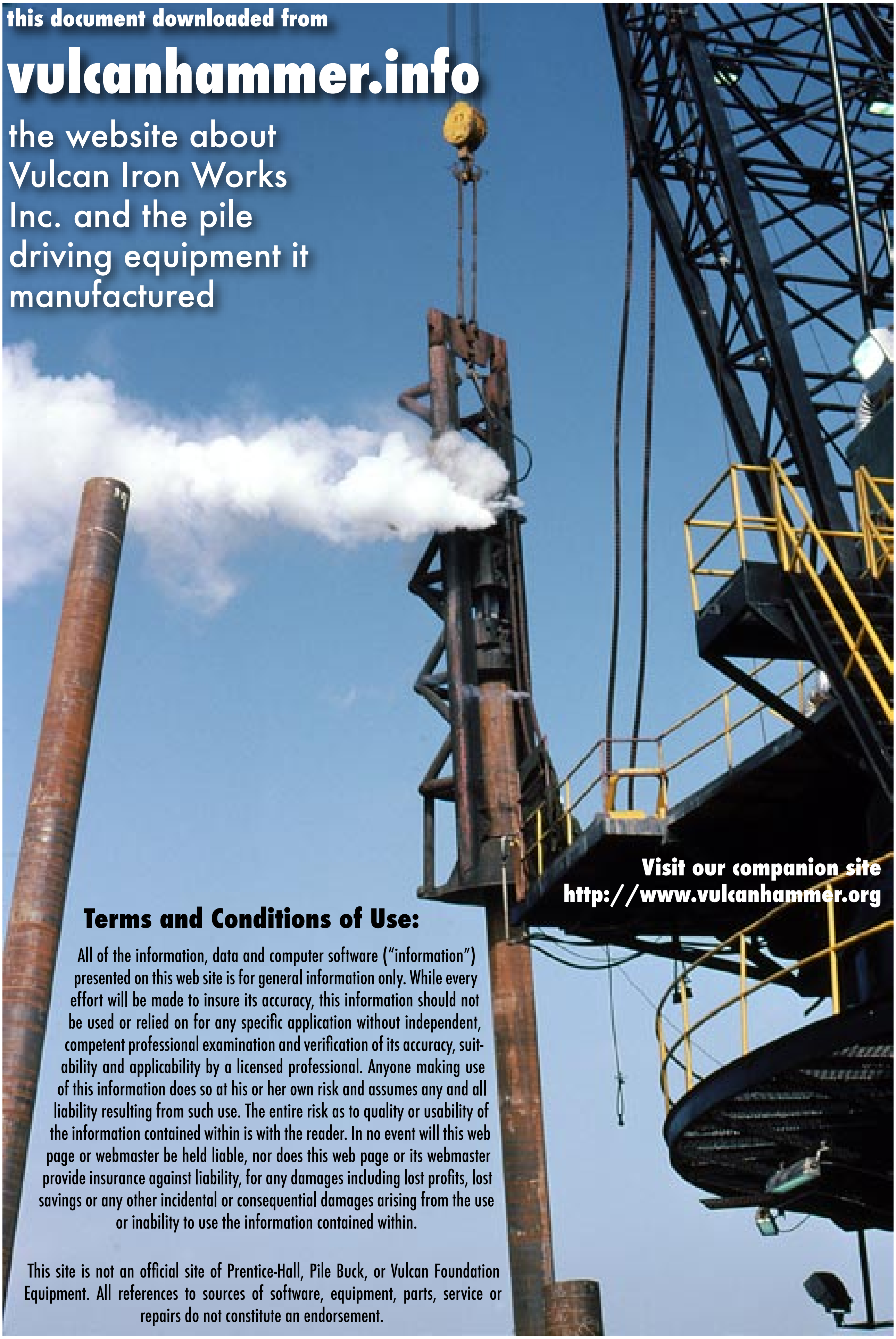

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4. Pile drivability predictions by Capwap

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The CAPWAP analysis is performed on data obtained during the installation of a conductor pipe. Dynamic soil properties are derived and are used for analysing the drivability of the jacket piles. A case study is described in which the driving characteristics of jacket piles were predicted and compared with the results obtained during platform installation.

INTRODUCTION

A challenging task in the design and installation of offshore drilling platforms is the design of the piling and the driving system so that the applied loads are adequately supported and the piles can be efficiently installed. A new approach to this problem is discussed in this Paper, with emphasis placed on the latter aspect.

2. The problem of analysing a pile and its driving system for drivability is one that has received increasing attention in the past few years. In the case of offshore piles, the proportions of the system make the problem quite unusual when compared with piles that are used on land. Typically the ram is quite light compared with the weight of the pile, the piles are long, and they commonly have a variable cross-section. Generally they are driven open-ended, and they derive most of their strength from skin friction. The problem is made more difficult by the fact that the soil data available at a given site is usually limited and frequently not particularly quantitative in character. And yet, structures must be designed and installed under these circumstances; these structures costing huge sums of money.

3. The approach to predicting pile drivability presented in this Paper is based on the use of an analysis (CAPWAP) which is performed on a pile that is driven [illegible] conductor pipe. From the analysis dynamic soil properties are obtained which are then used to analyse the drivability of the jacket piles. The conductor pipe data would be obtained during the installation of exploratory well conductor pipes. If the decision was made to develop the area where the exploratory well was drilled, and the permanent platform was not located on exactly the same location, then a soil boring would be made at the site of the platform and also at the location of the exploratory well so that comparative information could be obtained regarding the characteristics of the materials at the two sites. It is assumed that the platform would be installed near enough to the location of the exploratory well for the soils to be similar.

ANALYSIS ACCORDING TO CAPWAP

4. During an extensive research project conducted at Case Western Reserve University, Cleveland, Ohio, over a period of several years, the capability was developed to measure force and acceleration at the pile top during driving, and record this information on analogue magnetic tape. The accomplishment of these measurements had become a routine matter by the end of the project. Light, portable transducers were developed for direct attachment near the top of the pile to measure the strain a short distance under the hammer, and attachment devices were also developed for accelerometers that were located at the same cross-section. Alternatively, in some applications, a large transducer was fixed to the top of the pile for the same measurements. A variety of procedures was developed for verifying the validity and accuracy of the measurements.

5. The acceleration measurements were accomplished using low output impedance, piezoelectric devices and the strain transducers were designed to accommodate the use of resistance strain gauges. Both of these transducers were reusable. After signal conditioning, this data is recorded by a four-channel analogue magnetic tape recorder together with a voice record for noting the unusual events during the operation. The measurement system is shown schematically in Fig. 1.

The Case Pile Wave Analysis Program (CAPWAP) was developed to determine the soil resistance forces and their distribution using the measured force and acceleration record. Actually, the velocity record of the top is the information that is used, so in the first operation of data processing, the acceleration is integrated to obtain velocity: the velocity so obtained is referred to in this Paper as the measured velocity. It is useful to perform additional data processing in the field, and to this end a special-purpose analogue computational device, known as the Pile Driving Analyzer, has been developed for routine field use. This device is not discussed in this Paper. The computational procedures embodied in the Pile Driving Analyzer are quite different from the CAPWAP method.

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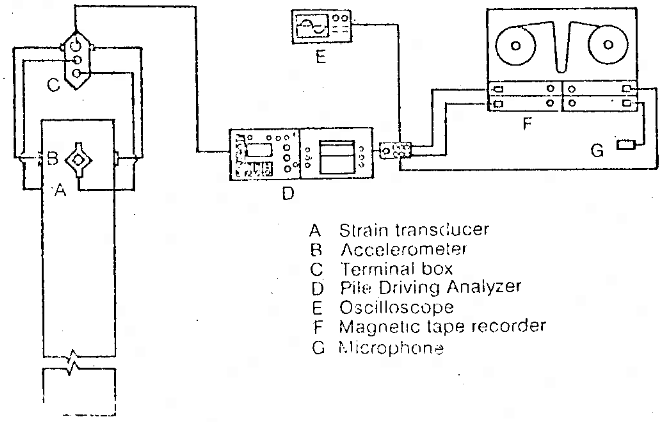

Fig. 1. Pile driving data acquisition system

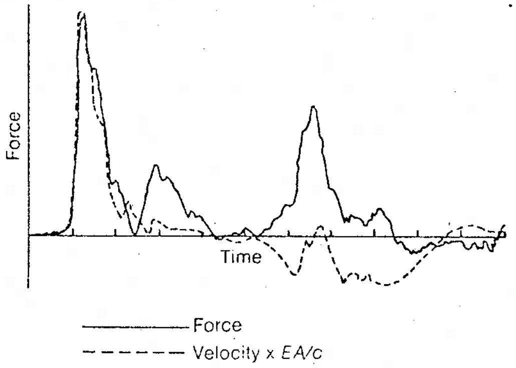

Fig. 2. Example of force and velocity record

7. The measurements stored in analogue form on magnetic tape can be processed automatically by electronic digital computer. The presence of a blow is sensed, and the important part of the signal is converted to digital form using an analogue-to-digital converter controlled by the computer. The resulting digital record can be stored on some sort of peripheral storage device such as digital magnetic tape, or disc, and can then be used in computation or recreated with a digital plotter. An example of a force and velocity record plotted by digital plotter is shown in Fig. 2.

8. In order to perform the CAPWAP analysis the pile, below the point where the transducers are attached, is modelled in the form of a series of lump masses and springs, and the soil resistance is modelled both along the side and at the toe as an elastic-plastic spring and linear dashpot. This model is similar to that proposed by Smith,[1] and later used in the development of a number of wave equation programs for the analysis of pile driving.[2,3] It differs from the wave equation models in that it does not include the driving systems and it excludes all of the pile above the location of the measurements. The model is illustrated in Fig. 3. Consider now the problem which must be solved. In this description computational details are avoided in order that the larger concept of the analysis can be described. The measured velocity at the pile top, treated as an input quantity, is imposed on the top element in the model. The resistance characteristics (i.e., the magnitude of the damping at each element, and the two parameters required to describe the elastic–plastic soil resistance at each element) must now be determined so that when the applied

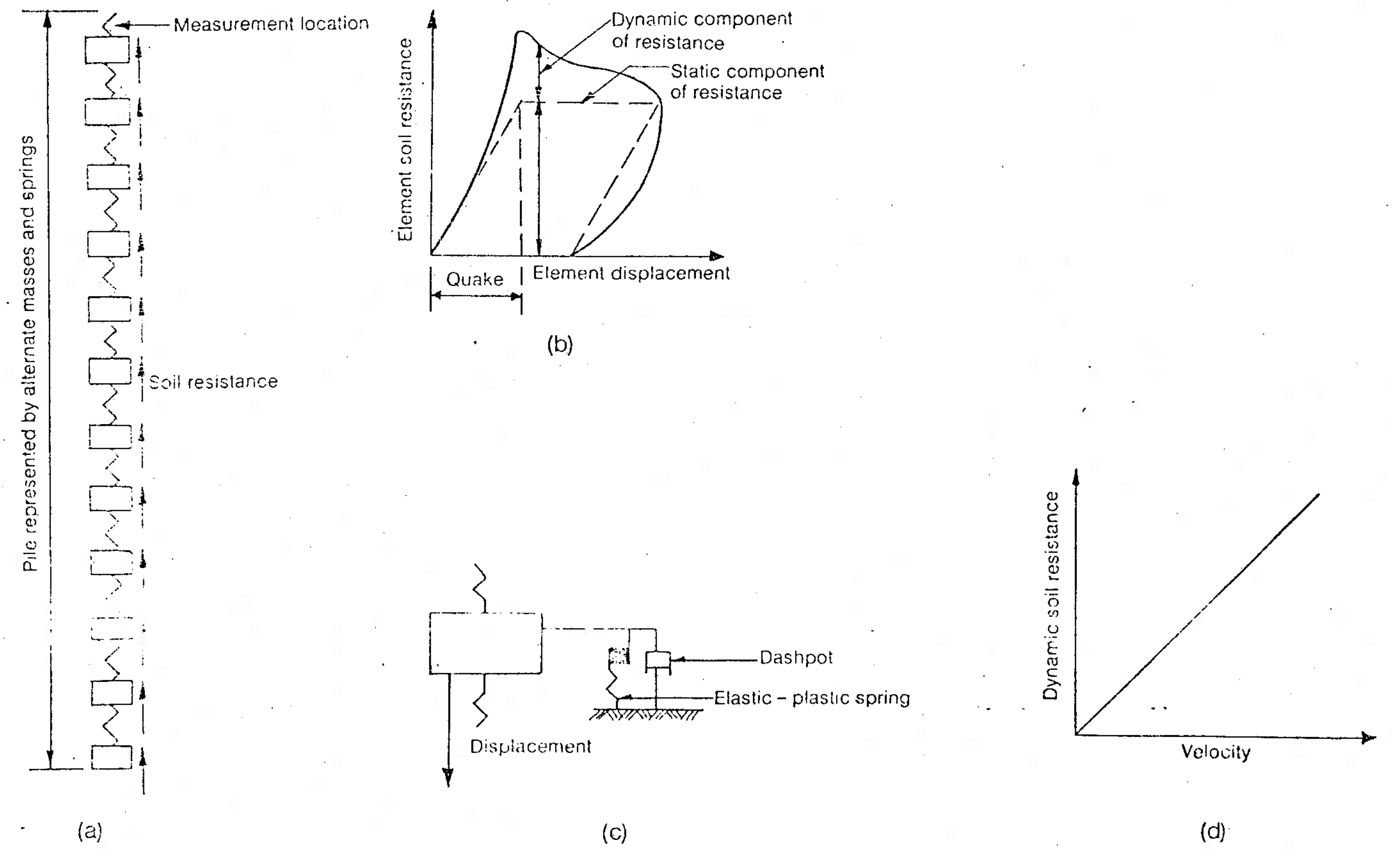

Fig. 3. Mathematical model for CAPWAP: (a) pile model; (b) total soil force–displacement relationship; (c) pile element/soil model; (d) dashpot resistance

velocity is imposed at the top element of the pile the force calculated at the top element will be the same as the measured quantity. In the original version of this method, a procedure was developed for automating the computational process.[4] For a pile of uniform cross-section the force and velocity must be proportional so long as there are no reflections coming from soil resistance. If the pile is of variable cross-section with no soil resistance, the top force can be calculated from the input velocity. Likewise, the force associated with an input velocity, including the reflection from the free end of the pile, can also be directly and readily determined. This quantity is referred to as the free pile solution. When the measured force deviates from the measured velocity (or the free pile solution) it must be concluded that this difference has been caused by the reflection of a soil resistance force. The presence of a deviation at some time interval after impact indicates the location at which the resistance first occurs. This type of information gave a basis for a first estimate of resistance distribution. Subsequent modifications of the resistance were based on the deviation of the calculated and measured force curves. An iterative approach was used to obtain a solution.

9. The automatic computational procedure for resistance distribution was reasonably satisfactory for use with the relatively short piles that are commonly encountered on land (i.e., piles probably about 20 m long and only rarely over 35 m long). When this computational procedure was applied to offshore piles with their very great length it was found that the cost of performing the analysis became excessive. Therefore, the program has been modified to compute the resistance forces and their distribution using an interactive mode. In the interactive mode the measured force and velocity records are input and held available in core storage. The velocity is applied to the pile together with an assumed resistance distribution. For that resistance distribution and magnitude, the force at the pile top as a function of time is calculated and this force record is compared with the measured force. With the calculated and measured force on display and an understanding of one-dimensional wave mechanics it is possible to enter a new resistance distribution. Thus, by successive analysis the resistance distribution can be found that gives the smallest difference between the measured force curve and the calculated force. This, then, is the correct resistance. By matching the calculated and measured force over $4L/c$ of the record (where L is the pile length and c is the stress wave transmission speed) it is possible to separate the static and dynamic resistances.

APPLICATION OF CAPWAP IN [illegible] ANALYSIS

10. The use of soil constants obtained in a CAPWAP analysis for predicting driving characteristics can best be presented by the description of a test case. In 1977 additional wells were drilled on a platform that had been installed some years earlier in the Gulf of Mexico. During the driving of the conductor pipe for one of those wells dynamic measurements as described above were made. A CAPWAP analysis was performed on those measurements at three depths of penetration to obtain soil parameters. The soil parameters were then scaled up to apply to the much larger jacket piles, and wave equation analyses were made using the driving system that was actually used to drive the jacket piles. Blow counts obtained from the wave equation analysis for the jacket piles were compared with the driving record recorded during the installation of the jacket.

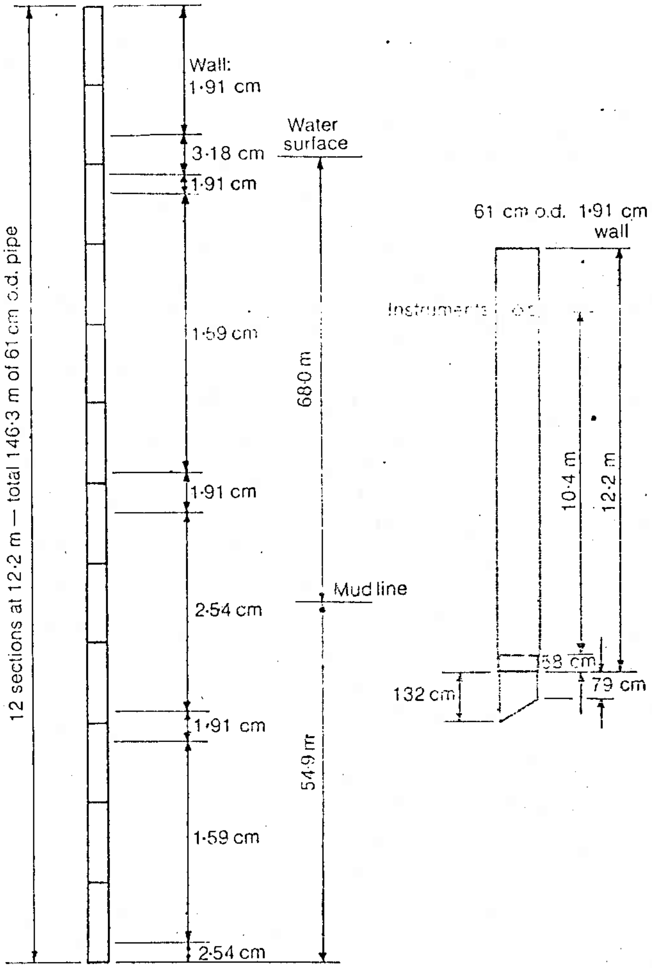

Fig. 4. Conductor pipe details

11. The conductor pipe on which the measurements were made is shown in Fig. 4. It was 61 cm in diameter and 146.3 m long. It penetrated the ocean floor 54.9 m. When measurements were made an instrumented drive nipple was added at the pile top. The driving was accomplished with a DELMAG D–30 hammer.

12. In order to show the performance of CAPWAP some steps are reproduced for one of the blows that was analysed from data obtained at the end of driving. A total of 20 analysis cycles were performed. The resistance parameters used are given in Table 1 and the comparisons between calculated and measured force records are shown in Fig. 5. In the first trial (Fig. 5(a)) the agreement between calculated and measured force is poor. Much too large a resistance has been assumed and it has been applied too far up the pile. There are also deviations between calculated and measured forces in the early part of the record. Since there is no soil resistance in this region and at later times the agreement is nearly perfect these differences must be ascribed to measurement inaccuracies. It is inappropriate to attempt to improve the agreement.

13. In trial 2 (Table 1 and Fig. 5(b)) the resistance was reduced and moved down the pile. The match is substantially changed in the region of the tip reflection.

Now there is too little resistance somewhat above the tip. The result is a dramatic decline in the calculated force to where it is now too low in the region above the tip. In trial 3 (Fig. 5(c)) static resistance was moved up the pile with the total resistance only slightly changed. The agreement is substantially improved up to the $2L/c$ time. In trial 5 (Fig. 5(d)) further adjustments were made in the static resistance to try to improve the match just after the $2L/c$ time.

14. Up to this point a typical damping value has been used and no attempt has been made to improve the agreement after the $2L/c$ time. A poor agreement generally exists in this part of the record. Before discussing damping adjustments it is necessary to discuss the various damping constant definitions. In this paper the damping force is defined by the relationship

$$R_D(t) = Jv(t) \tag{1}$$

where J is referred to as the viscous damping constant and may carry the subscript s to refer to side damping or t to denote tip damping. This constant carries the units kN s/m. In work reported previously[4] a damping constant j_c was defined by the relationship

$$R_D(t) = j_c(EA/c)\,v(t) \tag{2}$$

where E is the pile material modulus, A is the pile cross-sectional area, c is the velocity of wave propagation in the pile and j_c is the Case damping constant. With this definition the damping constant j_c is dimensionless. Smith[1] suggested a damping constant stated as

$$R_D(t) = j_s R_u v(t) \tag{3}$$

where R_u is the element ultimate resistance and j_s is the Smith damping constant. The damping constant j_s has units s/m. Extensive experience with CAPWAP analyses shows that none of these relations gives fundamental soil properties. Additional research is necessary in this area.

15. In Table 1 the damping constants shown are Case constants. However, the damping force is distributed in the same fashion as the static resistance.

16. Between trials 5 and 12 the agreement between the two curves was not substantially changed by modifying the static resistance distribution. In trial 12 the damping magnitude was increased and the distribution modified, giving an improvement in the match near the tip. Further modifications in damping were made up to trial 14 and now a longer time interval is being considered. However, a troubling positive spike in the calculated force record cannot be eliminated. In trial 15 a change was made in the mass distribution, with the addition of more pile weight primarily at the pile tip. In trial 15 the undesirable force characteristic has been eliminated.

17. Further modifications, primarily in damping magnitude and distribution, were attempted up to trial 27, the final trial.

18. The final results are shown in Table 2. The results from the other two blows analysed are given in Tables 3 and 4. As might be expected, the capacity increased with depth of penetration. The static resistance distribution is illustrated in Fig. 6.

19. The conductor pipe analysed above was driven at an operating platform. Information is available on the driving of three of the leg piles. They were driven using a Vulcan 0–60 hammer with a capblock of alternating layers of 1 in steel cable and ¼ in steel plates. The leg pile characteristics are shown in Fig. 7 and the driving records in Fig. 8. The driving record is shown only to somewhat below the depth penetrated by the conductor. Unfortunately a soil profile and other soils data is not available for this site.

Table 1. CAPWAP interactive data input

Iteration	R_u, kN	j_{cs}	j_{ct}	Q_s, cm	Q_t, cm	Remarks
1	4248	0.5	0.5	0.25	0.25	Element 0–60=0; bottom trapezoidal distribution
2	2825	0.5	0.5	0.25	0.25	Element 0–60=0, 61–65=54 kN, 66–70=200 kN, 71–74=345 kN, 75=165 kN
3	2811	0.5	0.5	0.25	0.25	Element 0–47=0, 48–60=93 kN, 61–65=58 kN, 66–70=98 kN, 71–75=165 kN
5	1890	0.5	0.4	0.25	0.25	Element 0–48=0, 48–53=89 kN, 54–58=107 kN, 59–60=18 kN, 61–66=13.3 kN, 67–69=89 kN, 70–74=71 kN, 75=89 kN
12	1401	0.2	0.1	0.25	0.25	Element 0–48=0, 49–54=27 kN, 55–58=40 kN, 59–70=49 kN, 71–75=98 kN; damping replaced element 49–54=69 kN s/m, 55–58=71 kN s/m, 59–66=15 kN s/m
14	1539	0.2	0.1	0.05	0.05	Element 0–48=0, 49–54=31 kN, 55–58=49 kN, 59–70=58 kN, 71–73=116 kN, 74–75=58 kN; damping replaced element 49–54=69 kN s/m, 55–58=71 kN s/m, 59–66=15 kN s/m
15	1557	0.2	0.1	0.05	0.05	Element 0–48=0, 49–54=36 kN, 55–58=44 kN, 59–70=53 kN, 71–75=107 kN; damping same as iteration 14; weight added at element 5=2.8 kN, 74=4.4 kN
25	1548	0.2	0.1	0.13	0.13	Element 0–48=0, 49–54=9 kN, 55–61=18 kN, 62–65=9 kN, 66–75=133 kN; damping element 49–54=75 kN s/m, 60–61=40 kN s/m, 62–65=6 kN s/m, 66–70=79 kN s/m, 71–74=28 kN s/m, tip=147 kN s/m
Final	1548	0.2	0.1	0.13	0.13	Element 0–48=0, 49–54=9 kN, 55–61=18 kN, 62–65=9 kN, 66–75=133 kN; damping element 49–54=75 kN s/m, 55–59=106 kN s/m, 60–61=40 kN s/m, 62–65=6 kN s/m, 66–70=79 kN s/m, 71–74=28 kN s/m, tip=147 kN s/m; added weight unchanged

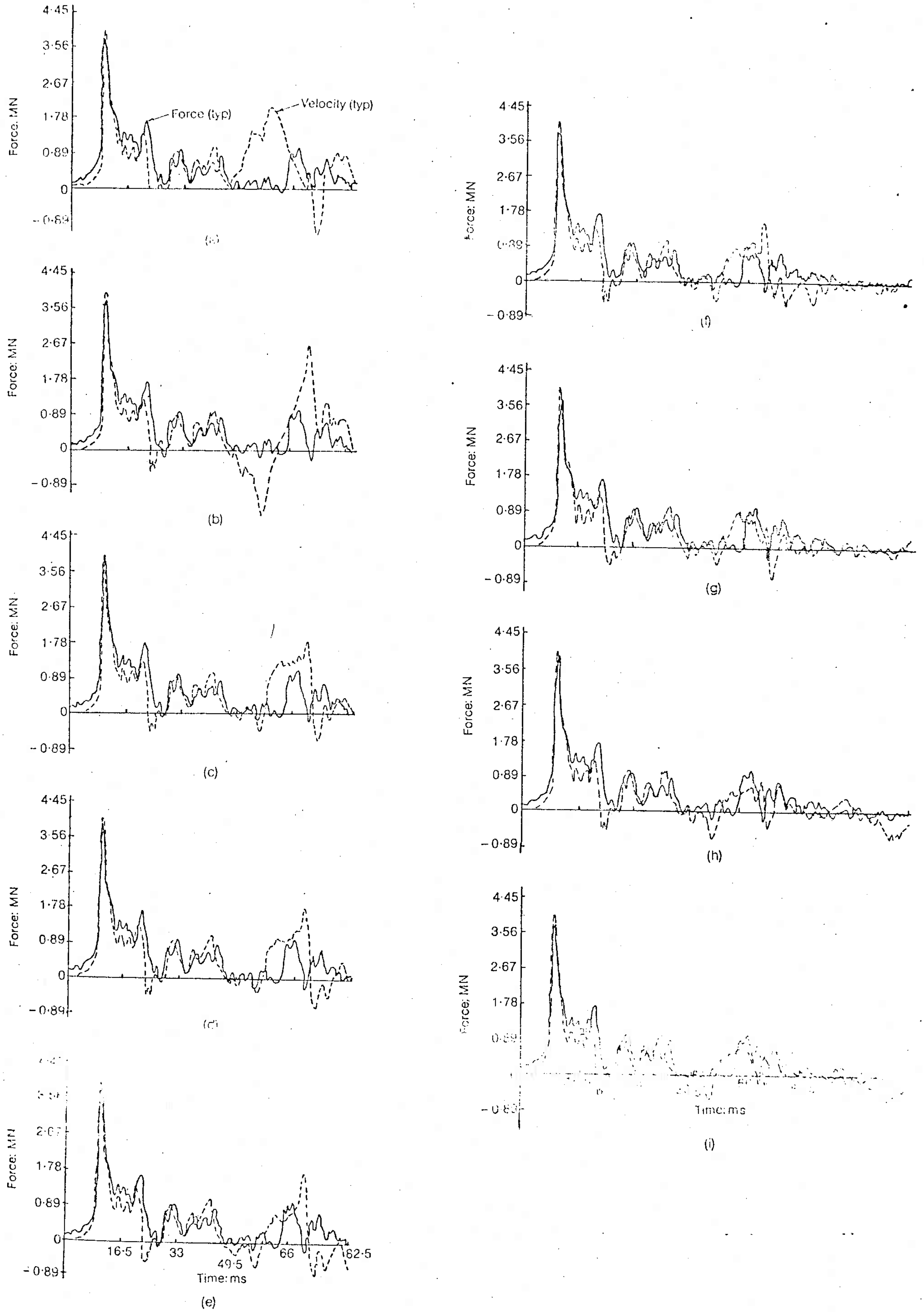

Fig. 5. Calculated and measured force records: (a) trial 1; (b) trial 2; (c) trial 3; (d) trial 5; (e) trial 12; (f) trial 14; (g) trial 15; (h) trial 25; (i) final trial

Table 2. Resistance distribution—54.9 m penetration

Element	Penetration below mud line, m	Quake, cm	Static resistance, kN	*J*, kN s/m
48	0	0.13	0	0
49	2.1	0.13	9	75
50	4.2	0.13	9	75
51	6.3	0.13	9	75
52	8.4	0.13	9	75
53	10.6	0.13	9	75
54	12.7	0.13	9	75
55	14.8	0.13	18	106
56	16.9	0.13	18	106
57	19.0	0.13	18	106
58	21.1	0.13	18	106
59	23.2	0.13	18	106
60	25.3	0.13	18	40
61	27.4	0.13	18	40
62	29.5	0.13	9	6
63	31.7	0.13	9	6
64	33.8	0.13	9	6
65	35.9	0.13	9	6
66	38.0	0.13	133	79
67	40.1	0.13	133	79
68	42.2	0.13	133	79
69	44.3	0.13	133	79
70	46.4	0.13	133	79
71	48.5	0.13	133	28
72	50.6	0.13	133	28
73	52.8	0.13	133	28
74	54.9	0.13	133	28
75	54.9	0.13	133	147
			1548	

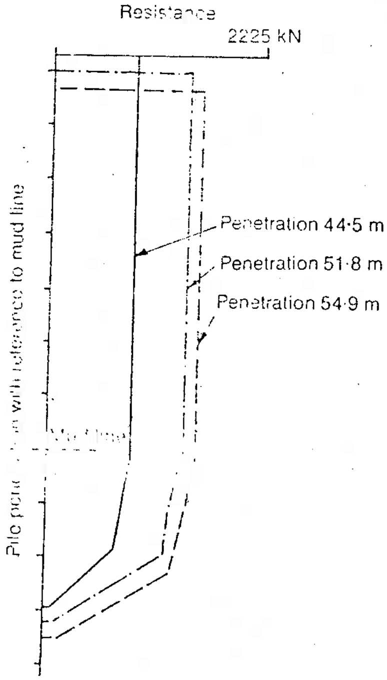

Fig. 6. Force in the pile under ultimate conditions, for the soil resistances calculated from CAPWAP

Table 3. Resistance distribution—50.6 m penetration

Element	Penetration below mud line, m	Quake, cm	Static resistance, kN	*J*, kN s/m
50	0	0.13	0	0
51	2.1	0.13	14	91
52	4.2	0.13	14	91
53	6.3	0.13	14	91
54	8.4	0.13	19	136
55	10.6	0.13	19	136
56	12.7	0.13	19	136
57	14.8	0.13	24	93
58	16.9	0.13	24	93
59	19.0	0.13	24	93
60	21.1	0.13	5	45
61	23.2	0.13	5	45
62	25.3	0.13	5	45
63	27.4	0.13	5	45
64	29.5	0.13	5	45
65	31.7	0.13	5	45
66	33.8	0.13	123	71
67	35.9	0.13	123	71
68	38.0	0.13	123	71
69	40.1	0.13	123	71
70	42.2	0.13	123	71
71	44.3	0.13	123	28
72	46.4	0.13	123	28
73	48.5	0.13	123	28
74	50.6	0.13	123	28
75	50.6	0.13	123	147
			1431	

Table 4. Resistance distribution—46.4 m penetration

Element	Penetration below mud line, m	Quake, cm	Static resistance, kN	*J*, kN s/m
52	0	0.13	0	0
53	2.1	0.13	5	8
54	4.2	0.13	5	8
55	6.3	0.13	5	8
56	8.4	0.13	5	8
57	10.6	0.13	14	23
58	12.7	0.13	14	23
59	14.8	0.13	14	23
60	16.9	0.13	14	23
61	19.0	0.13	9	15
62	21.1	0.13	9	15
63	23.2	0.13	9	15
64	25.3	0.13	9	15
65	27.4	0.13	9	15
66	29.5	0.13	9	15
67	31.7	0.13	80	132
68	33.8	0.13	80	132
69	35.9	0.13	80	132
70	38.0	0.13	80	132
71	40.1	0.13	80	132
72	42.2	0.13	80	132
73	44.3	0.13	80	132
74	46.4	0.13	80	132
75	46.4	0.13	80	147
			850	

20. The assumption was made that the soil resistance forces at a particular depth were a fixed value and related to the pile surface area. Therefore, the static resistance values were all multiplied by the ratio of the pile diameters (2.5). The same values of quake that were obtained from CAPWAP were used on the jacket piles. The viscous damping J was also multiplied by the same ratio. Since there was no scaling on pile impedance this implies that perhaps the Smith concept is relevant. It seems reasonable to assume that the damping resistance generated by the soil is independent of pile impedance. However, this study in no way supports the Smith concept since both quantities (static and dynamic resistance) were scaled by the same amount.

21. The wave equation analysis was made using the WEAP system.[3] The results for the three penetrations are shown in Table 5. At the two deeper locations the agreement is excellent while at the shallow depth the prediction is somewhat high. The predicted driving characteristics are shown in Fig. 8.

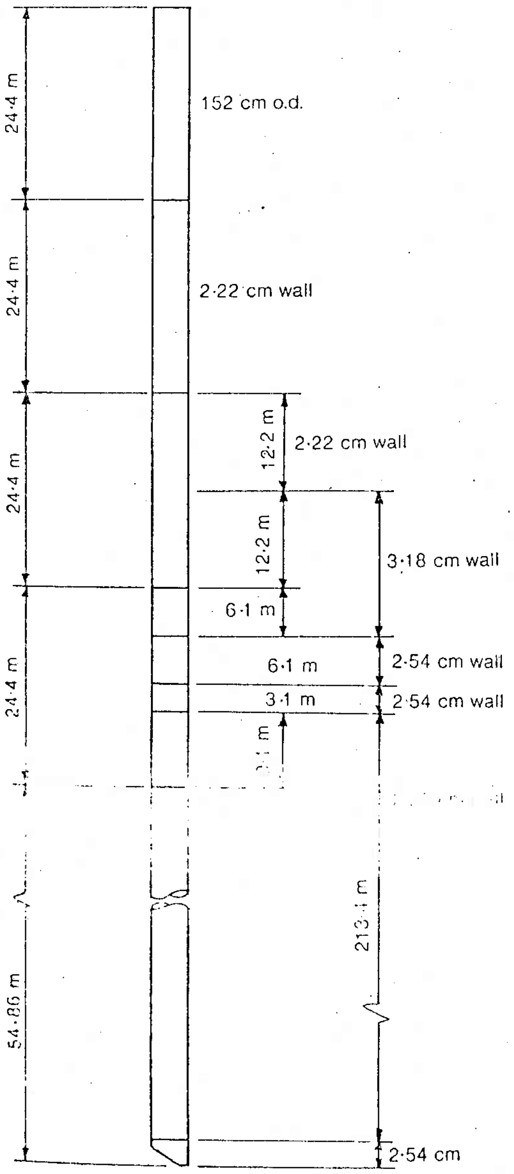

Fig. 7. Jacket pile details

Table 5. Results of WEAP analysis of leg pile

Penetration, m	Maximum stress, MPa	ENTHRU, kJ	Blow count, blows/ft
44.5	139	143.2	17
51.8	139	142.6	29
54.9	139	142.8	30

CONCLUSIONS AND COMMENTS

22. The use of an exploratory well conductor pipe as a 'penetrometer' for predicting pile drivability has been demonstrated. The performance in this case is very good. However, it is easier to correlate at these relatively low blow counts than it is with higher blow counts.

23. The Smith damping values obtained from the CAPWAP analysis are, in some cases, very large; they are commonly over 2.0 where expected values for a soil with high damping would not normally exceed 0.2. Changes in damping can substantially affect the blow count and therefore the problem is a serious one.

24. No mention has been made of set-up effects. If driving is interrupted in these soils a substantial strength increase results. An example of this phenomenon is seen in Fig. 8 where blow counts increase substantially and then decline with additional driving. This occurred when driving was interrupted for splicing. It is possible to measure these set-up effects using the system described here if controlled interruptions are used in driving the penetrometer pile. If this type of data were available it would be possible to

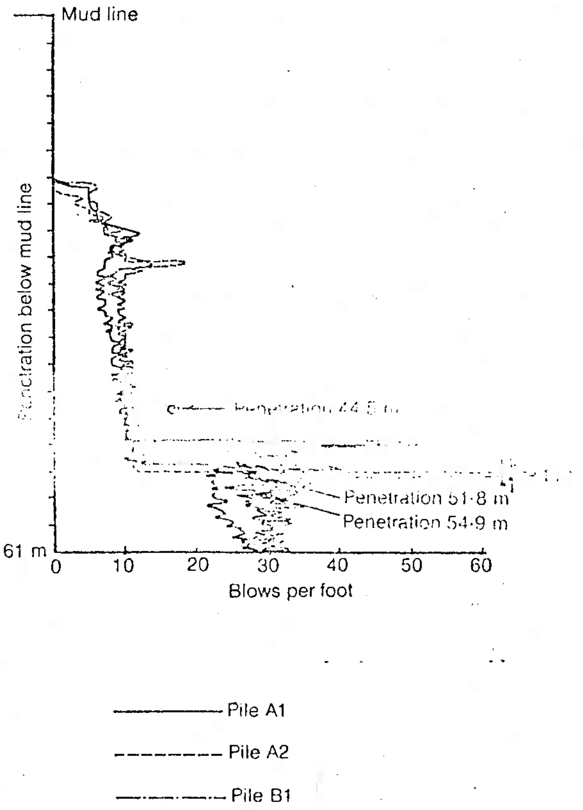

Fig. 8. Driving records for jacket piles

engineer the driving operation and possibly increase the accuracy of the pile capacity determination.

25. It seems, based on this study, that the approach presented can provide a much more reliable means of predicting drivability, and further study is justified.

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