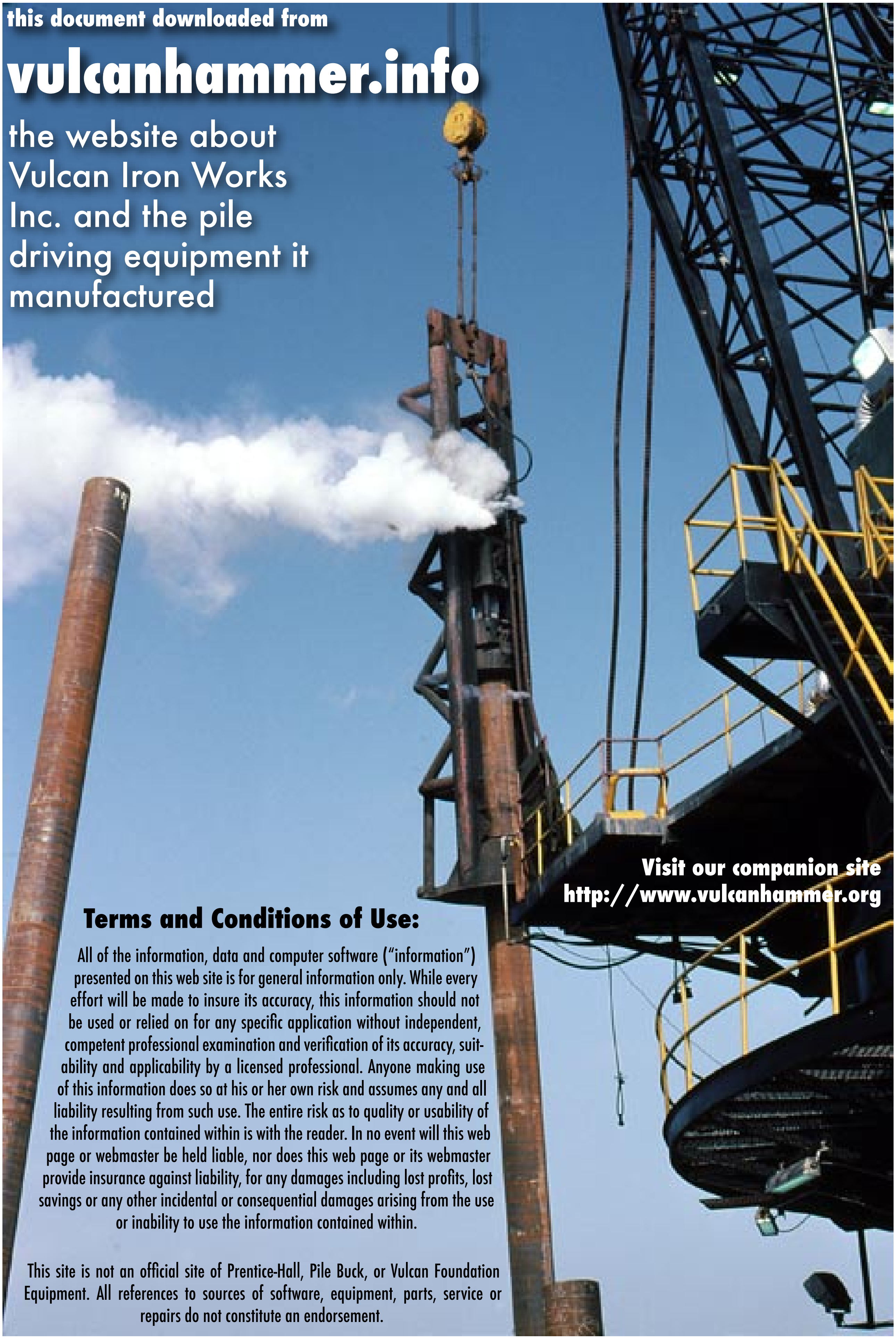

52

SELECTION OF MINIMUM COST PILE DRIVING SYSTEMS

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INTRODUCTION

The estimation of pile driving costs remains today a very inexact activity not greatly changed over the past half century. Contractors tend to limit their work to a particular geographical region relying on equipment of a familiar type. If a job must be estimated, the contractor will usually depend more on previous experience than on anything revealed by normal subsurface investigations. Equipment selection is usually made on a completely subjective basis with emphasis placed on the use of driving systems owned by the contractor.

If difficulty occurs on the job and the piles cannot be efficiently advanced, the typical result is quarrels between the contractor and the engineer, large cost overruns and litigation. To avoid these problems, engineers have sometimes tended to specify the job more tightly. Commonly, however, due to the engineer's lack of knowledge of pile driving, he specifies a condition that cannot be driven. Now the contractor is in an excellent position to obtain extra payment.

In the past decade techniques have become available that can convert this very artistic approach to a scientific one. It is possible today for a contractor to make rational predictions of driving resistance. These predictions, while still of limited reliability, are at least better than any other available approach.

. Pile driving costs can be categorized in several activities including: mobilization, system testing and modification, dead times (that time when the hammer is not running) and hammer time. All but the last of these subdivisions will be quite dependent on the characteristics and size of a particular job and the manner in which the contractor organizes his operations. They can be estimated using current procedures. The cost of the system testing and modification phase will be strongly dependent on the driving system selected. If it is the correct one, it is likely that the cost will be much less. Substantial cost savings can be achieved by efficient organization of the job. In fact, the greatest savings may be possible here by reducing dead time. The one part of the cost that can now be rationally estimated is hammer time and that part of the estimating process will be emphasized in this paper.

A procedure will be presented here for pile driving cost estimation. This procedure will be illustrated by applying it in a hypothetical example. It will be seen that important aspects of hammer characteristics are very effectively illustrated. The purpose of this paper, however, is to present a *procedure* for cost estimation and no general conclusions about driving system efficiency should be drawn from the example presented.

Estimating Procedure

For the purpose of this illustration all mobilization and system testing and modification costs will be neglected. Clearly this is not realistic but in dealing with a hypothetical case it is difficult to do better in any realistic fashion. In addition, the effects of equipment ownership and previous partial or full depreciation will be ignored. The equipment costs used will be straight rental cost. A more realistic treatment can be accomplished by a simple modification of the procedures presented here when job particulars are known.

Since only daily cost and productivity are considered, only two of the cost categories given above will be present, hammer time and dead time. The latter category is clearly a very important one in controlling costs. Contractors should devote great effort to minimizing it. It includes such time as equipment maintenance and repair, coffee, clean up, start up, crane moving and the time required to put the pile under the hammer, align the system and start the hammer.

The job operation should be carefully scheduled so that the piles are placed near where they are to be driven so that they can be quickly put under the hammer. Careful study of the operation from hammer shut-down to start-up can usually produce time savings. For the example treated here it is impossible to make a meaningful evaluation of this activity. It is probably quite independent of the hammer system used and that is the basic question being examined. The assumption was made that only seven hours were available per shift and that a total of ten minutes would elapse between hammer shut-down and start-up.

Finally, the principal problem of this paper—hammer time—must be estimated. It is assumed that soil borings of the usual type will be available. As a first step pile driving equipment and procedures will be selected. For each candidate driving system wave equation analyses will be made at various depths to determine the total number of hammer blows required to drive the pile.

Wave equation programs have been generally available since the early work of Hirsch and Lowery and their associates at Texas A. and M. University (Ref. 1). These developments produced a public domain program that began to receive selected use about 15 years ago. It is surprising that a more widespread usage did not develop. Probably this was due to a lack of knowledge of driving system parameters, a lack of confidence in the soil parameters and a poor performance of this program when analyzing diesel hammer systems. Other public domain wave equation programs did not perform substantially better.

Recently a new wave equation program was developed by Rausche and the first author under contract with the Federal Highway Administration (Ref. 2). This program, known as WEAP, offers several important advantages over other available programs, particularly in analyzing diesel hammers. The total operating cycle including precompression, combustion, expansion and stroke has been modeled. Thus, stroke for single-acting hammers and bounce chamber pressure for double-acting hammers is obtained as an output. Proper impact velocities and operating speeds are obtained. In addition, the program performance has been extensively checked against the measurements made during the piling research project at Case Western Reserve University (Ref. 3). Its ability to predict driving stresses has been extensively tested. Of course, this program is subject to some of the weaknesses in the soil model that have been known for other wave equation programs. The soil model is clearly quite limiting and it is sometimes difficult to determine the proper constants from available soil data.

Predicted driving records can be produced for each candidate driving system and from this the total required number of hammer blows. With the speed of operation, the hammer time can be determined. Now additional equipment can be selected to complete the system. One additional weakness in this study occurs here in that it is difficult to select a required acceptable crane operating radius. Obviously, driving cost will be affected by the crane radius. In such an example as this it must be rather arbitrarily chosen.

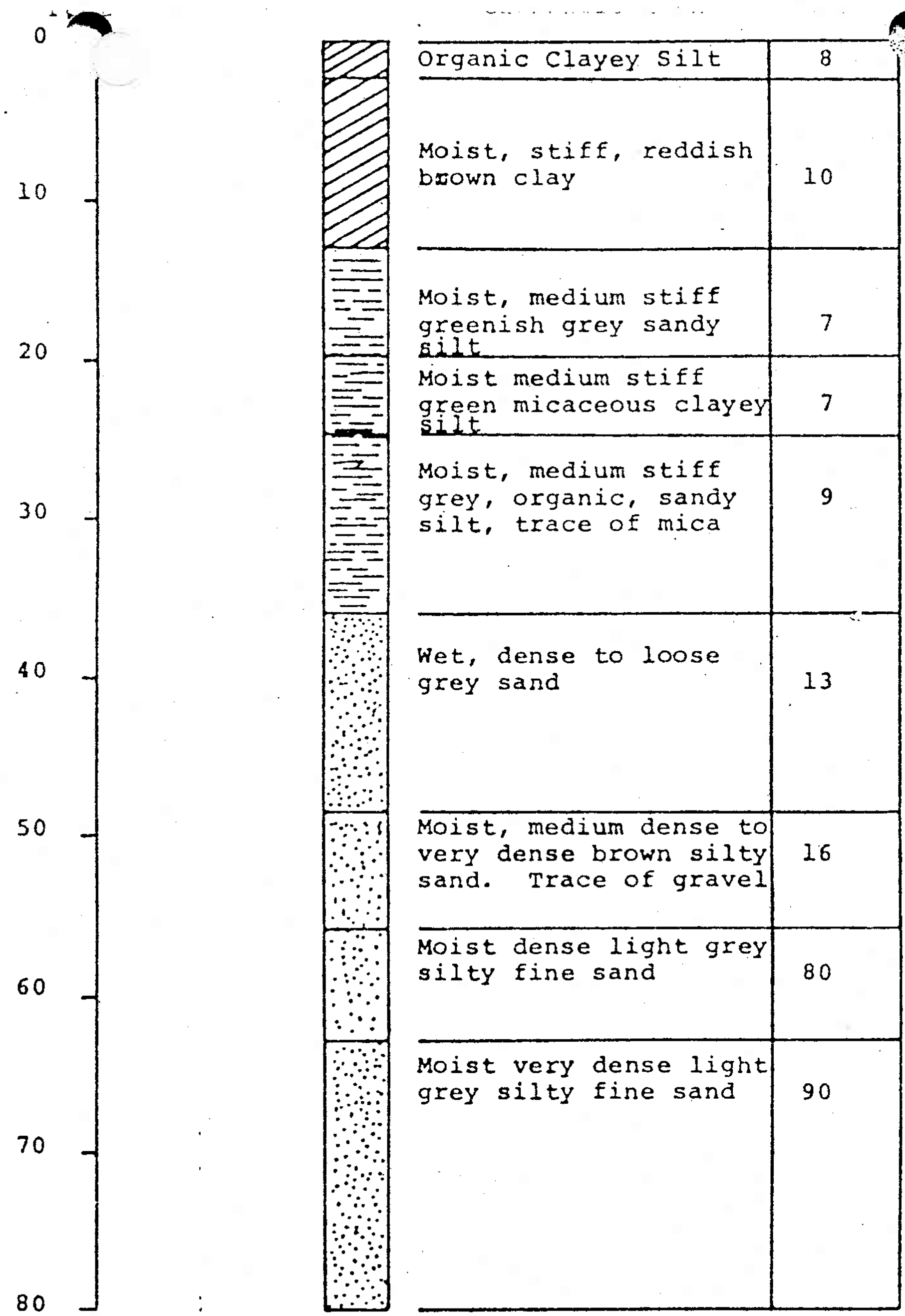
Direct costs are calculated based on equipment rental costs and crew costs. Overhead and profit have been neglected since this should be a factor on the above expenses and was assumed independent of the driving system used. It may be that overhead is more dependent on labor than equipment cost and if this is the case some changes would result in relative costs. With a knowledge of system productivity and cost, a cost per pile can be determined and the least costly system selected.

Example Problem

An example was selected from available job information. The pile to be driven was a 12 3/4 in. diameter pipe with a wall thickness of 0.375 in. The pile was to be driven to a design capacity of 100 tons with a factor of safety of two. Thus, an ultimate capacity of 200 tons is required. The pile design indicated that the piles would be 65 ft in length and that a typical soil boring was as indicated in Fig. 1. A bearing capacity analysis indicated that at a depth of 65 ft a capacity of 222 tons should be reached. Therefore, the contractor should use care before bidding the job to determine if the pile is to be driven to depth or blow count. All wave equation analyses were made for both cases; 200 and 222 tons. It should be emphasized that a difference in two, independently performed, static analyses of only 10 percent represents very close agreement.

The performance of six driving systems was examined, three air/steam hammers and three open end diesel hammers. The air/steam hammers selected were the Vulcan 06 (19,500 ft lb), 08 (26,000 ft lb) and 010 (32,500 ft lb). Diesel hammers used were the DELMAG D-15 (27,100 ft lb), D-22 (39,780 ft lb) and D-30 (54,200-23,870 ft lb).

For the air/steam hammers the wave equation analysis proceeded to first



Soil Boring Data

Figure 1

[illegible] of 36, 48, 62.5 and 65 ft using the two static capaciti[illegible]lated at each depth. The output of the wave equation analysis for ea[illegible]ndition is blow count for the particular static capacity. By summing the blow counts at each foot penetration (area under the curve) the total number of blows required to drive the pile is obtained. The results of these analyses for each of the air/steam hammers are given in Fig. 2. It was assumed that the hammers would operate at a steady 50 blows per minute (not exactly correct since they operate slower in easy driving) so total driving time can be calculated. The curves of Fig. 3 show rate of penetration for the air/steam hammer.

For the diesel hammers a more detailed analysis must be made. Fortunately, the WEAP program produces all of the necessary information. As with the air/steam hammers the run is first calculated. Next one must determine when the hammer will start. In very easy driving with relatively light piles, diesel hammers have the weakness of refusing to start. They will operate when they have sufficient resistance. It is estimated that a stroke of 3.8 ft must be achieved in order to cause the hammer to operate

Wave equation analyses are performed and, with the WEAP program, stroke is obtained in addition to blow count and driving stresses. Successive wave equation runs are made with increasing resistance until a stroke in excess of 3.8 ft is achieved. For that portion of the driving record having strokes less than 3.8 ft it is assumed that the hammer will operate at a speed of 6 blows per minute. The crane is picking up the ram and the hammer is firing once only.

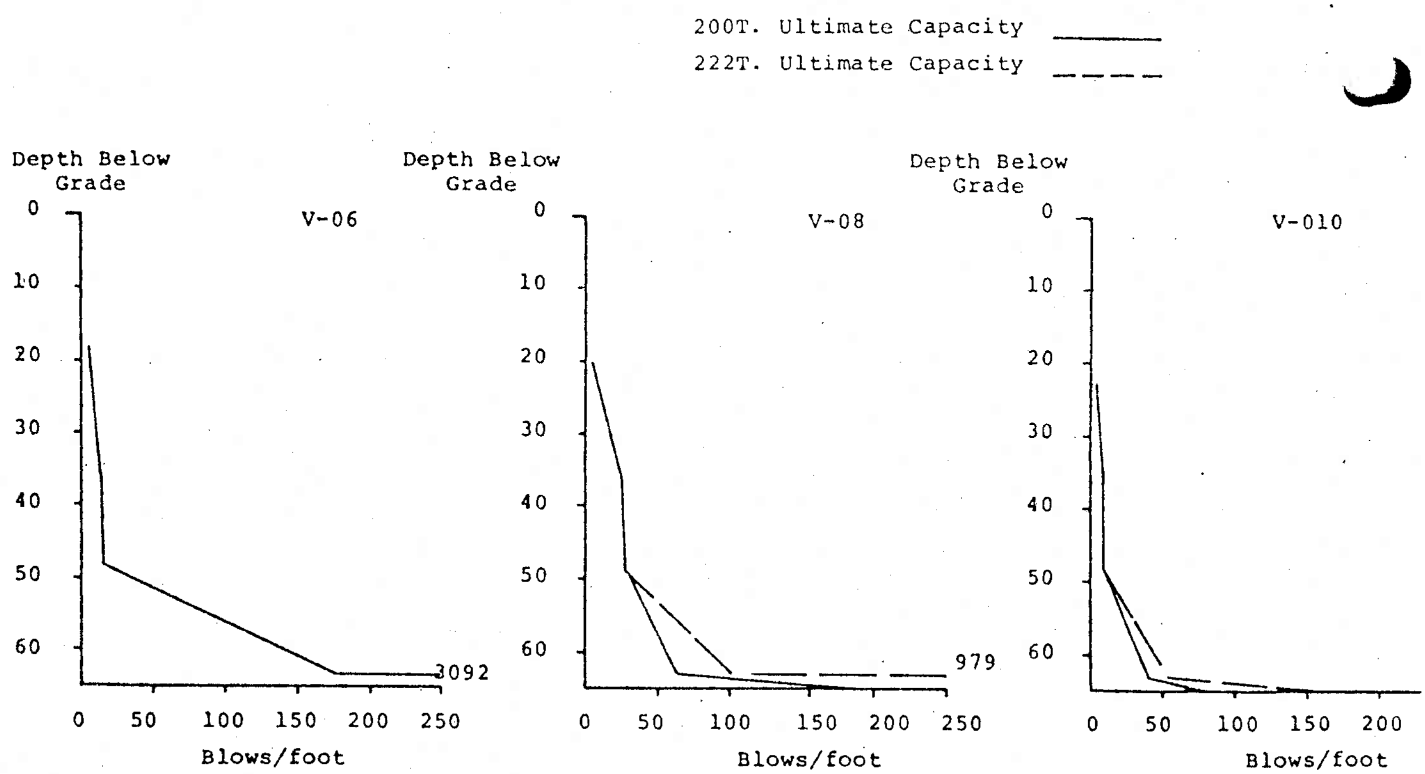
Probably this calculation is excessively conservative since if the ram fires once, more than a single blow will be achieved as the hammer "bounces down". This is at least a crude attempt to analyze performance. It is thought that this is the first attempt to determine by analysis in advance if an open end diesel hammer will operate in easy driving. The analysis should be checked with actual field performance.

After the hammer begins to operate the analysis proceeds as with the air/steam system with wave equation analyses made for various depths of penetration. In addition to determining blow count, operating speed is also found. Since stroke varies with resistance the speed of operation also varies. Both of these curves are shown for each hammer type in Figure 4.

Stresses were also checked at each analysis. A stress of 34 ksi was used as the allowable stress in dynamic loading. If this allowable stress is exceeded, the throttle was reduced by one step and the operation was repeated. By dividing the speed of operation by the rate of penetration in blows per foot, the rate of penetration in feet per minute is obtained. These curves are shown in Fig. 5. The area under the curves of Fig. 5 gives the time required to drive the pile.

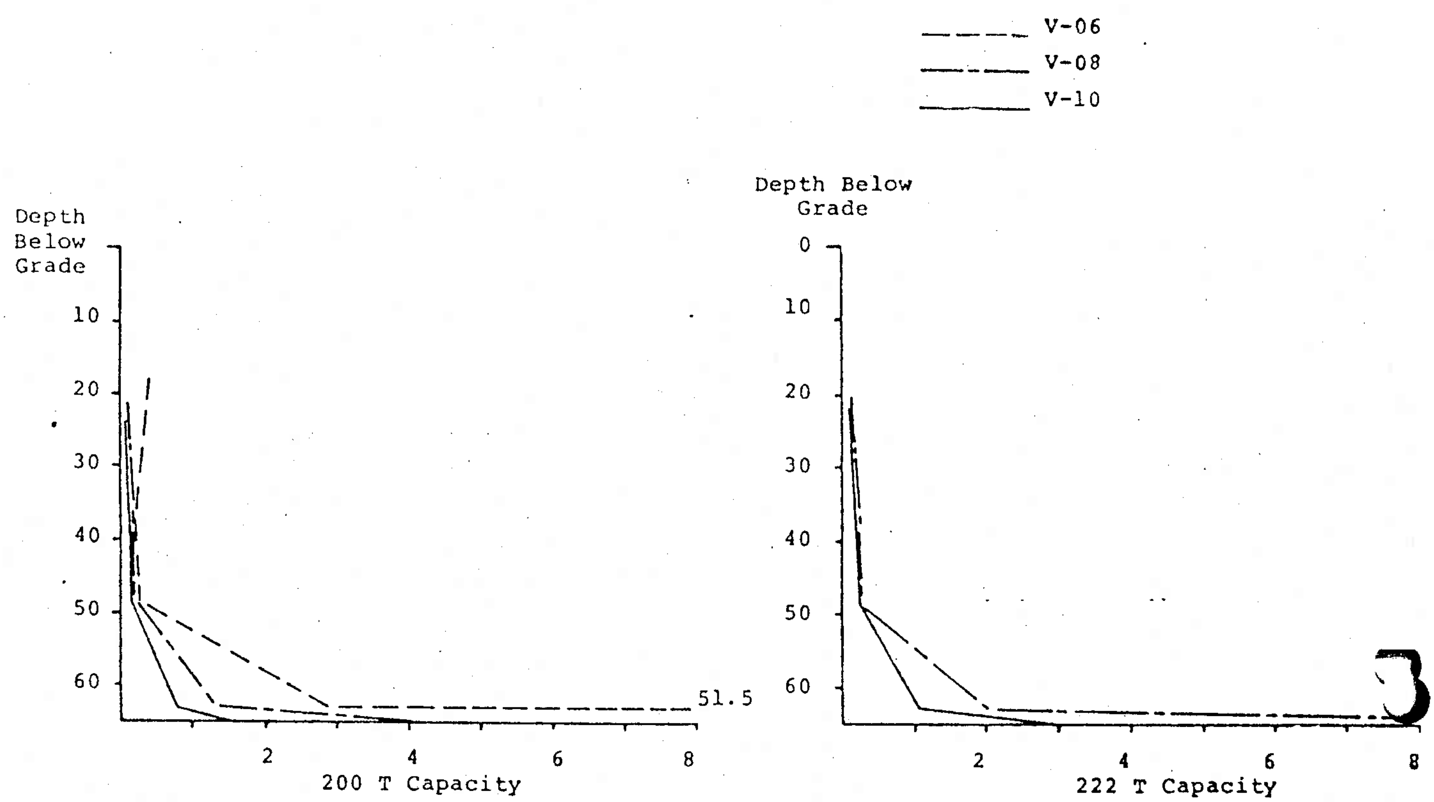
The results of these analyses give the time required to drive a pile with each hammer for both 200 and 222 tons resistances. These results are summarized in Table I. It should be noted that the Vulcan 06 hammer cannot drive the pile to the 222 ton capacity but it can achieve 200 tons although at rather high blow counts.

With the time per pile breakdown given in Table I the production rate per day can be determined. Since the start-up time for diesel hammers is not reliable and, in fact, experience would indicate that for the soil profile shown the hammer would start immediately a productivity assuming Immediate start-up was also calculated. The results are given in Table II. All values in Table II were calculated based on a seven hour day.



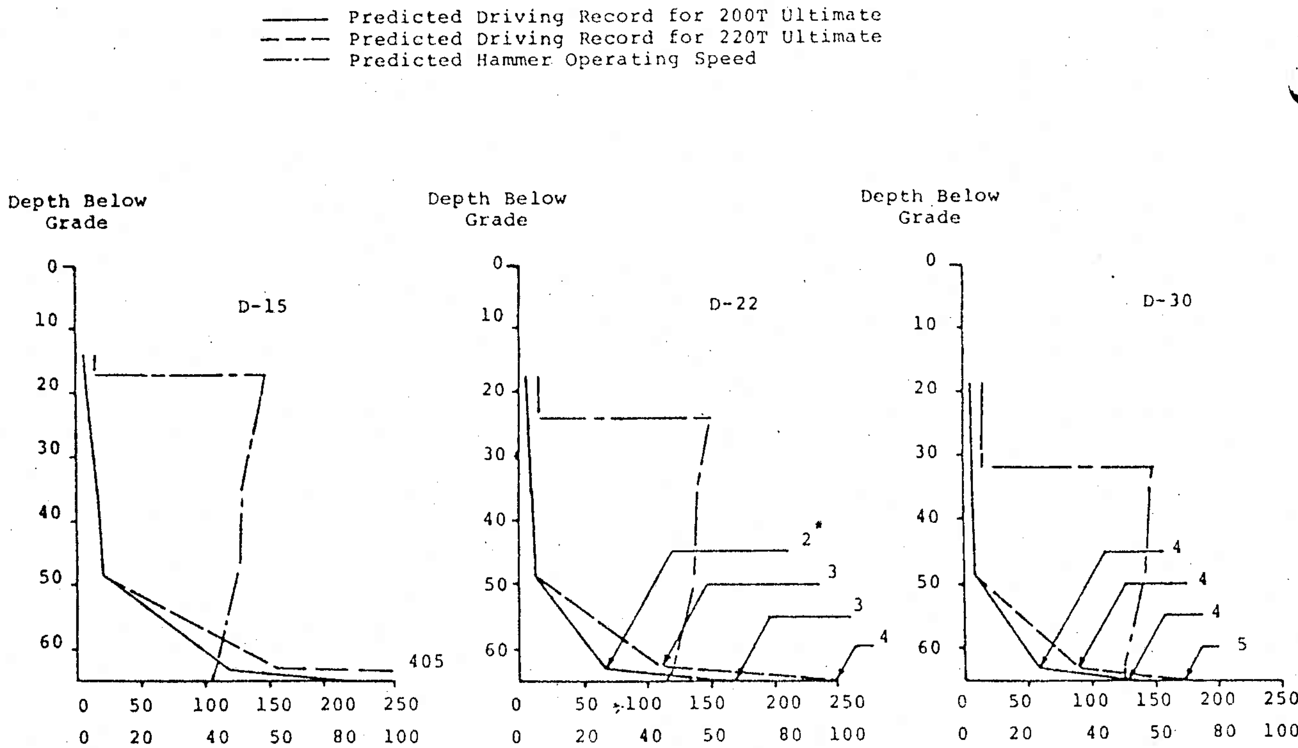
Predicted Driving Records For The Air/Steam Hammers

Figure 2



Rate of Pile Penetration for Air/Steam Hammers

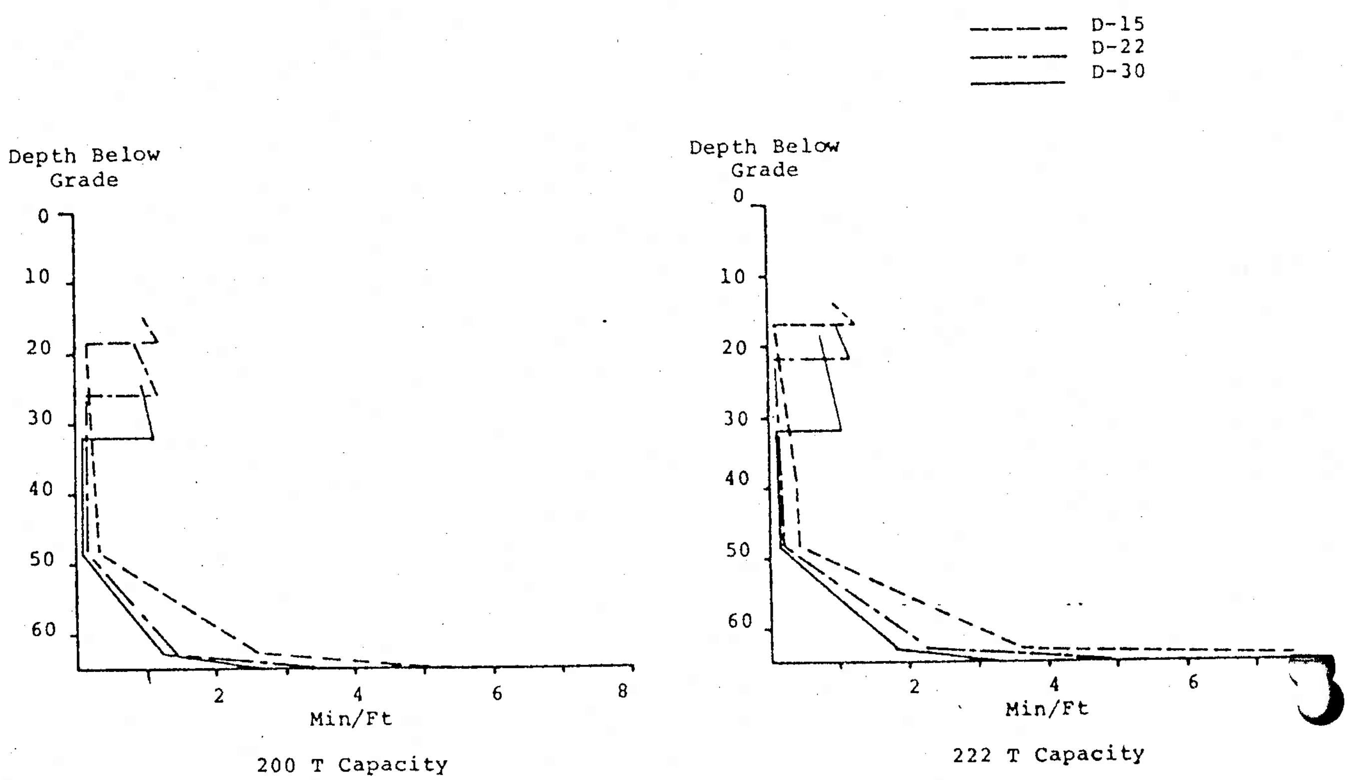
Figure 3



Predicted Driving Records for the Diesel Hammer

Figure 4

* Hammer Throttle Setting



Rate of Pile Penetration for Diesel Hammers

Figure 5

TABLE I

Breakdown of Operating Time in Minutes per Pile

Hammer	Dead Time	200T Pile Start Time	200T Pile Driving Time	200T Pile Total Time	222T Pile Start Time	222T Pile Driving Time	222T Pile Total Ti
V-06	10	0	84.1	94.1	0	∞	∞
V-08	10	0	21.6	31.6	0	45.0	55.0
V-10	10	0	13.3	23.3	0	18.4	28.4
D-15	10	3.8	35.5	49.3	3.3	51.8	65.1
D-22	10	7.5	19.3	36.8	5.5	30.0	45.5
D-30	10	7.1	14.5	31.6	12.6	22.2	44.8

System Productivity in Piles Per D

	200T	222T	200T no start-up time	222T no start-up time
V-06	4.5	0		
V-08	13.3	7.6		
V-010	18.0	14.8		
D-15	8.5	6.5	9.2	6.8
D-22	11.4	9.2	14.3	10.5
D-30	13.3	9.4	17.1	13.0

Cost calculations were divided into two parts, labor cost and equipment cost. The labor cost was calculated using standard union rates for Ohio. A crew was assumed to consist of one Foreman, four Pile Drivers, one crane operator and for the diesel hammers one oiler while for the air/steam hammers two oilers were assumed. A sample of labor cost calculations are summarized in the Appendix.

Equipment costs were all based on rental rates as given by 28th Rental Compilation for Construction Equipment. The diesel hammer rates were obtained from the Foundation Equipment Company of Newcomerstown, Ohio, and the weights of all elements in that driving system were based on the use of their leads as a swinging system. For the air/steam hammers the leads were also assumed to be swinging and to weigh 200 lbs per foot. A required radius of 30 ft was assumed for crane selection. This latter assumption is a critical one and if it is changed the results will also change. An example of equipment cost computation is given in the Appendix for the D-22 hammer.

The driving costs are summarized in Table III using the productivity based on the calculated starting time for the diesel hammers. If the starting time is neglected there are some substantial changes in costs. Using this assumption, the resulting costs are summarized in Table IV.

DISCUSSION AND CONCLUSIONS

The purpose of this paper was to illustrate a rational procedure for pile driving equipment selection. While the wave equation sometimes produces inaccurate results it is surely an improvement over a contractor's guess unless there is experience with very similar sites. It must be used with care and obviously incorrect results must be ignored. Experience has shown that it is less accurate for high blow count driving. It depends on a reliable static soils analysis and it can be quite misleading for cases where high blow counts are combined with relatively small errors in the soils analysis. For example, the case of the Vulcan 06 the pile can be driven to depth if it has a 200T ultimate capacity but if the capacity is only 10 percent higher the pile cannot be driven.

TABLE III

Example Problem Cost Summary, Calculated Diesel Start-Up Time

Hammer Type	Labor Cost Per Day	Crane Rental Cost Per Day ($)	Driving System* Rental Cost Per Day ($)	Cost Per Day ($)	Productivity Piles/Day	Cost Per Pile ($)	Cos Per F ($)
Vul 06	687.76	198.30	127.16	1013.22	4.5 (0)	225.16	3.
Vul 08	687.76	232.96	146.32	1067.04	13.3 (7.6)	80.23 (140.40)	1. (2.
Vul 010	687.76	232.96	181.04	1101.76	18.0 (14.8)	61.21 (74.44)	0. (1.
D-15	626.64	176.00	127.40	930.04	8.5 (6.5)	109.42 (143.08)	1. (2.
D-22	626.64	176.00	177.60	980.24	11.4 (9.2)	85.99 (106.55)	1. (1.
D-30	626.64	176.00	197.60	1000.24	13.3 (9.4)	75.21 (106.41)	1. (1.

* Driving system refers to hammer, helmet, leads and for air/steam hammers, the compressor

Numbers in parentheses are based on the 222 T pile capacity

Example Problem Cost Summary, Neglecting Diesel Start-Up Time

Hammer Type	Cost Per Day $	Productivity Piles/Day	Cost/Pile $	Cost/Foot $
Vul. 06	1013.22	4.5 (0)	225.16	3.46
Vul. 08	1067.04	13.3 (7.6)	80.23 (140.40)	1.23 (2.16)
Vul. 010	1101.76	18.0 (14.8)	61.21 (74.44)	0.94 (1.15)
D-15	930.04	9.2 (6.8)	101.09 (136.77)	1.56 (2.10)
D-22	980.24	14.3 (10.5)	68.55 93.36	1.05 (1.44)
D-30	1000.24	17.1 (13.0)	58.49 76.94	0.90 (1.18)

Numbers in parentheses are based on the 222T pile capacity.

A weakness of the open end diesel hammer is illustrated in the difficulty of starting in very easy driving. The analysis presented here is *totally* unproven and appears to be excessively conservative. As these techniques are applied a reliable analysis procedure must be developed.

The costs will be very sensitive to the required crane radius. Due to the much greater weight of the air/steam systems they will increase in cost more rapidly than the diesels with increased required radius.

No overhead was included in the cost estimates. Since it is surely much greater on labor than equipment this will also increase the cost of the air/steam systems relative to the diesel.

The purpose of this paper was to illustrate a procedure. Since the authors have little experience in construction cost estimation, the reader must be patient with obvious oversimplifications. Hopefully the procedure will be used and tested by pile driving contractors.

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