets (233 blows).

The soil conditions proved to be ideal

since the driving resistance built up somewhat and then dropped dramatically as the pile apparently broke through a limerock layer. The stroke, driving record, and Case Method capacity prediction plotted versus blow number is shown in Fig. 4.

Easy driving was experienced for the first 60 blows. At the point where the pile apparently broke through the limerock layer the set increased to almost 5 in. per blow. It is important to notice that at the same time the stroke dropped from 6.5 to 5.0 ft. As the resistance again increased, the stroke also increased.

For Test Pile No. 1 the ultimate capacity according to the Case Method climbed rapidly to a peak value of nearly 800 kips at about Blow No. 100 and then decreased steadily throughout the remainder of the driving to a final value of 400 kips.

Maximum measured compression stress at the pile top and maximum measured tension stress at the pile midlength are also shown plotted against blow number in Fig. 5. Maximum tension occurred at about Blow 65. This point in the driving record is not associated with particularly easy driving conditions (½-in. set).

The tension stresses were much lower at the maximum set condition at Blow 41. The maximum measured tension stress was 2.16 ksi.

A possible explanation for the changes in stress, particularly tension stress, when driving was interrupted, is that the resistance distribution changed as pore water pressure declined.

Driving was stopped on this pile when it exhibited signs of damage at the top. This damage was probably what rendered the top strain transducers ineffective during the last data set. No visible sign of tension cracking appeared in spite of the large tension

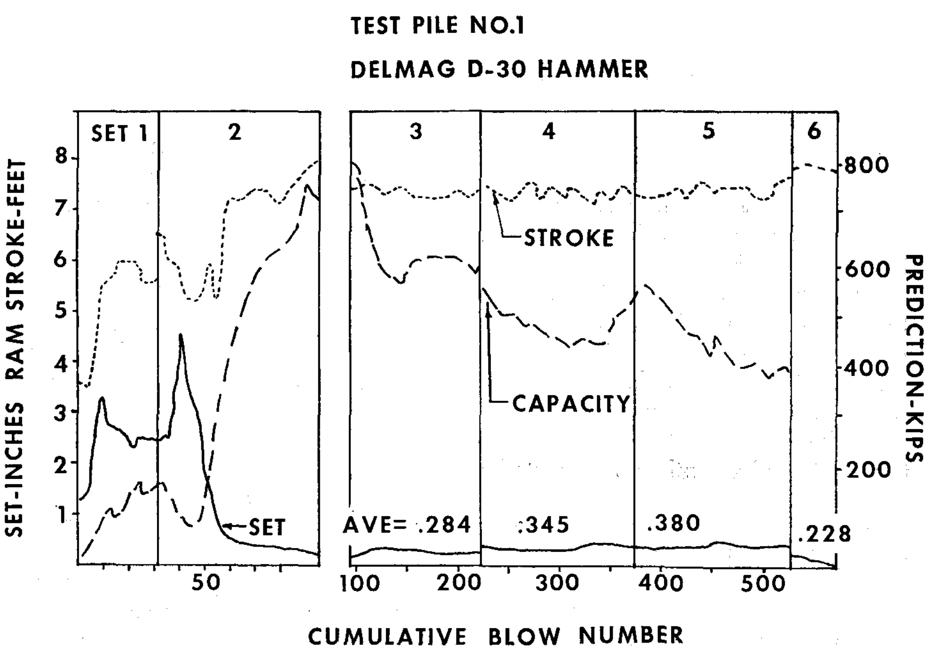

Fig. 4. Driving data for Test Pile 1, D30 hammer.

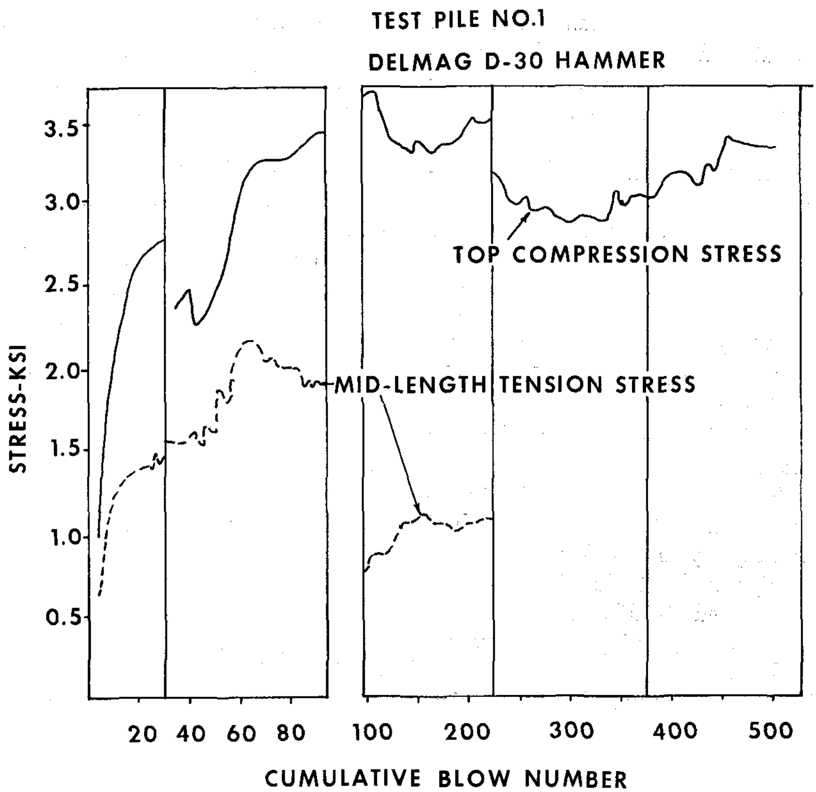

Fig. 5. Maximum measured stresses for Test Pile 1, D30 hammer.

stresses recorded.

Test Pile No. 2 was 60 ft long and was driven by a D-22 hammer about 27 ft from Test Pile No. 1. Driving and testing began after the pile had been set in a predrilled hole about 11 ft deep. A total of 741 hammer blows were recorded and analyzed.

Again, the data was broken into six sets, primarily to facilitate processing. All of the recorded data proved satisfactory, but inadvertently no ram stroke data were recorded during Set 5. A strain transducer was located at the pile midlength for the first two sets (201 blows).

The stroke, driving record (set), and Case Method capacity prediction are shown in Fig. 6. Easy driving was encountered between approximately Blows 15 and 45 in the first data set. The set reached a maximum value of about 4 in., apparently after breaking through a hard layer of limerock.

Note that at the same time the ram stroke decreased from 4.5 to 4.0 ft. As the resistance again increased (i.e., set decreased) the ram stroke values immediately increased to 5.0 ft and then gradually climbed to 5.8 ft as the set reached a low of 0.055 in. per blow during the last 100 blows.

This amounts to a blow count of 218 blows per ft as compared with only 3 blows per ft at about Blow 32 of the first set. During the easy driving portion the Case Method Capacity indicated about 75 kips and this increased to 130

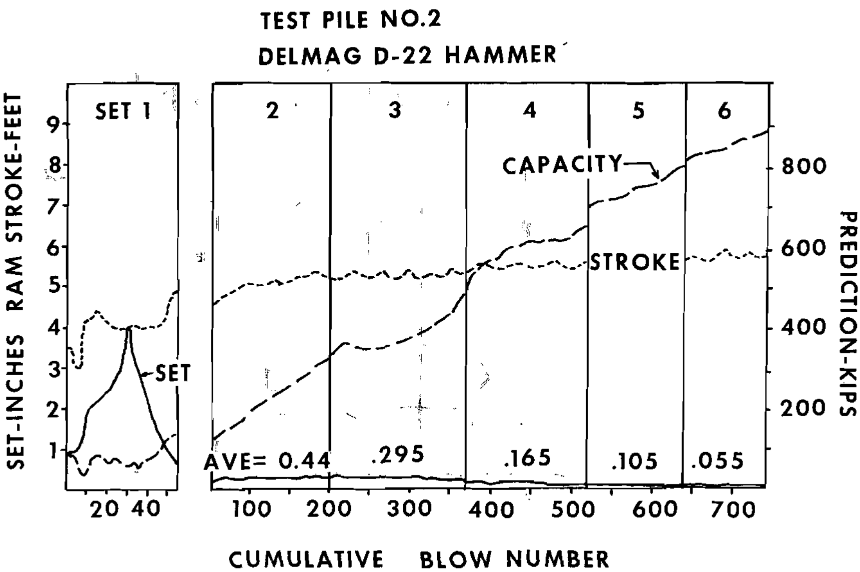

Fig. 6. Driving data for Test Pile 2, D22 hammer.

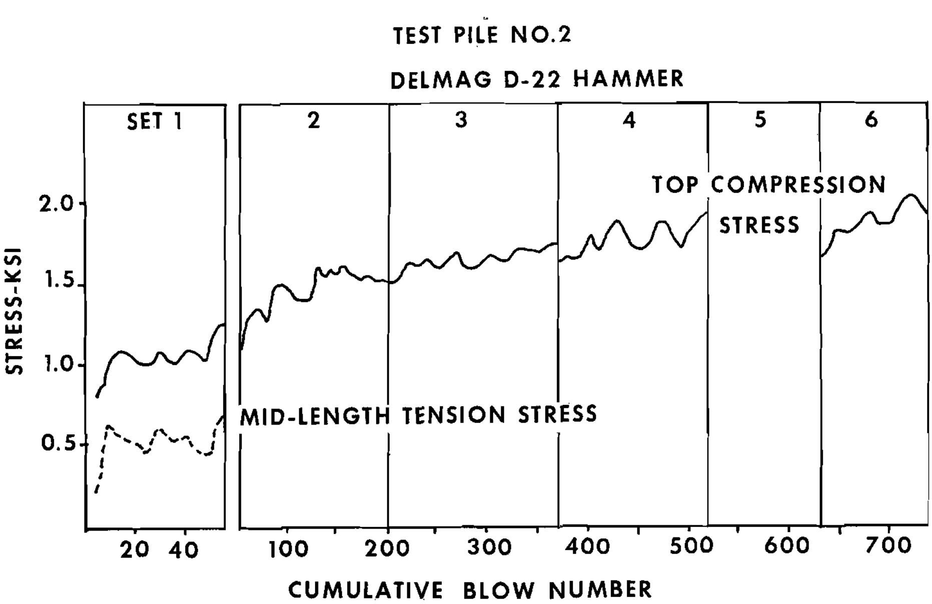

Fig. 7. Maximum stresses for Test Pile 2, D22 hammer.

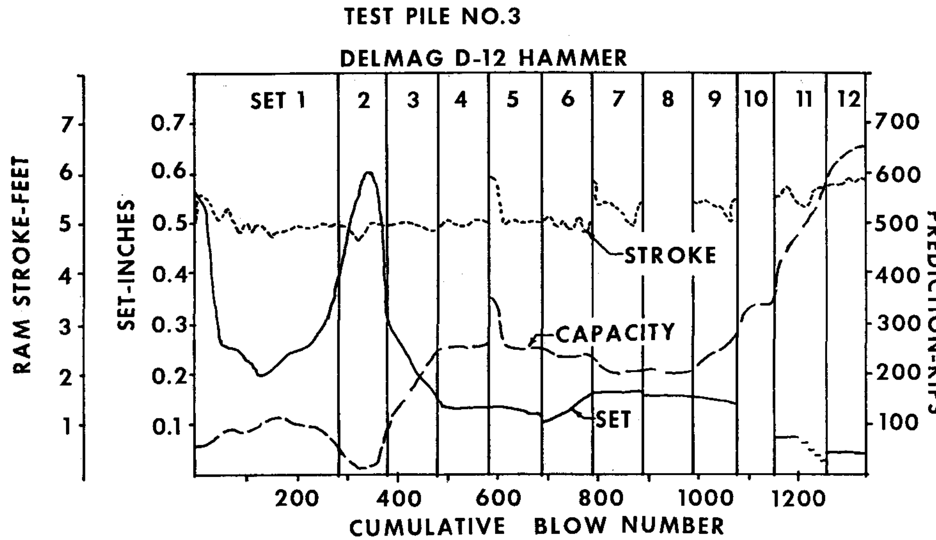

Fig. 8. Driving data for Test Pile 3, D12 hammer.

kips at the end of Data Set 1.

By the end of Data Set 2 the capacity was 350 kips and it continued to rise steadily until it reached a value of 880 kips at the end of driving. This is quite a different performance than that exhibited by Test Pile No. 1 and is a disturbing characteristic of the soil involved.

Maximum measured compression stress at the pile top and maximum measured tension stress at the pile midlength are shown plotted against blow number in Fig. 7. The top compression stress shows a gradually increasing trend but is considerably lower than that recorded on Test Pile No. 1.

Unfortunately, tension stress data were obtained for only the first data set. The transducer malfunctioned during the second set and then had to be removed because of the ground surface. Tension stresses are considerably lower than measured on Test Pile No. 1.

Test Pile No. 3 was 60 ft long and was driven by a DELMAG D-12 hammer at a location an additional 22 ft beyond Test Pile No. 2. Testing was begun after the pile had been set in a predrilled hole about 11 ft deep.

A total of 1330 hammer blows were recorded and analyzed. The data were broken into 12 data sets. A strain transducer was located at midlength for the first nine data sets (1075 blows).

Note in Fig. 8 that as the pile broke through a hard layer (around Blow No. 300), the set increased rapidly until it reached a maximum value of 0.6 in. per blow at about Blow No. 350 in Set 2.

At about this time, the stroke decreased from 5.0 ft to about 4.6 ft and then went back up to 5.0 ft as the resistance increased.

Note that the Case Method capacity prediction also decreased as the driving resistance went down (as would be expected). The stroke remained at 5 ft through about Blow No. 800 and then slowly increased to 5.8 ft at the end of driving.

This is shown in Fig. 8 along with the driving record (set), and Case Method prediction versus cumulative blow num-

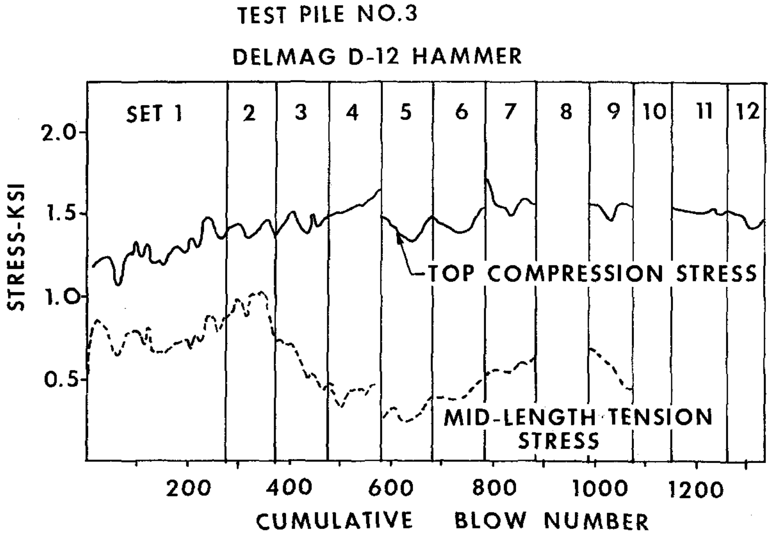

Fig. 9. Maximum stresses for Test Pile 3, D12 hammer.

ber. Near the end of Set 11 the blow count climbed up to 400 blows per ft and then fell back to 267 blows per ft during Set 12.

Maximum top compression stress and midlength tension stress are shown as a function of cumulative blow count in Fig. 9. The largest tension stress occurs with the largest sets but it is much smaller than those measured with the D-30.

Analysis of Results

To get a general view of the large volume of data obtained, several important parameters were examined to obtain trends. In Fig. 10 the stroke for each of the hammer tests is shown as a function of pile set.

The data were plotted and from them the bands shown were obtained as were the average lines. For both the D-22 and the D-30 the same characteristic is shown. The stroke was constant for set values greater than about 1½ in. For smaller sets the stroke increases to about 6 ft for the D-22 and 8 ft for the D-30.

Still greater strokes would probably have been achieved in the D-30 test if driving had not been stopped due to the pile top damage. The D-12 hammer showed the beginning of the same trend but due to its small size only rather small sets were achieved.

Important is that the stroke achieved by the smaller hammers was smaller. Apparently, the short stress wave induced did not transmit rebound energy back to the ram as effectively as did the longer stress wave associated with the heavier ram.

In Fig. 11 the maximum top compression stress is shown as a function of ram stroke. Since it is known that stress is proportional to impact velocity, the trend of the data is as expected.

It should be explained that the D-30 data are shown as two blocks since very few blows occurred with strokes between 6½ and 7½ ft. However, the data trend is consistent with the other

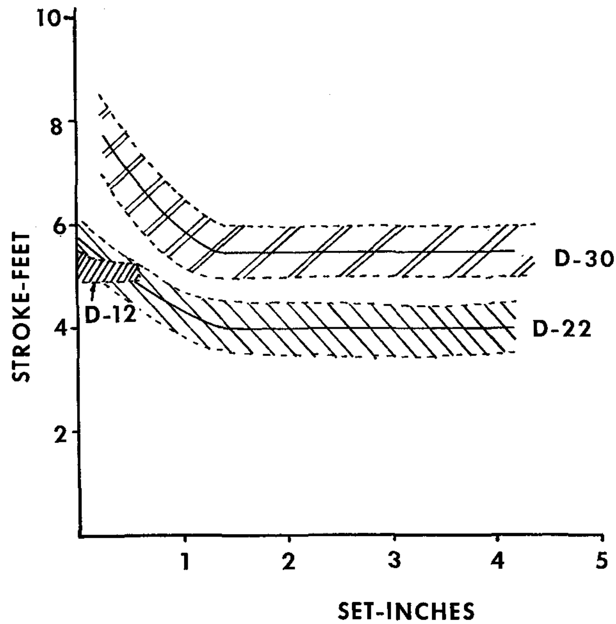

Fig. 10. Measured ram stroke versus pile permanent set showing increase in stroke as driving resistance increases.

hammers.

In Fig. 12 the maximum top compression stress for each hammer blow is shown as a function of pile set. Since the stress and the stroke are closely related these curves have the same shape as the stroke versus set results. The D-30 data show a greater increase in stress with decreasing set.

In Fig. 13 the maximum tension stress is shown as a function of set. The behavior is more complex here. The D-12 results show an increase in tension stress with increasing set but only over the very short available range of set.

The D-22 results are constant over a wide range of sets with an indication of increase at the smallest available values of set. It is unfortunate that some data were lost in exactly this region.

The D-30 results probably are the most general and can be explained as follows:

As the set decreased from 4 in. to about 1½ in., the maximum tension stress remained approximately constant. In this range the ram stroke was about constant inducing a constant maximum compression stress. Since there was very little tip resistance a constant maximum tension was also produced by the reflected tension stress wave. As the set decreased below 1½ in., the stroke began to increase substantially producing a much greater compression stress. However, the tension stresses increase at a slower rate because the tip resistance has also increased allowing less tension to be reflected. As the tip resistance increases further it finally causes the maximum tension stress to become smaller.

It should be noted that changes in resistance distribution may have a substantial effect on the magnitude of the induced tension stresses.

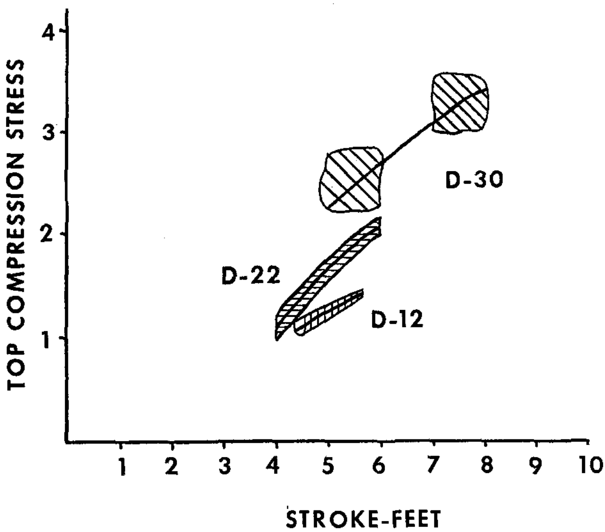

Fig. 11. Measured relationship between maximum top compression stress and ram stroke.

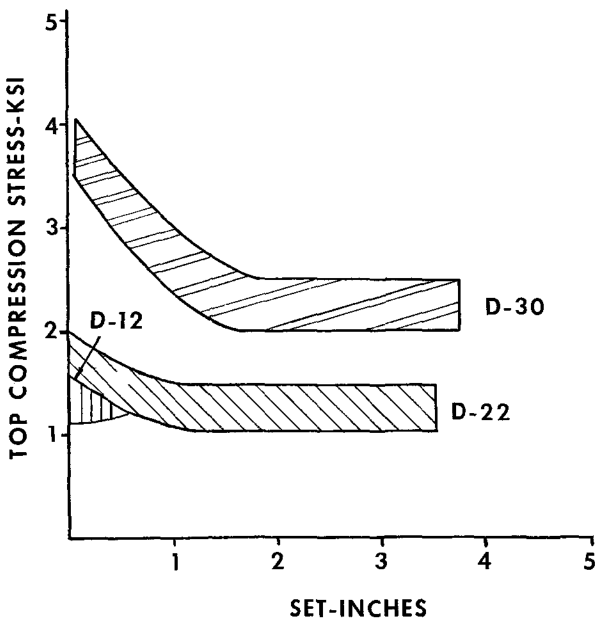

Fig. 12. Maximum measured pile top stress versus pile permanent set. Since the stroke increases as the set decreases, the maximum top stress also increases.

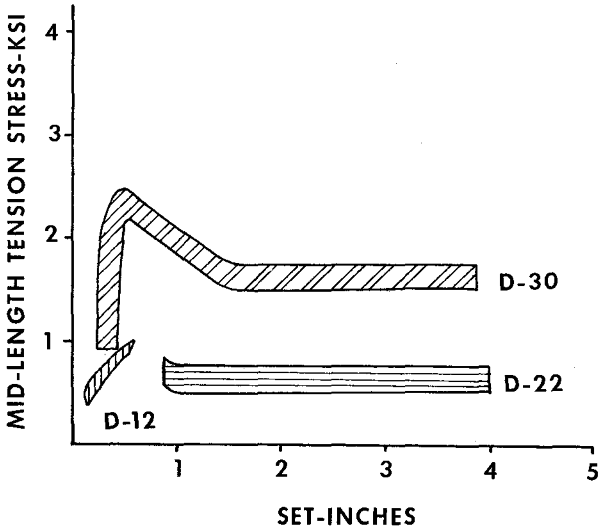

Fig. 13. Maximum measured pile midlength tension stress versus permanent set. With decrease in set tension stress increases until the tip resistance is great enough to reduce the tension reflection.

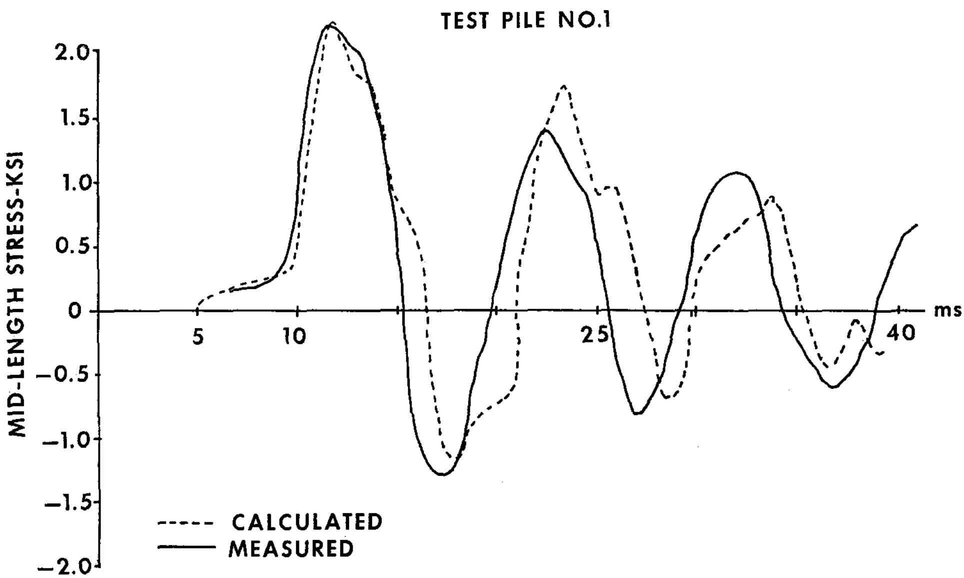

Fig. 14. Predicted versus measured midlength stress versus time curves. Maximum tension stress is accurately determined from top measurements using CAPWAP.

Computation of Maximum Tension Stress

It is not always possible or convenient to measure tension stresses along the pile length. Therefore, the determination of maximum tension stresses using the CAPWAP program combined with measurements at the pile top was tested. This technique uses the measured acceleration at the pile top as an input, and adjusts the soil resistances so that the calculated force at the pile top matches the measured force.

The primary reason for developing this capability was to determine the soil resistance and its distribution from measurements of force and acceleration at the pile top. In this case, it can also be used to obtain a complete stress distribution in the pile during a single hammer blow.

After determining the resistance magnitude and distribution from the measured top acceleration and force, the calculated forces at midlength could be compared with the measured value. A sample result is shown in Fig. 14.

Probably further refinement of the computer program will produce still better correlation. These results, however, indicate that the CAPWAP program can be a useful tool in evaluating d-iving stresses.

Reduced Throttle Tests

After completion of the driving of Test Pile No. 3 to refusal with the D-12, the D-30 hammer was used to drive the pile further using a variety of throttle settings.

This machine is equipped with a throttle having 10 discrete settings, each of which gives a metered quantity of fuel. About 30 blows were recorded at each of six different throttle settings.

The resulting mean measured values of ram stroke, maximum top compression stress, and pile set are shown in Fig. 15. The throttle is seen to provide a convenient means of controlling induced stresses, but it does this with a penalty on productivity.

Conclusions

1. It is feasible and practical to make routine measurements of acceleration and force under the hammer during pile driving. Furthermore, large volumes of this data can be examined using currently available real time data processing systems.

2. The CAPWAP program can be used to evaluate induced tension stresses from measurements made at the pile top.

3. The use of pile-ram weight ratios in controlling tension stresess in piles during driving is quite unsatisfactory when applied to diesel hammers. While these conclusions are based on tests at only one site, it is just the soil conditions present at this site which the limiting pile-ram weight ratio is supposed to control. In fact, the *highest* measured tension stresses were generated by the heaviest ram. The reason for this performance is described in the paper. If current pile-ram weight ratios are used for selecting driving equipment, damage problems will be more frequent and severe. While tests at a single site can hardly be used to justify replacement limitations, they do prove conclusively the inadequacy of the pile-ram weight ratio.

4. Throttle controls on diesel hammers can provide a convenient means of controlling induced stresses, but only with a penalty on productivity.

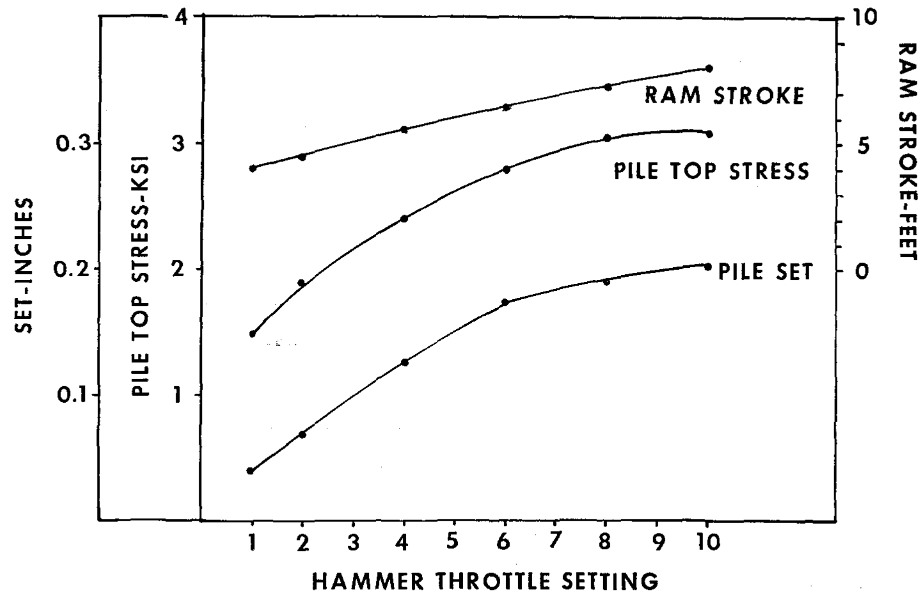

Fig. 15. Ram stroke, pile set, and maximum pile top compression stress versus hammer throttle setting for the DELMAG D30 hammer. As the throttle is reduced, maximum top compression stress also decreases as does system efficiency.

Recommendations

The Dade County tests have shown conclusively that pile-ram weight ratio is not a satisfactory parameter for selecting hammers to avoid tension cracking. The measurements made there are supported by experience at other sites where less comprehensive testing was done.

However, it is inadequate to state that a particular parameter, such as pile-ram weight ratio, is unsatisfactory without offering alternatives for the consideration of the profession.

These alternatives are based on the most extensive field measurement program yet reported, now involving well over 100 sites with many piles tested on each site. Unfortunately, the recommendations must be more complicated that just a simple ratio.

The best procedure for equipment selection is the use of field measurements on either a predesign test program or on the first production piles. Since electronic equipment is now at a stage where it can be used routinely it is possible to measure both maximum compression and tension stresses induced during driving. The driving equipment and procedures can be modified so that satisfactory stress limits are maintained.

If field tests are not possible or possibly as an adjunct to them, the driving system can be checked by wave equation analysis. However, such an analysis is meaningful only if the driving system and soil conditions, as modeled in the computer, realistically reflect the actual conditions.

Soil modeling is inexact at best. Furthermore, wave equation programs which are generally available do not accurately model the thermomechanical operation of diesel hammers. Results obtained from wave equation analysis cannot be expected to be better than the program used.

If neither of the above procedures is available, equipment selection becomes difficult. Further recommendations are presented recognizing that much more data are necessary to provide a reliable, comprehensive answer.

In dealing with a phenomenon as complex as pile driving it is unlikely that a single set of guidelines will apply in all cases.

The recommendations presented below are based on preventing pile damage while maintaining the highest possible driving system efficiency. There may be other considerations which will also govern equipment selection.

I. Piles less than 40 ft long

No special requirements must be satisfied. A softwood cushion loaded across the grain and having a minimum thickness of 2 in. should be used. If damage occurs at the pile top, system alignment should be checked and if damage still occurs the cushion thickness should be increased.

II. Piles over 40 ft long

A. Air-steam hammers

The pile-ram weight ratio must not exceed 4.0 and a softwood cushion of at least 4 in. thickness should be used. As the pile length increases, the cushion may have to increase in thickness. Probably for piles greater than 60 ft long, at least 6 in. of cushion should be used.

B. Diesel Hammers

1. Closed-end hammers

Use at least 2 in. of softwood cushion. In easy driving reduce the throttle to the minimum setting which causes the pile to move and the hammer to run. As the driving resistance increases, open the throttle. If damage occurs at the pile top, increase the cushion thickness or reduce the throttle.

2. Open-end hammers

(a) For hammer energy-pile weight ratios* less than 2.0, use 2 in. of softwood cushion.

(b) For hammer energy-pile weight ratios greater than 2.0, use at least 2 in. of softwood cushion and reduce the throttle so that the hammer energy-pile weight ratio of 2.0 is not exceeded for blow counts less than 30 blows per ft. For higher blow counts the throttle can be opened to achieve more power. If top damage occurs either reduce the throttle or increase the cushion thickness. The hammer energy-pile weight ratio limitation can be satisfied by increasing the thickness of softwood cushion used. The manufacturer's rated energy is decreased by 10 percent of the rated value for each 1½ in. of softwood cushion added in addition to the 2 in. minimum.

In the application of a dynamic formula the manufacturer's rated energy should be decreased by 10 percent of the rated value for each 1½ in. of softwood cushion (of course, this reduction should be applied to the 2 in. minimum cushion also).

*The hammer energy-pile weight ratio is defined as the manufacturer's rated energy in foot-pounds divided by the pile weight in pounds.

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Discussion of this paper is invited. Please forward your discussion to PCI Headquarters by June 1, 1976.