VARIATION OF CAPWAP RESULTS AS A FUNCTION OF THE OPERATOR

Bengt H. Fellenius

University of Ottawa

Department of Civil Engineering

FELLENIUS, B.H., 1988. Variation of CAPWAP results as a function of the operator. Proceedings of the Third International Conference on the Application of Stress-Wave Theory to Piles, Ottawa, May 25-27, 1988, pp.814 - 825.

Proceedings of the Third International Conference on the Application of Stress-Wave Theory to Piles, Ottawa, May 25 - 27, 1988, pp. 814 - 825.

VARIATION OF CAPWAP RESULTS AS A FUNCTION OF THE OPERATOR

Bengt H. Fellenius

The CAPWAP signal matching technique for determining pile capacity was first presented in the pioneering paper by Rausche et al., 1972. During the past 16 years and in an increasing degree, the CAPWAP procedure has become a indispensable tool for the practicing engineers in the analysis of driven piles. Despite the widespread awareness of the principles and importance of the CAPWAP method, the number of engineers capable of performing a CAPWAP analysis is small. Today, around the world, the method is applied commercially by no more than about two dozen individuals employed by some 15 organizations.

That so few individuals perform CAPWAP analysis is not surprising. While the principles involved are simple, the analysis necessitates education in aspects of soil mechanics and in the practice of piling installation. The iterative procedure employed requires frequent judgment decisions. Therefore, not until after many and long hours of training is the CAPWAP engineer able to perform commercially viable analyses.

As in other small groups of specialists, a certain kinship has developed amongst "CAPWAPers". Still, most analyses are made in a competitive atmosphere and there is only little direct outside influence on the analyses performed by the organizations involved. Therefore, one may wonder if the judgment element imposed by one person in an analysis is adequately similar to what an other person would have exercised. And, as the element of judgment is a function of knowledge and experience, which differs from person to person, one wonders if result of one specific CAPWAP analysis performed by one person similar to that performed by an other?

To shed light on the question, the Author sent a disk containing records from four blows to all individuals trained to perform a CAPWAP analysis asking each to send back the results of his best match. This paper reports the compilation of the analyses received.

PARTICIPANTS

A total of 19 individuals participated, which is all but one invited. (This latter person, who is not with a commercial organization, declined for lack of time). Thus, the study covers all organizations performing CAPWAP analysis commercially. A total of 18 separate analyses were made. The individual persons participating are listed in alphabetical order in Table 1. Some of the participants are very experienced in performing a CAPWAP. Others have only limited experience. For three persons, the four blows included in the study were their first independent CAPWAPs after completion of their initial training. A few had only little steel-pile experience. As no purpose is served by identifying the analysis made by one particular individual, the eighteen analyses are numbered in a different order to the listing of participants in Table 1.

TABLE 1. Participants in the CAPWAP Study

EDDE, Robert	Anna Geodynamics, Ottawa, Canada
GRAVARE, Carl-John	Balken Piling System, Goteborg, Sweden
HAMZEH, Mohamad	University of Ottawa, Ottawa, Canada
HANNIGAN, Patrick	STS Consultants, Fairfax, USA
HOLLOWAY, Michael	In-Situ Tech, Oakland, USA
HOLM, Goran	Swedish Geotechnical Institute, Linkoping
KENNEDY, Bruce	Maunsell and Partners, Melbourne, Australia
KIGHTLY, Michael	Testing and Analysis, Somercotes, England
KOPONEN, Antti	Lohja Corporation, Nummela, Finland
LIKINS, Garland	GRL Associates, Cleveland, USA
MENDEZ, Antonio	Pruebas Dinamicas, Mexico City, Mexico
MINER, Bert	GRL Associates, Denver, USA
PLESIOTIS, Sam	RCA, Victoria, Australia
RAUSCHE, Frank	GRL Associates, Cleveland, USA
RAVICHANDRA, Ravi	RCA, Victoria, Australia
SEIDEL, Julian	Piletest, Brisbane, Australia
SHOUCAIR, John	Schmertmann and Crapps, Gainesville, USA
SKOV, Richard	Centrum Paele, Vejle, Denmark
WEBER, Lucien	TradeArbed, Esch sur Alzette, Luxembourg

All participants received initial training from either Garland Likins or Frank Rausche (who both participated and who performed their CAPWAPs independently of each other). Therefore, the CAPWAPs performed by Garland Likins and Frank Rausche would be of interest as reference to the others. The author is grateful for receiving Garland and Frank's permission to identify their analysis in the records: Analyses 11 and 17, respectively.

BLOWS SELECTED

The four blows were chosen according to the following principles:

1. The hammer should have moved the pile so that mobilized resistance is equal to the actual capacity of the pile.
2. Two blows should be relatively simple to CAPWAP and two should be on the difficult side.
3. The piles should be from both clay and sand soils
4. At least one pile should be long.

The four blows are selected from the monitoring records of the driving of four piles denoted JI, JA, AM, and LW. Details on the piles are presented in Table 2.

TABLE 2. Pile Data

Pile	JI	JA	AM	LW
Material	Steel	Steel	Steel	Steel
Shape	Pipe	H-pile	Pipe	Pipe
Size		W310x79		
O. D. (mm)	324	-	245	406
Wall (mm)	9.5	-	14	13
Area (cm^2)	94	101	100	157
Pile toe	Plate	Plate	Open	
Total Length (m)	42.7	28.0	57.4	17.5
Embedment (m)	35.2	21.6	57.0	14.6
Hammer	A/S	Drop	Diesel	Drop

The soil data are summarized in Table 3, as obtained from routine borehole information. The soils at the site of Piles JI and JA are similar to soils found at many piling sites: At Pile JI, the main deposit (Depth 6 m thorough 26 m) consists of essentially clayey silty soils in which considerable pore pressures would develop during the initial driving. Therefore, because the unit shaft resistance is a function of the effective stress in the soil during the driving, the unit shaft resistance in this deposit would be small and not increase linearly with depth. In contrast, at the site of Pile JA, sandy soil dominates. Therefore, pore pressures are not expected to develop during the initial driving, which means that the unit shaft resistance would increase linearly with depth.

The soils at the site of Piles AM and LW are more unusual. The clay soil at the site of Pile AM is very sensitive. During initial driving, this soil is completely liquefied and provides no resistance to pile penetration. The Author has even observed closed-toe piles in the area floating up due to buoyancy when the hammer was removed from the pile. The blow record analyzed is from restriking the pile after the pile has penetrated one inch (25 mm) for the first ten blows. The penetration resistance for the next three inches was 7, 6, and 5 blows, respectively. For the analyzed blow, the shaft resistance is still being progressively broken down from blow to blow. Therefore, the values of shaft quake, shaft damping, and shaft static shear resistance are not constant during the blow in contrast to what the CAPWAP analysis assumes. Therefore, the CAPWAP analysis was expected to be difficult to perform and the results to show a spread of values.

At Pile LW, the pile is being driven into a weak sandstone, which crumbles into sand soil as the pile is advanced. Again, this is not the simple elastic-plastic, static-viscous toe resistance assumed in the CAPWAP analysis.

Fig. 1 shows the penetration resistance recorded during the initial driving of the piles. For Piles JI, JA, and LW, the depth of the pile toe for the blow chosen for analysis is marked out in each diagram. For Pile AM, the blow chosen was the tenth blow of restriking performed 14 days after the initial driving. This information was provided to all participants.

TABLE 3. Soil Data

Depth (m)	Soil Type
JI Pile (Embedment **35.2** m)	
0.0	Miscellaneous earth fill
6.0	Soft to medium stiff compressible postglacial silty clay and clayey silt
25.5	Mixed glacial soil: sandy silt, sand, and clayey silt
81.5	Dolomite bedrock
JA Pile (Embedment **21.6** m)	
0.0	Sandy gravel fill with lenses of frost
1.3	Coarse to medium coarse sand with layers of silty sand and lenses of frost
3.6	Sandy gravel
4.3	Medium to fine compact brown sand with layers of silt
22.9	Fine and medium compact sand, trace silt
27.9	End of borehole
AM Pile (Embedment **58.2** m)	
0.0	Fill: Sand and clay with pieces of weathered shale
1.4	Loose to medium dense silty fine sand
1.8	Medium soft to stiff fissured silty gray clay
18.0	Stiff to very stiff silty gray clay
48.0	Dense soil; End of borehole
LW Pile (Embedment **14.6** m)	
0.0	Peat
0.4	Silt
3.1	Stiff to firm gray silty, sandy clay
10.4	Brown weathered sandstone with silty clayey shale
13.5	Bentonitic sandstone
15.6	End of borehole

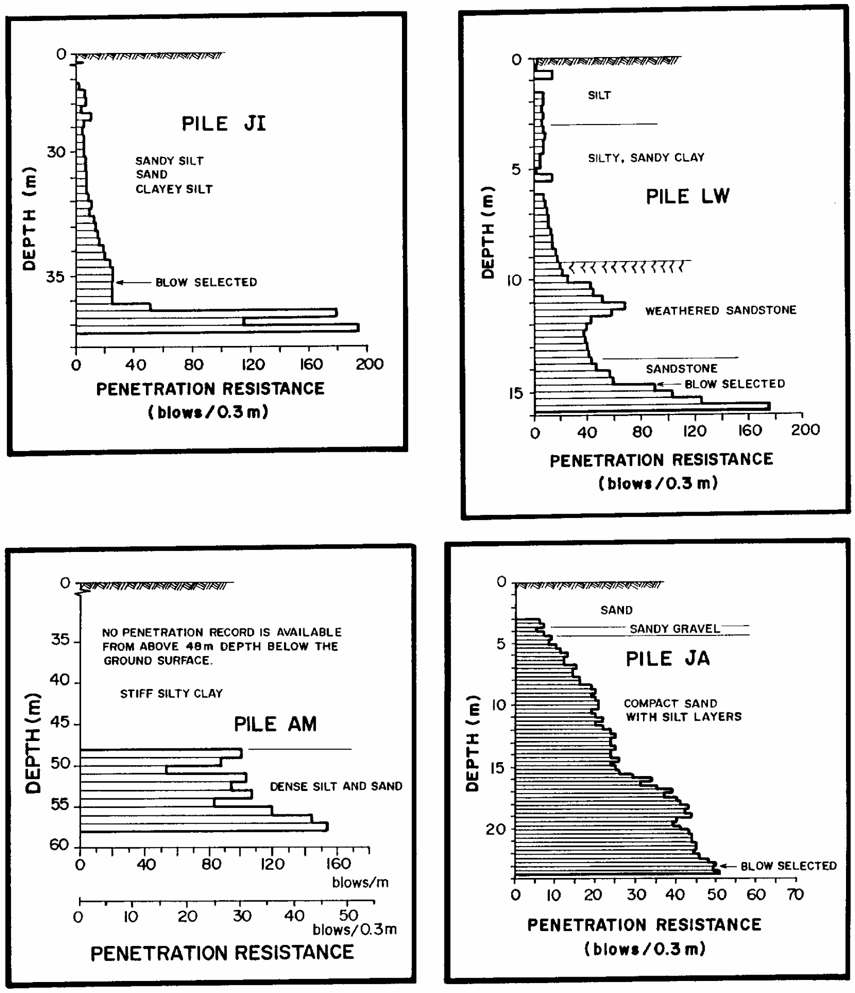

FIG. 1 Penetration resistance recorded during initial driving

For Piles JI, JA, and LW, the blow chosen for analysis is from the initial driving of the pile and there is no static loading test or any other means of verifying the capacity of the piles. However, one day before the restriking of Pile AM, a static loading test was performed. The result of the static test is given in the load-movement diagram in Fig. 2. This information, even the existence of it, was not known by the participants.

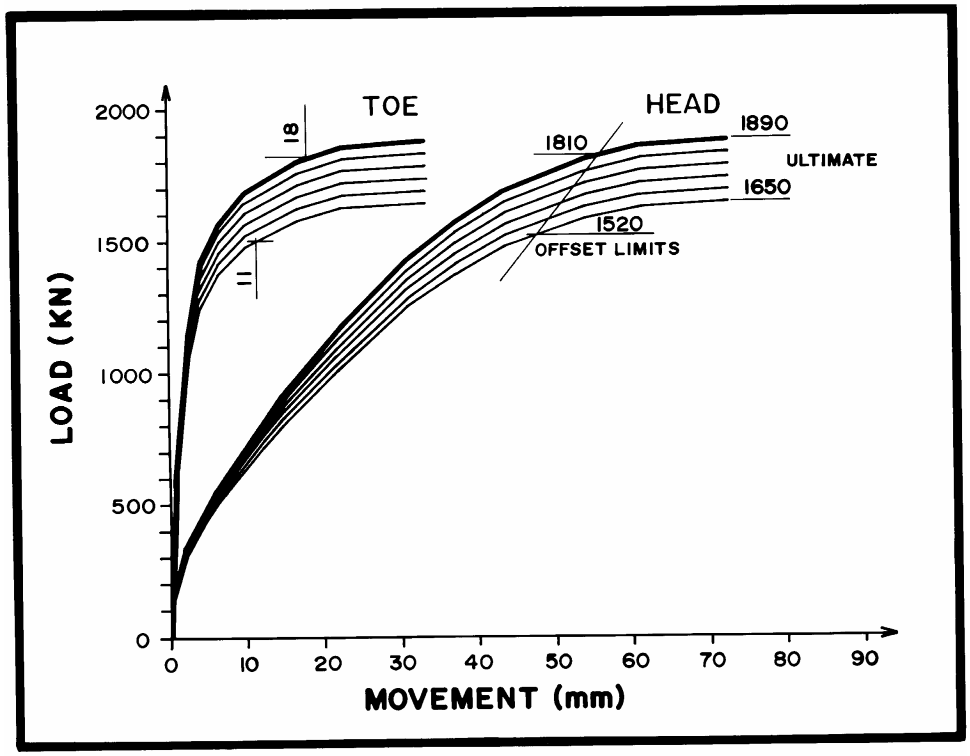

FIG. 2. Results from Static Loading Test on Pile AM. Load-Movement curves.

The pile failed in plunging when the load applied to the pile head in the static loading test was 1,890 KN, as determined from the jack pressure. However, the jack pressure is an unreliable means of determining the applied test load. It usually results in an error of overestimation in the range of 10 to 20 percent of the applied load (Fellenius, 1984). The error is caused by eccentric loading, friction in the jack, etc. Considering the potential error, the true maximum load applied to Pile AM in the test could have been about 1,650 KN, i. e., about 15 % smaller than "measured". The curves which could have been obtained had a load cell been used are indicated in Fig. 2.

In recognition of the potential error in the measure load, the test result is shown in Fig. 2 as a band of load-movement curves, rather than a single curve. The upper thick line is the measured curve indicating the load determined from manometer readings of the pressure in the hydraulic jack.

At the maximum load, the pile had obviously reached a plunging failure state - the ultimate resistance. The Davisson offset limit was 1,810 KN (or as low as 1,520 KN). As shown in Fig. 2, the movement of the pile toe was recorded during the static test and at the applied load corresponding to the offset limit load, the toe movement was about 18 mm (11 mm).

The driving of the piles was monitored by means of the Pile Driving Analyzer. Fig. 3 presents the wave traces obtained for the four blows.

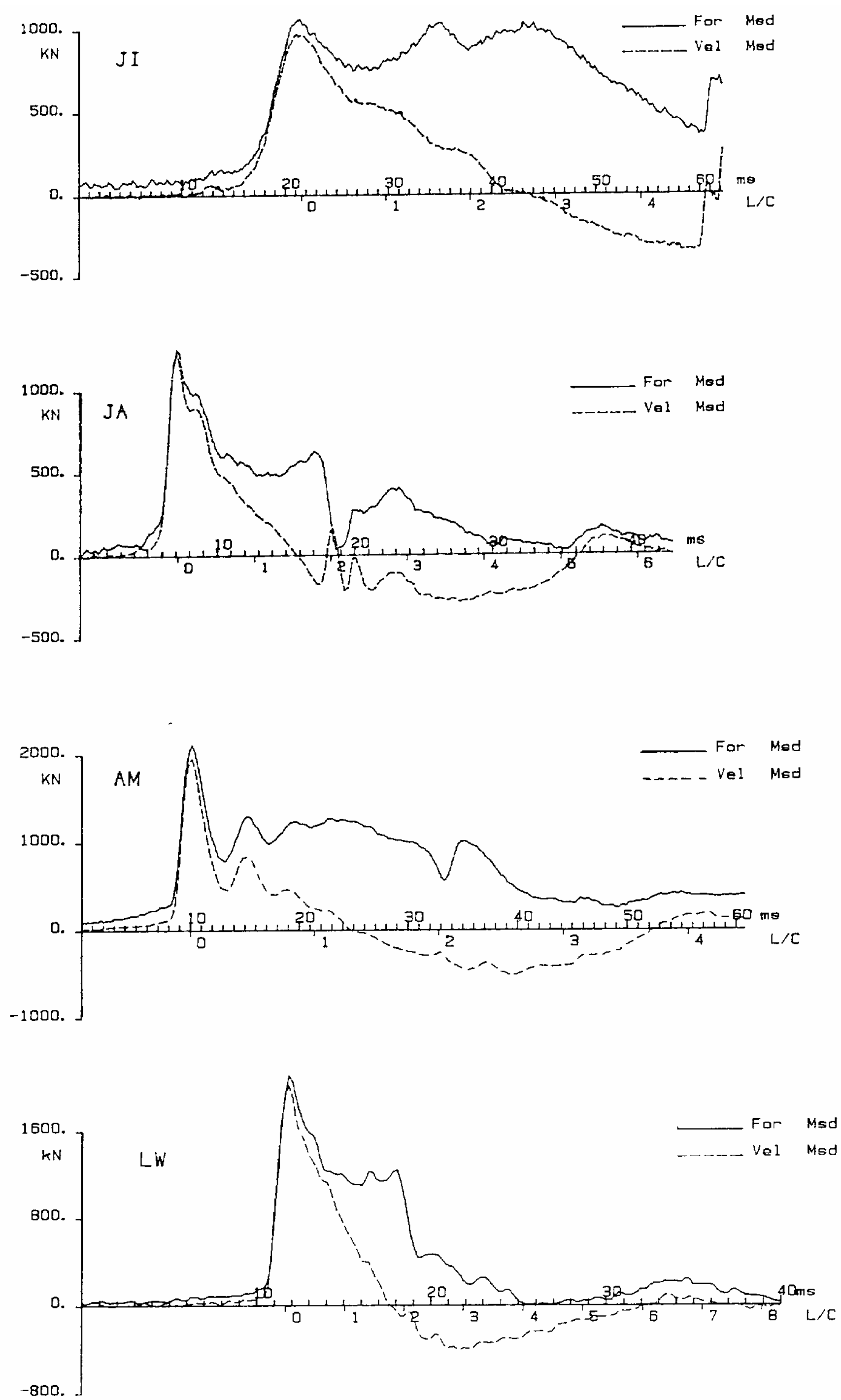

FIG. 3. Traces of Force and Velocity for the Four Blows

The basic results of a CAPWAP analysis are the total capacity, the shaft and toe quakes, and the shaft and toe damping values. Table 4 shows these data compiled from the CAPWAP results as returned by the 18 participants. Indicated below each column are the average capacities, quakes, and damping values. The standard deviations of the values are also given both as a dimension value and as a percentage of the mean (coefficient of variability).

TABLE 4. Compilation of Basic CAPWAP Results

PARTI-PANT	TOTAL CAPACITY (KN)				SHAFT QUAKE (mm)				TOE QUAKE (mm)				SHAFT DAMPING (Case)				TOE DAMPING (Case)			
#	JI	JA	AM	LW	JI	JA	AM	LW	JI	JA	AM	LW	JI	JA	AM	LW	JI	JA	AM	LW
1	1,100	666	2,072	851	3.1	2.6	4.0	2.0	3.0	4.8	6.0	1.0	0.16	0.48	0.30	1.06	0.38	0.31	0.31	0.21
2	1,103	632	1,810	780	2.5	2.5	5.0	2.5	2.8	4.0	5.0	2.5	0.00	0.90	0.10	1.00	0.45	0.06	0.60	0.30
3	1,122	645	1,681	927	1.0	1.5	4.0	1.5	2.8	2.0	2.8	2.0	0.25	0.25	0.25	1.20	0.22	0.46	0.45	0.20
4	1,103	647	1,715	908	2.5	2.5	2.5	3.5	8.9	0.4	2.5	1.3	0.49	0.82	1.14	1.10	0.24	0.06	0.19	0.28
5	1,081	629	2,617	958	0.3	1.4	0.5	1.4	5.0	1.0	4.2	7.0	0.16	0.66	0.11	1.06	0.43	0.04	0.18	0.10
6	1,030	540	1,734	688	2.2	3.0	3.0	2.6	13.5	6.5	1.8	3.3	0.18	1.19	1.00	1.15	0.35	0.01	0.05	0.56
7	1,065	624	1,919	988	1.6	2.5	2.5	2.5	5.1	2.5	3.9	3.7	0.65	0.83	1.11	1.12	0.19	0.04	0.22	0.06
8	1,000	575	1,500	900	2.0	2.5	2.5	2.5	4.0	5.0	6.5	5.0	0.10	0.69	0.42	0.60	0.58	0.42	0.65	0.51
9	1,122	583	1,667	838	6.0	2.0	8.0	1.5	6.0	5.0	3.0	1.5	0.30	0.66	0.10	1.20	0.30	0.30	0.60	0.10
10	1,021	609	1,799	721	4.2	2.5	5.0	3.2	8.0	4.5	6.0	4.0	0.70	0.97	0.85	1.02	0.17	0.11	0.35	0.54
11	1,132	644	1,891	803	2.0	2.3	3.9	3.0	4.0	2.5	3.9	3.0	0.34	0.73	1.24	0.81	0.07	0.08	0.19	0.51
12	1,166	670	1,799	778	2.0	2.5	6.0	2.5	4.0	2.5	6.5	2.5	0.27	0.40	0.27	0.76	0.05	0.27	0.59	0.64
13	1,051	621	1,696	636	1.5	3.0	4.0	3.0	5.0	3.0	4.0	3.0	0.60	0.50	0.50	0.80	0.40	0.30	0.40	0.80
14	1,091	687	1,819	1,042	3.5	3.5	4.5	3.0	8.0	0.8	3.0	3.0	0.15	0.32	0.25	0.73	0.30	0.39	0.62	0.46
15	1,006	608	1,684	725	1.4	2.2	3.5	1.0	6.9	2.5	3.0	8.1	0.40	0.82	0.81	0.98	0.26	0.10	0.13	0.36
16	981	690	1,619	976	2.8	1.8	2.0	1.7	7.0	4.5	2.6	2.0	0.56	0.54	1.27	0.84	0.23	0.07	0.12	0.33
17	1,144	622	1,726	960	2.5	2.8	3.0	2.0	5.5	3.3	6.5	6.5	0.28	0.85	0.80	1.01	0.16	0.07	0.18	0.26
18	1,126	580	1,770	921	2.9	2.5	6.5	3.2	8.8	2.5	6.5	6.5	0.37	0.95	1.05	1.27	0.11	0.02	0.17	0.14
Average	1,080	626	1,807	856	2.5	2.4	3.9	2.4	6.0	3.2	4.3	3.7	0.33	0.70	0.64	0.98	0.27	0.17	0.33	0.35
Std. Dev.	55	39	238	116																
Std. Dev. %	5	6	13	14																

The capacity data given in Table 4 are shown graphically in Fig. 4. The height of the bars indicates the total capacity for each participant. The solid horizontal line is the mean capacity. The dashed lines above and below the solid line show the capacity range resulting from adding and subtracting the standard deviation from the mean capacity.

The variation between the CAPWAP determined capacities is small for all four blows. As expected, the blows from Piles JI and JA do not show much spread: the standard deviation of the capacity for these blows are 5 % and 6 %, respectively. The capacities evaluated for Piles AM and LW have standard deviations of 13 % and 15 %, respectively.

The static loading test on Pile AM performed the day before the restriking indicated a capacity ranging between 1,800 KN and 1,900 KN, when disregarding the potential overestimation of the applied load due to measurement error. This range compares well with the majority of the CAPWAP determined capacities. The agreement is indeed very good considering that the breakdown of shaft resistance during the static test and the breakdown during the driving cannot be assumed equal.

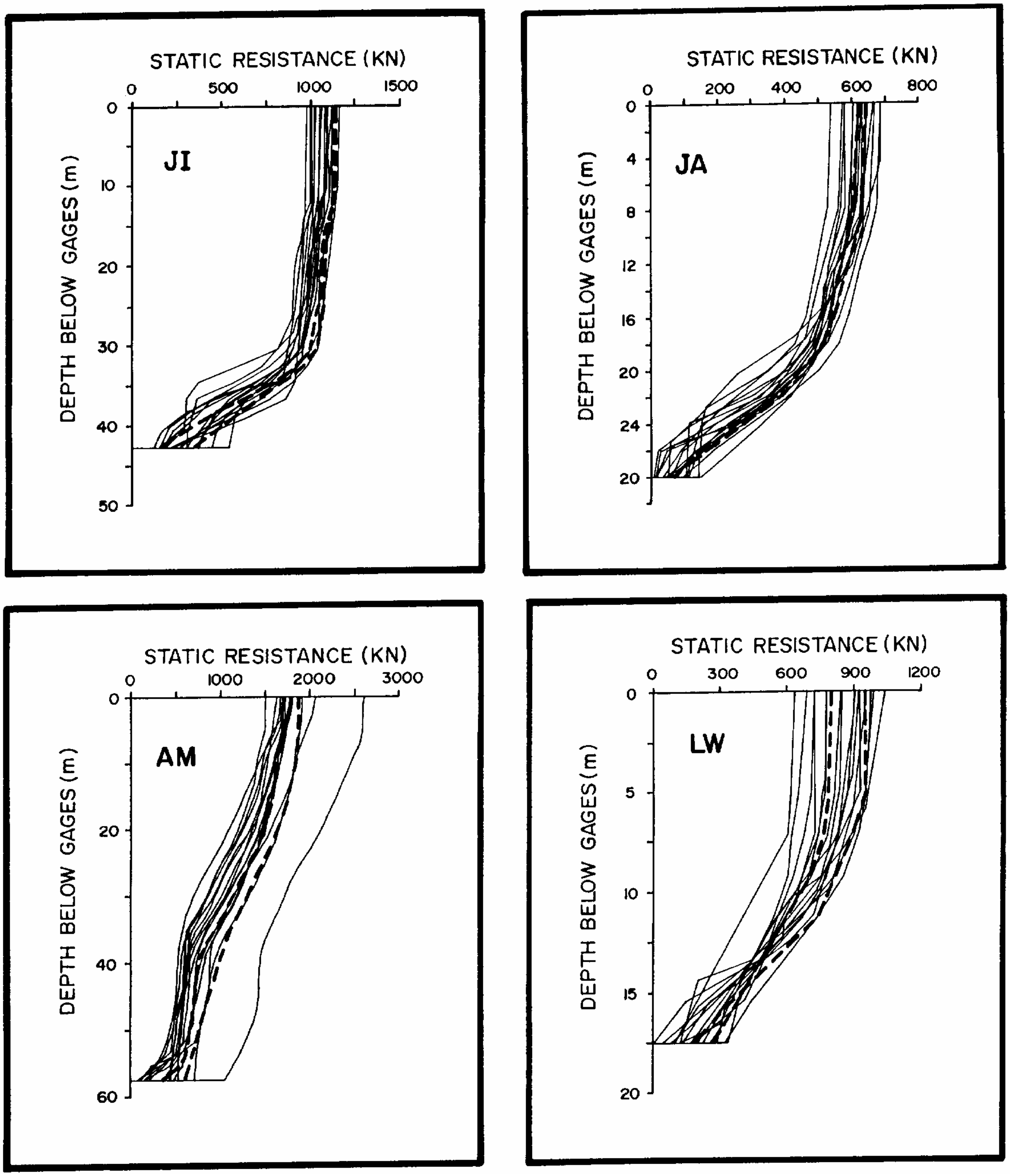

FIG.4. Participants Calculated Total CAPWAP Capacity

For Pile AM, one person (# 5) indicates a capacity which is considerably larger than the values received from all others: 2,617 KN as opposed to about 1,800 KN. This illustrates the pitfalls of performing a CAPWAP on data from a long pile in sensitive clay, where the unloading of the resistance and the damping change during the blow.

Fig. 5 shows the distribution of static resistance in the piles plotted from the resistance assigned to each pile element. Garland and Frank's distributions are indicated by thick, dashed lines.

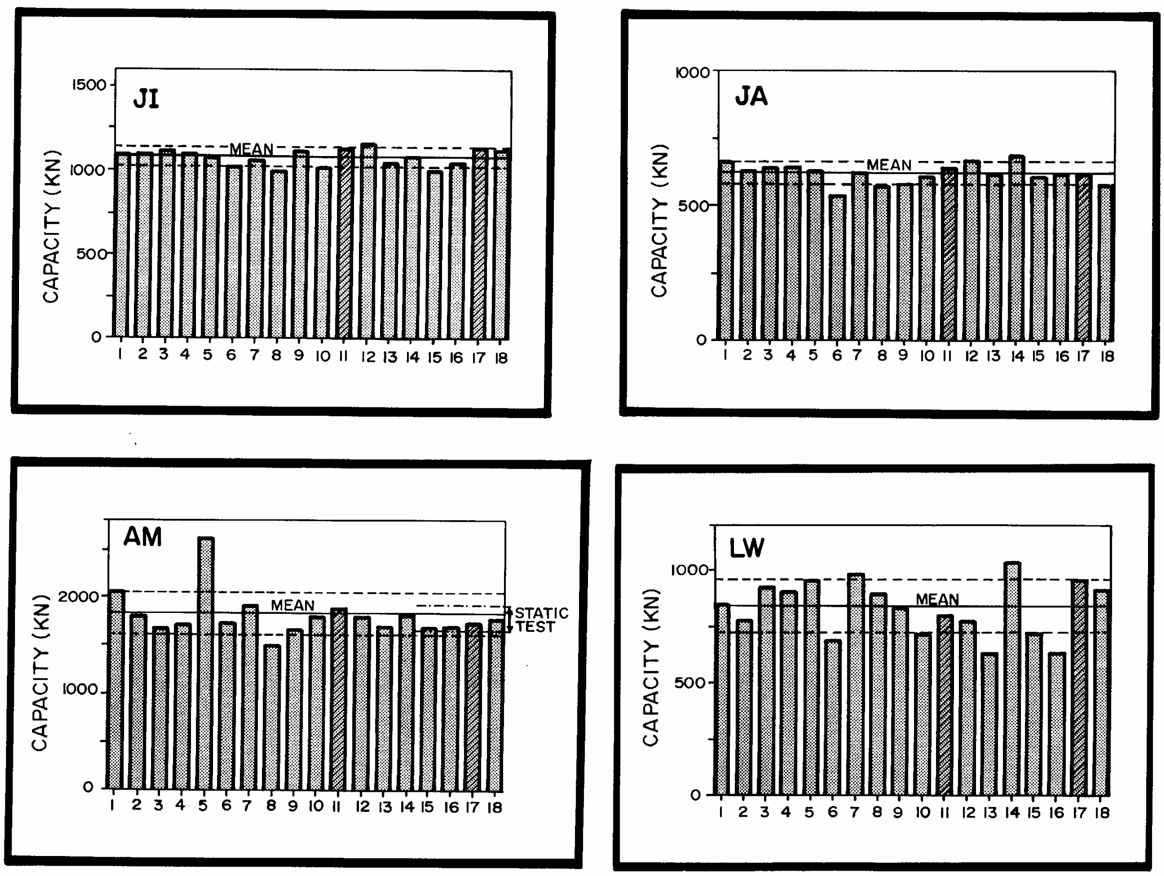

FIG. 5. Distribution of Static Resistance

Although some details differ between the individual analyses (for example, the magnitude of the toe resistance) there is considerable qualitative agreement. For Pile JI, all the analyses indicate only small shaft resistance in the clayey silty soil above the depth of about 26 metre below the ground surface (33 metre below the gages). This agrees with the contention mentioned above of reduced effective stress due to excess pore pressures in this soil.

For Pile JA, on the other hand, all analyses indicate a progressively larger shaft resistance, which is consistent with the resistance being proportional to the effective stress in the soil, i. e., linearly increasing unit shaft resistance.

The individual analyses show qualitative agreement also for Piles AM and LW. The deviations between the analyses are mostly associated with variations in toe resistance.

When performing a CAPWAP analysis, it is important to check that the calculated penetration resistance ("blow-count" value) agrees with the actually observed value. A deviation is not necessarily an indication of an incorrect analysis, but a flag for a potential problem. All the participants in the subject study did not provide the penetration resistance. For those who did, the values are compiled in Table 5. In the heading, the actually observed resistances are given as reference.

TABLE 5. Penetration Resistance (Blows/m)

Participant #	JI 80	JA 165	AM 330	LW 200
1	86	205	347	197
2	85	193	359	--
5	92	138	391	194
10	86	136	1195	263
11	95	161	2,230	203
12	106	150	665	194
13	132	165	427	243
14	101	150	405	292
15	93	172	278	178
16	106	145	376	180
17	97	172	309	233
18	100	168	5,577	331

For Piles JI, JA, and LW, Table 5 shows a good agreement between calculated and observed penetration resistance. For Pile AM, three values differ considerably from the other and from the observed resistance. The participants were informed about the observed penetration resistance and could have "matched" it by resorting to small adjustments of the data and continued fine-tuning of damping and toe resistance. A probable explanation to their not doing this is that the particular engineers recognized the futility of fine-tuning when working with imperfect data.

REFERENCES

FELLENIUS, B. H., 1984. Ignorance is bliss and that is why we sleep so well. Geotechnical News, Canadian Geotechnical Society and the U. S. National Society of the ISSMFE, Vol. 2, No. 1, p. 14.

RAUSCHE, F, GOBLE, G. G., and MOSES, F., 1972. Soil resistance from pile dynamics. American Society of Civil Engineers, ASCE, Journal for Soil Mechanics and Foundation Engineering, 111(3), 367-383.

ACKNOWLEDGEMENTS

The Author is indebted to Mr. Laval Samson and Terratech Ltd., Montreal, for permission to use the data from the four projects.