TESTS ON H-PILES DRIVEN TO ROCK

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In 1952 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 the effects of the change 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 hard rock (Sandusky) and the other a moderately dense overburden grading into a soft rock that became harder with depth (Cleveland). A soil profile for each site is given in Fig. 1 and 2.

A variety of hammers were used at each location and pile driving attempted to satisfy the 20 BPI criteria. During driving extensive dynamic measurements were made. After completion of driving most of the piles were load tested statically and all were 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	SPT Blows/6"	Plasticity Index	Unconf. Shear Strength	Compression Stress
				(ksf)	(ksi)
0	Top Brown Soil				
		2,3,6			
5	Clayey Silt				
			10	2.75	
10					
		2,2,3			
			11	2.59	
15	Clayey silt with few rock fragments		12	0.68	
		2,5,7		8.4	
20	Clay, silt with gravel				
					7.4
		16,24, 40			7.6
25	Hard Limestone				4.1

Figure 1 Soil Profile, Sandusky

Depth in Feet	Descrip- tion	SPT Blow/6"	Plasti- city Index	Unconf. Shear Strength	Compres- sion Stress	Silt %	Clay %
0				(ksf)	(ksi)		
	Br. & Gray Clay		7	8.64		42	58
5		5,9,12	6				
	Clay/Rock Fragments		11	10.02		36	64
	Silt Clay	6,10,15	7				
10							
	Silt Clay		12			90	10
	Gray Clay	3,5,10	7			95	5
15							
	Hard Clay to Clay Shale	50/4'	7				
	Weathered Clay Shale						
					1.2		
20	Clay Shale						
					2.2		

Figure 2 Soil Profile, West Cleveland

Sandusky Tests - Driving to Hard Redrock

All of the test piles were 10HP42. This section was selected such 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 points were driven with each hammer except the MKT 9B3. The 9B3 was not used for the piles with points since the hammer was so small that tip damage was not considered possible. One additional pile was driven by the Kobe K-25. This pile, designated K25-VE, was driven plumb without tip reinforcement to attempt to drive an unreinforced pile with a large hammer without inducing damage. The hammer was immediately shut down when it was observed that the tip had reached rock. Pile 08V was locally damaged at the pile top due to poor hammer alignment shortly after reaching rock; driving was discontinued.

During driving, blow count was recorded as well as complete set-rebound records and for diesel hammers stroke or bounce chamber pressure. In addition, force and acceleration was measured at the pile top and processed by the Pile Driving Analyzer. Analog records of each hammer blow were recorded on magnetic tape. The transducers and recording system 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 in Table I.

FIGURE 3 Case Method Pile Driving Analyzer and recording system with transducers on the pile (foreground left)

TABLE I: HAMMERS AND PILES AT SANDUSKY

Hammer	Rated Energy ft-lbs	Ram Weight lbs	Pile	Apparent Penetration	Capacity Kips	
					Case Method	Static
MKT 9B3	8,750	1600	9B3-V**	22' - 4"	128*	386***
			9B3-B	22' - 11"	239*	400
Link Belt 520	30,000	5070	520-V	26' - 2"	141	120
			520-P	22' - 1"	423	410
			520-B	24' - 11"	316	354
Vulcan 08	24,000	8000	08 -V	22' - 2"	443	362***
			08 -P	22' - 0"	439	
			08 -B	26' - 4"	186	151
Kobe K-13	24,000	2870	K13-V	24' - 6"	157	154
			K13-P	21' - 10"	416	
			K13-B	22' - 10"	346	350
Kobe K-25	50,700	5510	K25-V	25' - 10"	160	231
			K25-P	22' - 2"	435	
			K25-B	25' - 10"	336	350
			K25-E	20' - 6"	462	414***

*Hammer too small to overcome quake and mobilize the full static capacity during dynamic tests; **V pile driven vertically, B pile at 1:4 batter (no point protection) P pile with Associated Pile & Fitting Corp Pruyn Point 75600 or 75750 driven vertically; ***Failure was not reached in load test.

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

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 protective pile points, the bottom of the pile promptly buckled and further apparent penetration of the pile was due to additional pile damage. The amount that the piles were shortened can be determined by subtracting the overburden soil depth of about 22 feet.

During driving, the performance of all piles with tips was the same. Shortly after reaching rock the portion of the pile extending above the ground failed in gross column buckling. Of course, these buckled pieces were removed before performing the load tests.

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. 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 5, 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 9.6 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 Figure 4 did not affect the pile capacity.

FIGURE 4 Sandusky Pile 9B3-V

FIGURE 5 Sandusky Pile 520-V

FIGURE 6 Sandusky Pile 520-P

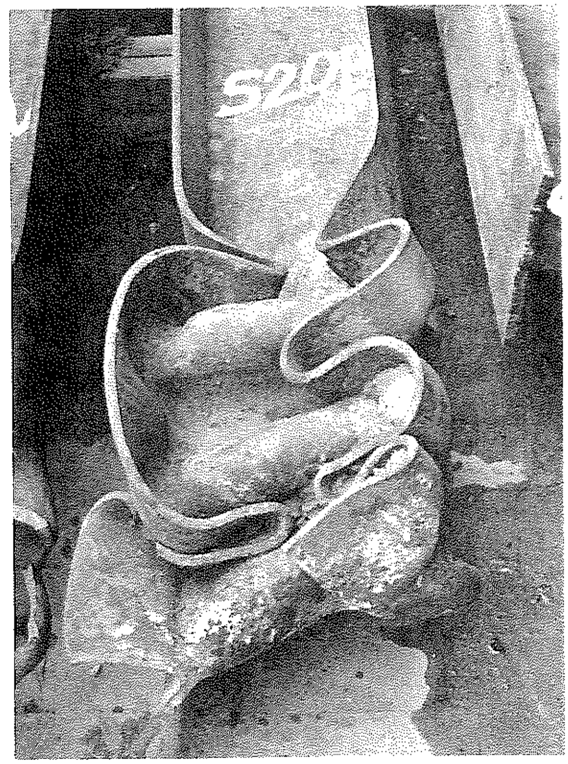

FIGURE 7 Sandusky Pile 520-B

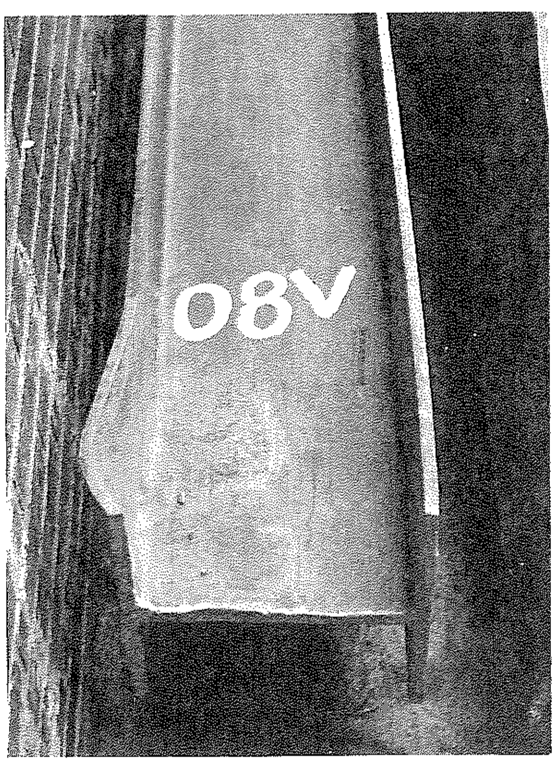

FIGURE 8 Sandusky Pile 08-V

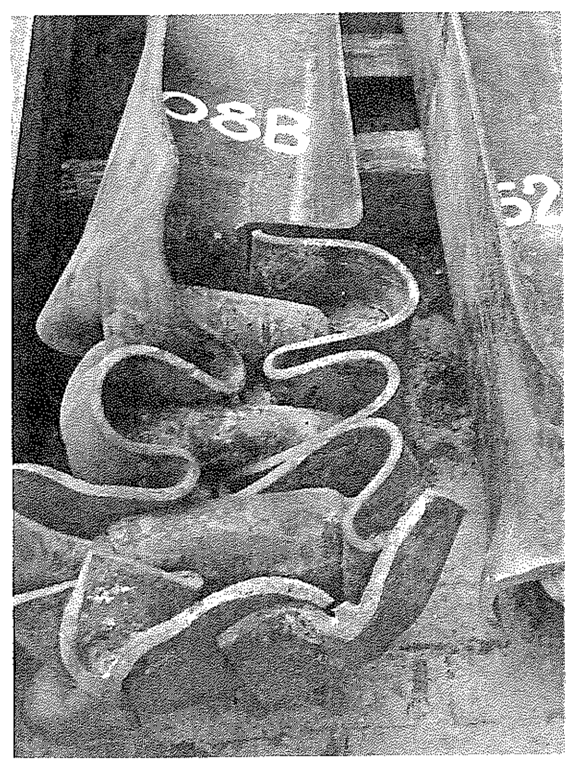

FIGURE 9 Sandusky Pile 08-B

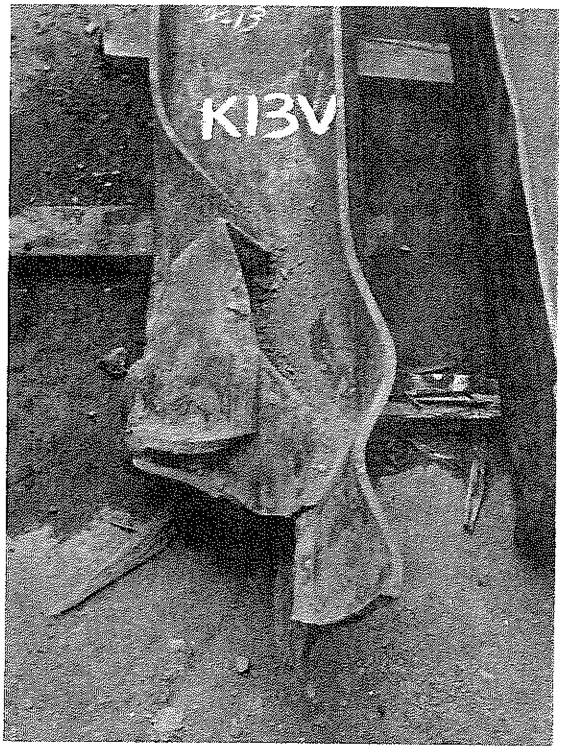

FIGURE 10 Sandusky Pile K13-V

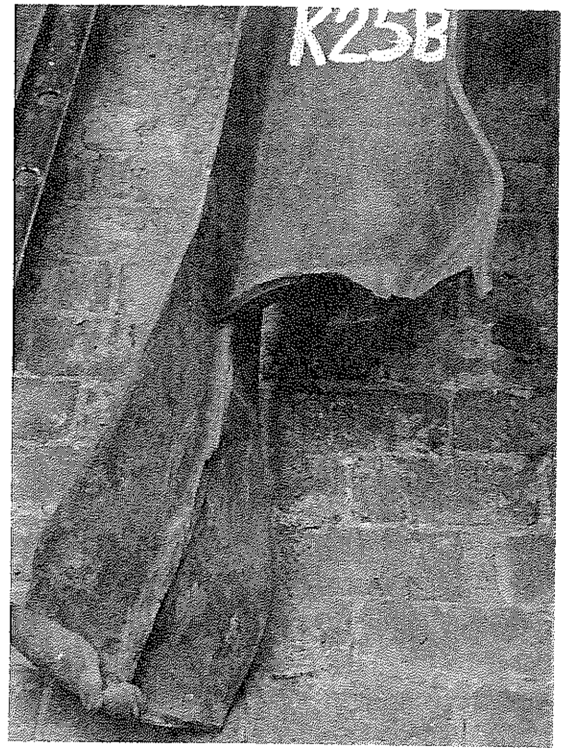

FIGURE 11 Sandusky Pile K25-B

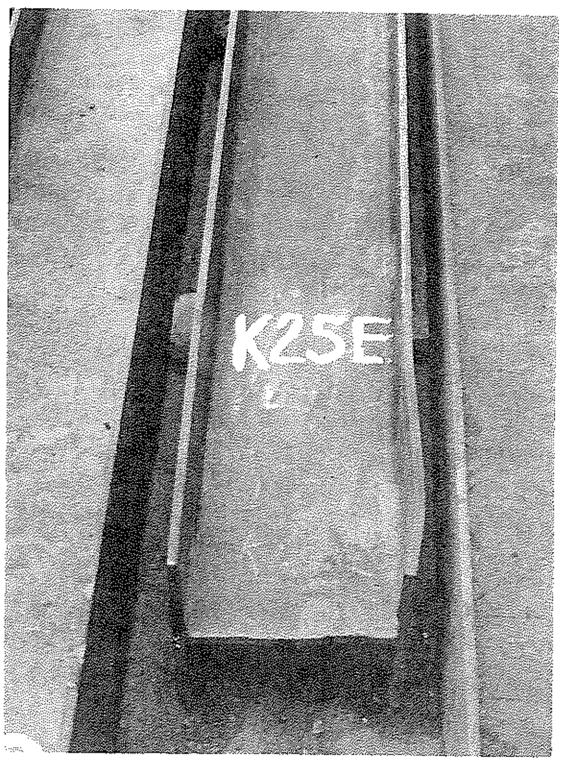

FIGURE 12 Sandusky Pile K25-E

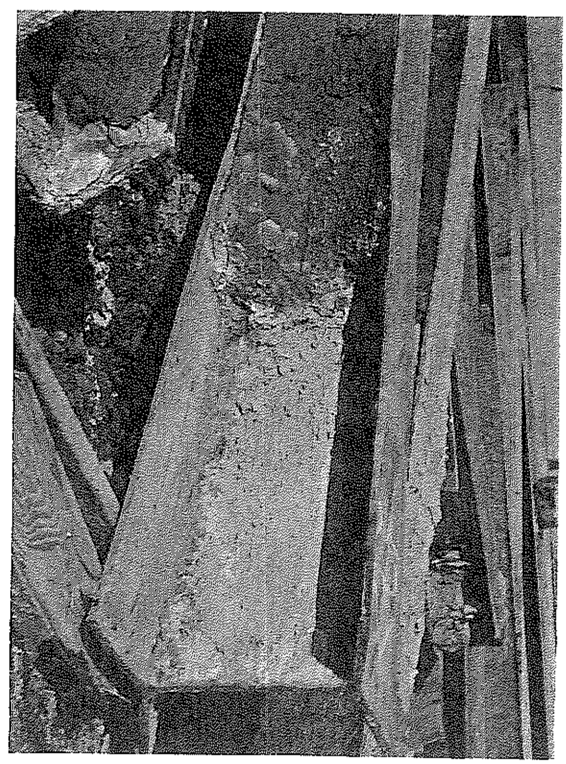

FIGURE 13 Cleveland Pile K25-V

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. Most piles reached 20 BPI without any sign of damage. Four piles (D15P and all K25 piles) were damaged at the top before refusal criteria was reached. A summary of the piles is given in Table II.

TABLE II: HAMMERS AND PILES - SOFT SHALE AT CLEVELAND

Hammer	Rated Energy ft-lbs	Weight lbs	Pile	Apparent Penetration	Capacity Kips	
					Case Method	Static
MKT 9B3	8,750	1600	9B3-V*	16' - 5"	152	160
			9B3-P	16' - 6"	170	168
			9B3-B	17' - 5"		
Delmag D5	9,100	1100	D5 -V	16' - 5"	146	141
			D5 -P	16' - 2"	123	124
			D5 -B	15' - 10"	81	
Link Belt 520	30,000	5070	520-V	17' - 4"	282(213**)	184
			520-P	17' - 3"	302	
			520-B	17' - 10"	295	
Vulcan 08	24,000	8000	08 -V	17' - 7"	380(224**)	240
			08 -P	18' - 3"	395	
			08 -B	18' - 1"	363	
Delmag D15	27,100	3300	D15-V	17' - 3"	332	194
			D15-P	18' - 3"		
			D15-B	18' - 5"	371	197
Kobe K25	50,700	5510	K25-V	18' - 9"	501	264
			K25-P	19' - 1"		317
			K25-B	19' - 0"	481	
RESTRIKE Link Belt 440	18,200	4000	520-V		213	184
			08 - V		224	240

*V pile driven vertically, B pile at 1:4 batter (no point protection);
P pile with Associated Pile & Fitting Corp. Pruyn Point 75600 or 75750 driven vertically.
**Restrike

The results of the static load tests were surprising because the piles carried much smaller loads than expected. The static capacities for all piles driven with the 9B3 and the D-5 which penetrated only the upper portions of the weathered shale, showed excellent agreement between static capacity and Case Method prediction. For all of the others, the static capacities, measured about two weeks after driving, were substantially smaller than capacities measured by the Case Method during driving. 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 then were substantially smaller and in good agreement with the statically measured values indicating a relaxation effect in the shale.

At Cleveland, as at the Sandusky site, all piles were extracted. There was no major damage; 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. Apparently the flange warping did not affect the pile static capacity. No significant difference was observed at the Cleveland site between capacities of piles with and without points.

CONCLUSIONS AND RECOMMENDATIONS

In this brief paper it is not possible to present and discuss all test procedures and 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 short interruption of the contractor's operation.
2. The Case Method capacity shows good agreement with the pile's static capacity at the time of dynamic tests. If soil strengths do not change after driving piles, dynamic predictions at the time of initial driving agree well with the static load tests. If soil strength 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 during initial driving and then after various wait times in a restrike operation.
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) uses dynamic pile top measurements to obtain the locations of resistance forces, and to separate the static and dynamic resistances. CAPWAP can also be used to investigate problems with driving stresses at locations other than the pile top.
6. Wave Equation analysis programs such as WEAP (Wave Equation Analysis of Piles) which contain realistic hammer models can be used effectively to investigate pile driving problems. The Wave Equation analysis is more accurate when the correct soil parameters as determined by CAPWAP are available. Comparisons of Wave Equation results with dynamic force-velocity measurements are necessary to verify that the hammer-capblock-helmet-cushion system is modeled correctly in the analysis. Incorrect input concerning hammer performance, cushion or capblock properties, and inaccurately assumed soil parameters are the main reasons why errors are caused in Wave Equation results.
7. All piles driven to the hard limestone were at one time capable of supporting loads approximately equal 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 20 BPI (blows per inch) for the last five inches of penetration into the hard rock causes 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 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 bedrock site. Piles then failed structurally above ground in gross column buckling during driving. This above-ground column failure (which was removed prior to static testing) 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.

14. Large hammers produced larger pile penetrations in the shale than small hammers when complying with the 20 BPI 1972 specification. Thus, piles driven by larger hammers also had higher capacities.

15. The 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. The greatest flange distortion was caused by the large hammers.

17. The capacities of piles driven by the 520, D15, 08 and K25 at the end of driving were adequate at the Cleveland site for a 9 ksi design and safety factor of 2.0; the static tests two weeks later revealed a significant loss in capacity. At the time of static testing only the piles driven by the 08 and K25 still had sufficient capacity.

18. The piles driven by the D5 and 9B3 had ultimate capacities at the end of driving and during static testing that were insufficient for a 9 ksi design with a safety factor of 2.0.

19. Dynamic Case Method testing by restrike at Cleveland 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 soil overburden.

20. In every case at Cleveland 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 Cleveland site. The soft rock prevented tip damage. Since the resistance developed gradually as the pile penetrated the rock, the lateral restraint was sufficient to prevent buckling of the pile tip.

Comparisons at Hard and Soft Rock Sites

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

23. 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 Cleveland site.

24. Major pile tip damage is much more likely when the rock is hard and the pile will not penetrate. Penetration into 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 Cleveland. 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. These two compression waves, when superimposed, are then likely to cause damage.

26. There was no evidence of lateral motion of the tips of the batter piles during load testing.

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 due to pile cap costs.

28. Based on the test results 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 when driving 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 the Cleveland site should be of serious concern. Piles driven into shale should be restruck after an adequate waiting time and blow counts should be carefully determined at the end of driving and compared with the blow counts at the beginning of restrike. These blow counts should 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. When large hammers are used care should be taken not to overdrive the pile. For hard rock the use of tip reinforcement in the form of pile points was effective. We recommend that they always be used when piles are to be driven to hard bedrock.

29. Due to limited data, we cannot define the line between hard and soft bedrock. Until more data is available, a definition remains subjective.

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

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