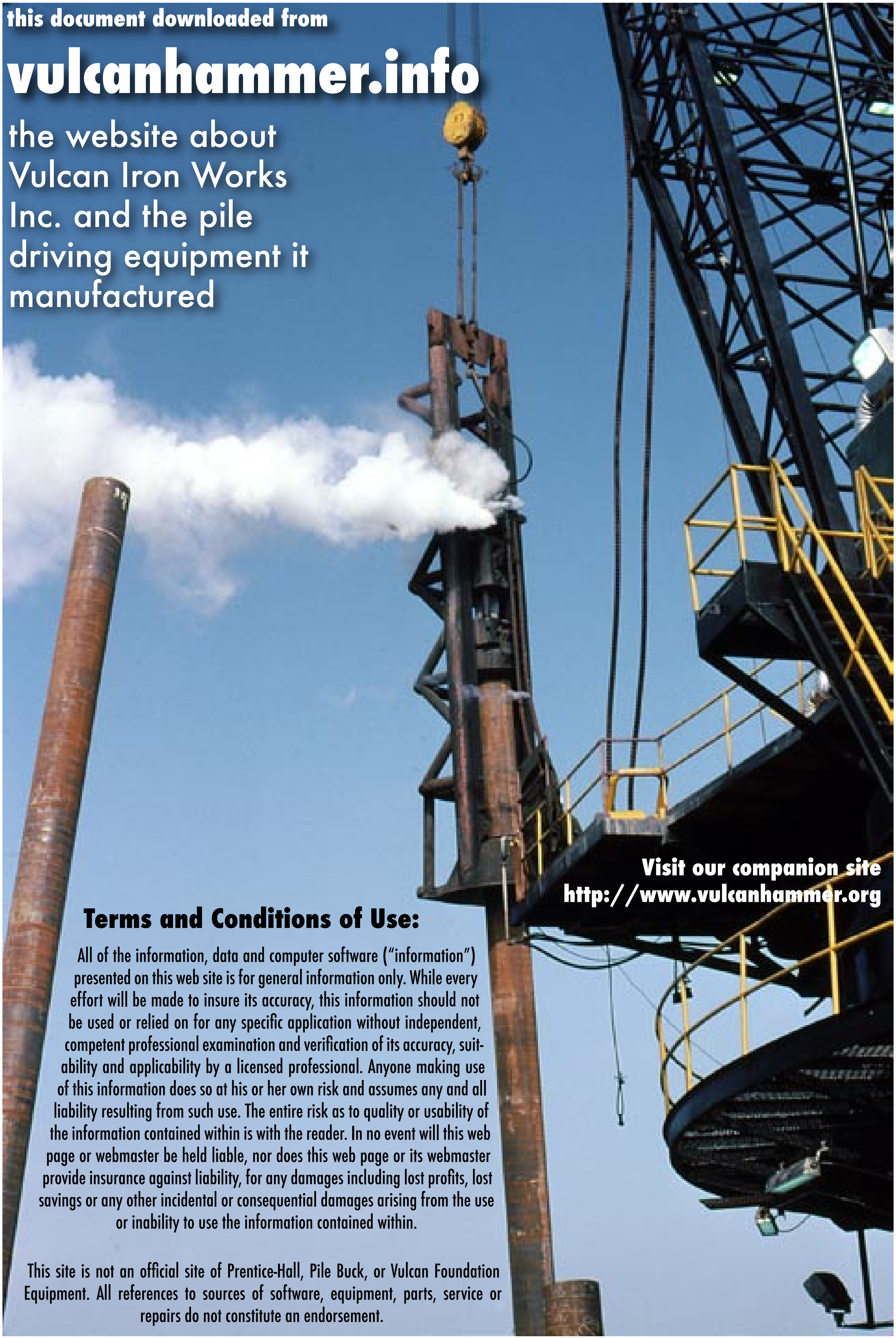

# FIVE DIFFERENT HAMMER

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In 1972 the Ohio Department of Transportation changed their pile driving specification to read, essentially, that H-piles driven to rock should be driven to a blow count of 20 BPI (blows per inch), independent of hammer size or any other consideration. Since this change in specification was controversial, a research project was undertaken to investigate it at Case Western Reserve University under the sponsorship of the Ohio Department of Transportation and the Federal Highway Administration.

The basic goal of this study was to examine the performance of steel H-piles driven according to the specification under a variety of conditions. Two sites were selected: one having a soft shallow overburden underlain by a [illegible] a moderately dense overburden grading [illegible] a soft rock that became harder with depth (Cleveland). A soil profile fo[illegible] e[illegible] is given in Fig. 1 and 2.

A variety of hammers were used at each location and the piles were all driven to the 20 BPI criteria. During driving extensive dynamic measurements were made. After completion of driving most of the piles were load tested statically and then extracted for visual examination.

The data obtained in these tests were quite voluminous. It will only be possible here to summarize the results with emphasis on the conclusions. A much more complete presentation of the results is contained in Reference 1.

| Depth in Feet | Description of Soil | Blows Standard Penetration | Moist. Content% | Wet Density lb./cu. ft. | Dry Density lb./cu. ft. | Liquid Limit % | Plastic Limit % | Unconf. Shear Strength | Compression Stress |
|---|---|---|---|---|---|---|---|---|---|
| 0 | Top Brown Soil | | | | | | | | |
| | | 2,3,6 | | | | | | | |
| 5 | Clayey Silt | | | | | | | | |
| | | | 26.4 | 128.4 | 101.6 | 30.8 | 20.5 | 2.75 | |
| 10 | | | | | | | | | |
| | | 2,2,3 | | | | | | | |
| | | | 26.8 | 128.0 | 101.0 | 31.1 | 20.2 | 2.59 | |
| 15 | Clayey silt with few rock frag- ments | | | | | | | | |
| | | | 27.5 | 130.0 | 102.0 | 30.8 | 18.4 | 0.68 | |
| | Clayes si't with gravel | 2,5,7 | | | | | | | |
| 20 | | | 13.0 | 146.9 | 130.0 | | | 8.4 | |
| | | | | | | | | | 7.4 |
| 25 | Hard Lime Stone | 16,24, 40 | | | | | | | 7.6 |
| | | | | | | | | | 4.1 |
| | | | | | | | | | 5.2 |
| 30 | | | | | | | | | 5.3 |
| | | | | | | | | | 5.7 |
| 35 | | | | | | | | | |

FIGURE 1 Soil Profile, Sandusky



| Depth in feet | Description of Soil | Blows Stand. Pen. | Moist. Content % | Wet Density lb./cu. ft. | Dry Density lb./cu. ft. | Liquid Limit % | Plastic Limit | Unconf. Shear Streng. | Compress. | Silt % | Clay % |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | | | | | | | | | | | |
| | Br.&Gray Clay | | 18 | | | 30.4 | 23.2 | 8.64 | | 42 | 58 |
| 5 | (some silt) | 5,9,12 | 18 | | | 30.0 | 23.9 | | | | |
| | Clay/Rock Fragments | | 19 | 122.7 | 105.8 | 34.0 | 22.8 | 10.02 | | 36 | 64 |
| | Silt Clay | 6,10,15 | 18 | | | 26.8 | 19.4 | | | | |
| 10 | | | | | | | | | | | |
| Clay | Silt Clay | | 18 | | | 32.0 | 20.2 | | | 90 | 10 |
| | Gray Clay | 3,5,10 | 15 | | | 25.0 | 18.2 | | | | |
| 15 | Hard Clay to Clay Shale | 50 .4' | 7 | 132.5 | 115.8 | 27.5 | 20.3 | | | 95 | 5 |
| Shale | Weathered Clay Shale | | 7 | | | | | | | | |
| | | | | | | | | | 1.2 | | |
| 20 | Clay Shale | | | | | | | | | | |
| | | | | | | | | | 2.2 | | |
| | | | | | | | | | 1.3 | | |
| | | | | | | | | | 1.1 | | |
| | | | | | | | | | 1.1 | | |
| 25 | Clay Shale | | | | | | | | | Grain sizes mostly med. to fine silts & coarse clay | |

FIGURE 2 Soil Profile, West Cleveland (W92)

## Sandusky Tests—Driving to Hard Rock

All of the test piles were 10 HP 42. This section was selected in order that load tests could be run to failure at a reasonable force magnitude. Table I gives the hammers used and the piles driven at the site near Sandusky, Ohio. One vertical pile and one pile battered at one horizontal to four vertical were driven to a blow count of at least 20 BPI or until the pile had obviously been extensively damaged at its tip. Vertical piles with APF points were driven with each hammer except the MKT 9B3. The 9B3 was not used for the piles with points since this hammer was thought to be too small to damage the piles without points so tip damage was not considered to be a problem. One additional pile was driven by the Kobe K-25. This pile designated K25-VE, was driven plumb without tip reinforcement and was used to attempt to drive a pile with a large hammer with no tip reinforcement and not induce damage. The hammer was immediately shut down when it was observed that the tip had reached rock.

During driving, blow count was recorded as well as complete set-rebound records and, for diesel hammers stroke or bounce chamber pressure. In addi-

TABLE I

HAMMERS AND PILES AT SANDUSKY

| HAMMER | RATED ENERGY FT-LBS | RAM WEIGHT LBS | PILE | APF * PILE TIPS | APPARENT FINAL PENETRATION | CAPACITY KIPS CASE METHOD | CAPACITY KIPS STATIC |
|---|---|---|---|---|---|---|---|
| MKT 9B3 | 8,750 | 1600 | 9B3-V** | No | 22' - 4" | 128 | 386 *** |
| | | | 9B3-B | No | 22' - 11" | 239 | |
| Link Belt 520 | 30,000 | 5070 | 520-V | No | 26' - 2" | 141 | 400 |
| | | | 520-P* | Yes | 22' - 1" | 423 | 120 |
| | | | 520-B | No | 24' - 11" | 316 | 410 |
| Vulcan 08 | 24,000 | 8000 | 08 -V | No | 22' - 2" | 443 | 354 |
| | | | 08 -P | Yes | 22' - 0" | 439 | 362 |
| | | | 08 -B | No | 26' - 4" | 186 | |
| K-13 | 24,000 | 2870 | K13-V | No | 24' - 6" | 157 | 151 |
| | | | K13-P | Yes | 21' - 10" | 416 | 154 |
| | | | K13-B | No | 22' - 10" | 346 | |
| K-25 | 50,700 | 5510 | K25-V | No | 25' - 10" | 160 | 350 |
| | | | K25-P | Yes | 22' - 2" | 435 | 231 |
| | | | K25-B | No | 25' - 10" | 336 | |
| | | | K25-E | No | 20' - 6" | 462 | 350 |
| | | | | | | | 414 |

* ...ated Pile & Fitting Corp. Pruyn Points
...le driven vertically, B pile at 1:4 batter (no point protection).
...pile with Pruyn Point 75600 or 75750 driven vertically.
** Failure was not reached in the load test.



tion, force and acceleration was measured at the pile [illegible] processed by the Pile Capacity Analyzer. Analog records of each [illegible]er blow were recorded on magnetic tape. Thetransducers and recording [illegible]em are shown in Fig. 3. Due to space limitation this recording and processing system will not be discussed further since it has been described extensively elsewhere (Ref. 2). The Case Method pile capacity is given for each pile in Table I.

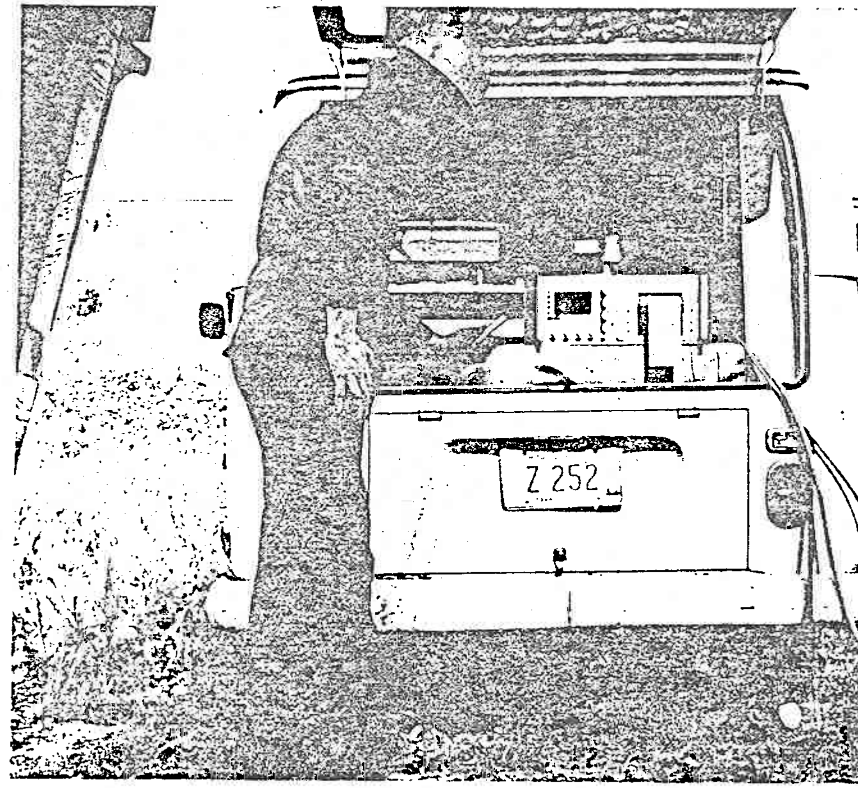

FIGURE 3 Case Method analyzer and recording system with transducers on the pile in the foreground.

After driving, 12 of the piles were load tested statically. The capacities measured are also reported in Table I. All load tests were at Constant Rate of Penetration; the Capacity was evaluated using Davisson's procedure.

The Sandusky site was almost ideal in supplying the desired conditions of a soft overburden over hard rock. In the overburden soil the blow counts were very low and in every case rock was reached within one foot of the same depth. Driving continued in an attempt to reach the desired blow count. In many cases for piles without pile tips the bottom of the pile promptly buckled and further apparent penetration of the pile was due to additional pile damage. Since the overburden soil is about 22 ft deep, the amount that the piles have been shortened can be determined by subtracting that amount.

During driving the performance of all of the piles with tips was the same. Shortly after reaching rock that portion of the pile extending above the

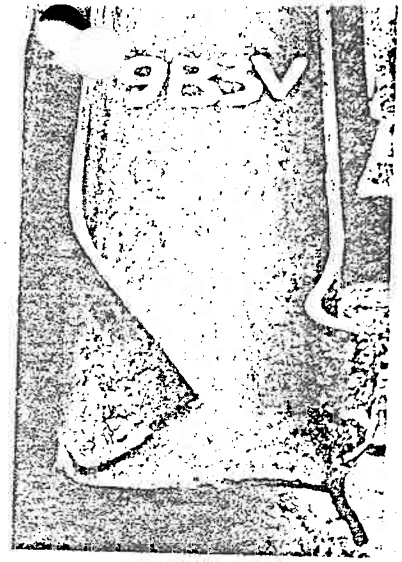

FIGURE 4 Sandusky Pile 9B3-V

FIGURE 5 Sandusky Pile 520-V

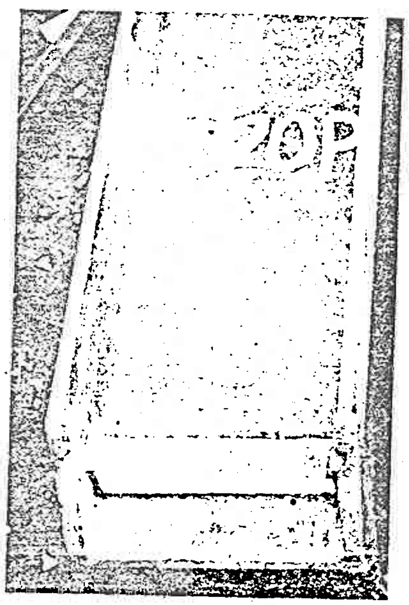

FIGURE 6 Sandusky Pile 520-P

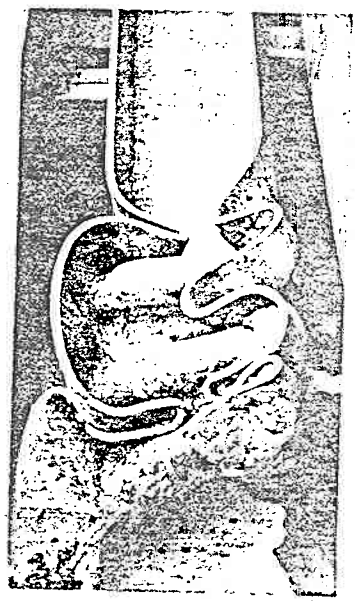

FIGURE 7 Sandusky Pile 520-B



ground failed in gross buckling. Of course, these buckle [illegible] were cut off before performing the load tests. Also pile 08-V bucki [illegible] ally at the top after reaching rock, probably due to poor driving system al[illegible]ment.

Some of the extracted piles are shown in Fig. 4 through 12. The condition of the 520-P pile in Fig. 6 was typical of all of the piles that had point reinforcement. When the piles were extracted a back-hoe was used to excavate to within about 4 ft of the tip to avoid additional pile damage during extraction. Even this depth of soil was sufficient to hold the tip and pull off some of the previously damaged section, as seen in Fig. 10 and 11. Some further comments are appropriate. Note that even though pile 520-B was badly buckled and probably was shortened by at least 3 ft, it still carried a static load of 354 kips which is associated with a stress of 28.5 ksi. The smallest failure stress was 8.6 ksi but that pile was further loaded to a stress of 12.4 ksi prior to discontinuing the test. Damage of the type shown in Fig. 4 did not affect the pile capacity.

## Soft Shale in West Cleveland

The soil at the second site graded gradually from a dense sandy silt to a decomposed shale that increased in strength with depth. The general procedure used in driving and testing was the same as at the Sandusky site. It was not possible to obtain exactly the same hammers. The Delmag D-15 replaced the Kobe K-13 and the Delmag D-5 was added. A Link Belt 440 was used in restrike testing.

In the soil of this site driving was quite different. All piles refused without any sign of damage except for one pile that was damaged at the top, probably due to hammer misalignment. A summary of the piles driven is given in Table II.

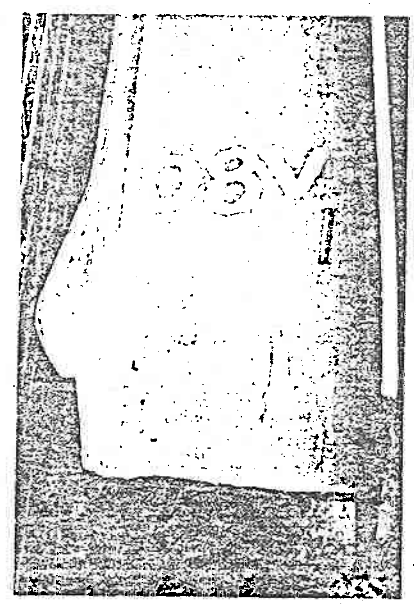


FIGURE 8 Sandusky Pile 08-V

FIGURE 9 Sandusky Pile 08-B

FIGURE 10 Sandusky Pile K13-V


FIGURE 11 Sandusky Pile K25-B

The results of the static load tests were surprising in that the piles that penetrated the shale carried much smaller loads than expected. The static capacities for all piles driven with the 9B3 and the D-5 showed excellent agreement between static capacity and Case Method prediciton. For all of the others the static capacities, measured about two weeks after driving, were substantially smaller. Two of the load test piles 520-V and 08-V were restruck shortly after completing the static load tests using a Link Belt 440 hammer. The Case Method Capacities obtained were substantially smaller and in good agreement with the statically measured values.

At Cleveland, as at the Sandusky site, the attempt was made to pull all piles. All but one, the K25-B were extracted. There was no damage except the more heavily driven piles had their flanges warped out as shown in Fig. 13. This phenomenon only appeared on the piles driven with the large hammers and not at all on those piles with tips. Apparently the flange warping did not affect the pile static capacity.

## CONCLUSIONS AND RECOMMENDATIONS

In this brief paper it is not possible to present and discuss the results thoroughly. However, the conclusions and recommendations will be presented without the detailed support. The reader having a deeper interest should refer to Reference 1.

1. The Case Method instrumentation provides a reliable, accurate means of measuring force and acceleration at the pile top during hammer blows.



The measurements are easily made and require only a s[illegible]ruption of the contractor's operation.

2. The Case Method capacity shows good agreement [illegible] the pile's static capacity at the time of dynamic tests. If no significant soil changes with time occur, dynamic predictions at the time of initial driving agree well with the static load tests. If soil changes with time are expected then comparisons of static testing should be made with dynamic testing by restriking the pile after a sufficient waiting period.
3. Setup or relaxation effects can be observed by dynamic testing both during initial driving and also after various wait times in a restrike application.
4. Measurements of force and velocity can be used to detect and determine the location of structural pile damage. This can be most useful for pile types where visual inspection is not possible.
5. The Case Pile Wave Analysis Program (CAPWAP) procedure can be used to obtain the locations of resistance forces and to separate the static and dynamic resistances using dynamic pile top measurements only. CAPWAP can also be used to investigate problems with driving stresses at locations other than the pile top.
6. Standard Wave Equation analysis programs such as WEAP (Wave Equation Analysis of Pile Driving) which contain realistic hammer models can be used effectively to investigate pile driving problems. The Wave Equation analysis is even more accurate when the correct soil parameters as determined by CAPWAP are available. Comparisons of Wave Equation results with force-velocity measurements are necessary to verify that the hammer-capblock-helmet-cushion system is performing as modelled in the analysis. Improper hammer performance, incorrect cushion or capblock properties and inaccurately assumed soil parameters are the main reasons why Wave Equation results are often in error.

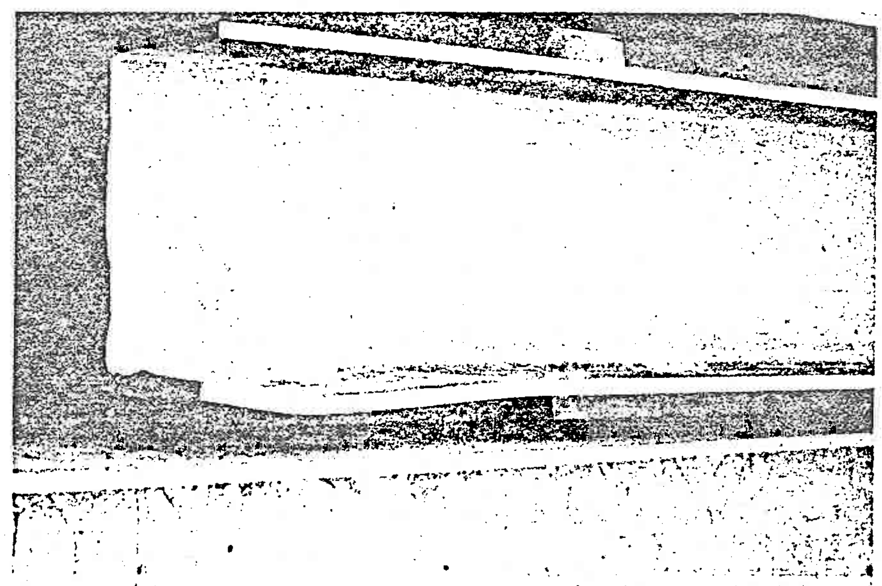

FIGURE 12 Sandusky Pile K25-E

TABLE II

HAMMERS AND PILES - SOFT SHALE AT CLEVELAND

| HAMMER | RATED ENERGY FT-LBS | RAM WEIGHT LBS | PILE | APF PILE TIPS | APPARENT FINAL PENETRATION | CAPACITY KIPS CASE METHOD | CAPACITY KIPS STATIC |
|---|---|---|---|---|---|---|---|
| MKT 9B3 | 8,750 | 1600 | 9B3-V* | No | 16' - 5" | 152 | 160 |
| | | | 9B3-P | Yes | 16' - 6" | 170 | 168 |
| | | | 9B3-B | No | 17' - 5" | | |
| D5 | 9,100 | 1100 | D5 -V | No | 16' - 5" | 146 | 141 |
| | | | D5 -P | Yes | 15' - 2" | 123 | 124 |
| | | | D5 -B | No | 15' - 10" | 81 | |
| Link Belt 520 | 30,000 | 5070 | 520-V | No | 17' - 4" | 282 | 184 |
| | | | 520-P | Yes | 17' - 3" | 302 | |
| | | | 520-B | No | 17' - 10" | 295 | |
| Vulcan 08 | 24,000 | 8000 | 08 -V | No | 17' - 7" | 380 | 240 |
| | | | 08 -P | Yes | 18' - 3" | 395 | |
| | | | 08 -B | No | 18' - 1" | 363 | |
| D15 | 27,100 | 3300 | D15-V | No | 17' - 3" | 332 | 194 |
| | | | D15-P | Yes | 18' - 3" | | |
| | | | D15-B | No | 18' - 5" | 371 | 197 |
| K25 | 50,700 | 5510 | K25-V | No | 18' - 9" | 501 | 264 |
| | | | K25-P | Yes | 19' - 1" | | 317 |
| | | | K25-B | No | 19' - 0" | 481 | |
| RESTRIKE Link Belt 440 | 18,200 | 4000 | 520-V | | | 213 | 184 |
| | | | 08 -V | | | 224 | 240 |

* Add VBP from Table I



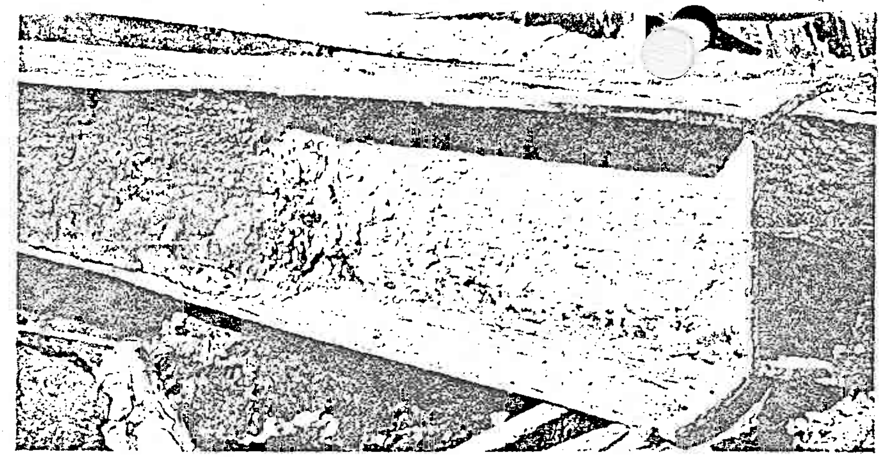

FIGURE 13 W92 Pile K25-V

7. All piles driven to the hard limestone were at one time capable of supporting loads similar in size to the pile yield load. These maximum pile capacities were observed by either Case Method testing or by static load tests.

8. Continued driving in the attempt to obtain several inches of penetration into the hard rock only led to structural pile damage, confirmed by electronic measurements and pile extraction. This structural damage was sometimes responsible for large reductions in load capacity.

9. Larger hammers (08, K25) clearly damaged the Sandusky piles before the 20 BPI (blows per inch) 1972 Ohio DOT driving specification was satisfied. If piles were not excessively driven (08V where driving was stopped early due to local top damage or K25VE which was stopped intentionally after only one blow on rock) then good static load test performance was achieved.

10. Pile tip protection prevented tip damage at the hard rock site. Piles then failed structurally above ground in gross column buckling during driving. This above-ground column failure did not adversely affect the compressive static load test capacity.

11. Best results for driving piles at the Sandusky site would not follow a blow count criteria. Blows per inch is meaningless since real rock penetration was not achieved. The blows per inch gave only an indication of how effective the hammer was in damaging the pile structurally. Driving beyond 30 BPI for the 520 and K13, and beyond 6 BPI for the 08 and K25; for one inch was an invitation for structural pile damage.

12. The dynamic field instrumentation did an excellent job in Sandusky of determining when the pile first had sufficient capacity or when the pile was being damaged.

### Different in Weathered Shale

13. For the rock condition of weathered shale gradually becoming more firm with depth, it was found that the largest pile capacities were obtained from the deepest pile penetrations. Similarly, the lowest capacities corresponded to the shallowest penetrations.

s...ller hammers before the 20 BPI 1972 specification was satisfied. Th... ...ven by larger hammers also had higher capacities.

...e largest hammers (K25 and 08) damaged the pile tops at the Cleveland test site before the 1972 driving criteria of 20 BPI was achieved.

16. Although no pile tip sustained severe structural damage which would reduce load test capacity, the flange tips of several of the piles were spread apart. This flange distortion was largest for the large hammers (or largest pile penetrations).

17. While capacities at the end of driving were adequate at W92 for a 9 ksi design and safety factor of 2.0 except for piles driven by the D5 and 9B3, static testing two weeks later revealed a signicant loss in static capacity. At this time only the piles driven by the 08 and K25 still had sufficient capacity.

18. Dynamic testing on restrike at W92 of the 520V and 08V piles after the static tests also showed a loss of capacity since the time of initial driving. Comparison of the CAPWAP analyses for these piles reveals that the loss of capacity was due to resistance losses in the shale. A small set up resistance was observed in the solid overburden.

19. Due to the substantial strength loss with time in the shale at W92, piles driven by the 520 and D15 also no longer met the design load with a safety factor of 2.0.

20. In every case at W92, the 1972 driving specification was not satisfied. Either the piles had insufficient static capacity for the 9 ksi design load and a safety factor of 2.0 (D5, 9B3, 520 and D15) or the pile was damaged due to excessive stresses before the 20 BPI was reached (08, K25).

21. Pile tip protection had little, if any, effect on static pile load performance at the W92 site. It is interesting to note that the effect of the soft rock was to prevent tip damage. It is hypothesized that since the resistance only developed gradually as the pile penetrated, the rock provided lateral restraint sufficient to prevent load buckling.

Comparisons at Hard and Soft Rock Sites

22. These two sites probably represent limiting conditions for the range of rock strengths of interest.

23. It is interesting to note that the pile stresses were substantially influenced by the rock stiffness and soil overburden. Gross buckling of the pile in the 6 to 8 ft of unrestrained column length above the ground occurred on all tip reinforced piles at the hard rock Sandusky site. No pile failed by gross buckling at the soft rock W92 site.

24. Major pile tip damage is much more likely when the rock is hard and the pile will not penetrate. Penetration into the soft rock prevents this structural damage.

25. The soil strength of the overburden is also important in determining the likelihood of damage. Large skin resistance forces tend to reduce the downward traveling compression wave with the result that the maximum force at the pile tip is reduced. This smaller tip force is less likely to cause tip damage. This was the situation at W92. Inspection of the maximum spring forces in CAPWAP shows a reduction in maximum forces with depth due to the relatively large skin friction. For the piles at Sandusky with little skin resistance, the input compression wave travels unchanged to the pile tip. If tip resistance is small, the wave reflects as tension and the net force is small at the tip. If tip resistance is large, however, the compression wave reflects in compression. The two waves superimposed are then likely to cause damage.



26. ... during load testing. At the Sandusky site the soil abo... ...ock was very soft and the rock was unusually level. Therefore, th... ...lem does not appear to be a serious one for pile design.

27. One of the primary considerations in pile design must be the magnitude of the load to be carried. If the structure loads are small, then high design stresses should not be used. It may be substantially more cost effective to use lower design stresses and more piles in some cases.

28. Based on the test results discussed here, we recommend that pile driving of H-piles to soft rock be controlled in the same manner as is the case for other pile types.

In general, load tests are unnecessary and driving can probably be governed by a formula. Hammers should be selected in the same fashion as is the case for friction piles. In unfavorable soils or other critical cases the Case Method can be used for capacity evaluation. The loss of strength of the shale at W92 should be of serious concern. Piles driven into shale should therefore be restruck with the longest possible wait time and blow counts should be measured with great care at the end of driving and the beginning of restrike. These blow counts should then provide a satisfactory construction control mechanism. For soil and rock conditions similar to Sandusky, piles could be driven with small hammers with little concern for damage. If large hammers are used, it is difficult to avoid damage at the pile tip.

For piles driven to hard rock, particularly when the overburden soils are soft, a blow count criteria is of limited usefulness. A penetration criteria may be more desirable and the use of large hammers should be carefully controlled, particularly if the piles are short. In such cases, it is more desirable to simply drive until rock is reached as identified by blow count and hammer performance. If large hammers are used, the inspector should be cautioned not to overdrive.

For hard rock, the use of tip reinforcement in the form of pile points was shown to be very effective. We recommend that they always be used on hard rock jobs.

29. Due to limited data, we cannot define the line between hard and soft rock. Until more data is available on a much broader range of rock types, this definition must remain subjective.

## ACKNOWLEDGMENTS

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*L. B. Foster, Inc. supplied the Kobe hammers. Associated Pile & Fitting Corp. furnished the Pruyn Points and the H-piles to which they were attached to supplement the tests on unprotected piles.*

*The opinions and conclusions expressed are those of the authors; they do not necessarily represent the views of the Ohio DOT or FHWA.*

1. Goble, G. G.; Likins, G.; and Teferra, W., "Pile and Pile Driving Hammer Performance for H-Pile Driven to Rock", Report No. OHIO-DOT-09-77 to the Ohio Department of Transportation, Dept. of Civil Engineering, Case Western Reserve University, November, 1977.

2. Goble, G. G.; Rausche, F.; and Likins, G., "Bearing Capacity of Piles from Dynamic Measurements, Final Report", Report No. OHIO-DOT-05-75 to Ohio Department of Transportation, Dept. of Solid Mechanics, Structures and Mechanical Design, Case Western Reserve University, March, 1975.