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COMPARATIVE STRESS WAVE MEASUREMENTS ON A CONCRETE PILE AND A STEEL FOLLOWER

By
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Gothenburg, Sweden

Ett utvecklingsprojekt med ekonomiskt bidrag
från Svenska Byggbranschens Utvecklingsfond

SBUF

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Introduction

Skanska AB in Gothenburg, has carried out a research project under the sponsorship of SBUF, the Development Fund of Swedish Construction Industry. The purpose of the project was to compare stress waves measured simultaneously on a concrete pile and the appurtenant steel follower on top of the same pile.

Background

Stress wave measurements during pile driving are carried out by a "Pile Driving Analyzer" (Enclosure 1) to which two strain transducers and two accelerometers are connected. The four gauges are bolted to the pile approximately 1 meter from the pile top. If the cut off level is below ground surface or water level, the pile has to be extended in order to make mounting of gauges and measuring possible. However, if it were possible to perform accurate measurements on a steel follower reflecting the conditions in the concrete pile, waste of pile material would be substantially reduced. Overlengths for attaching of the gauges would then no longer be required. Other benefits with this method would be:

- Minimizing time delay for the piling rig.
- Savings in work (drilling of holes) and material (expandable anchor studs).
- Reducing measuring time.
- Avoidance of having to excavate between piles.

There are two important conditions to be fulfilled if reliable measurements on the steel follower are to be obtained:

- The interface between the steel follower and the concrete pile has to be under compression unless the elements are joined together in such a way that tensile forces can be transmitted.
- The impedance (EA/c) of the steel follower has to be virtually the same as the impedance of the concrete pile being measured.

The two most common concrete pile dimensions in Sweden have a cross-sectional area of ⌀ 235x235 mm^2 and ⌀ 275x275 mm^2. Two steel followers were therefore manufactured, one for each pile size.

Fig 1. fig 2.

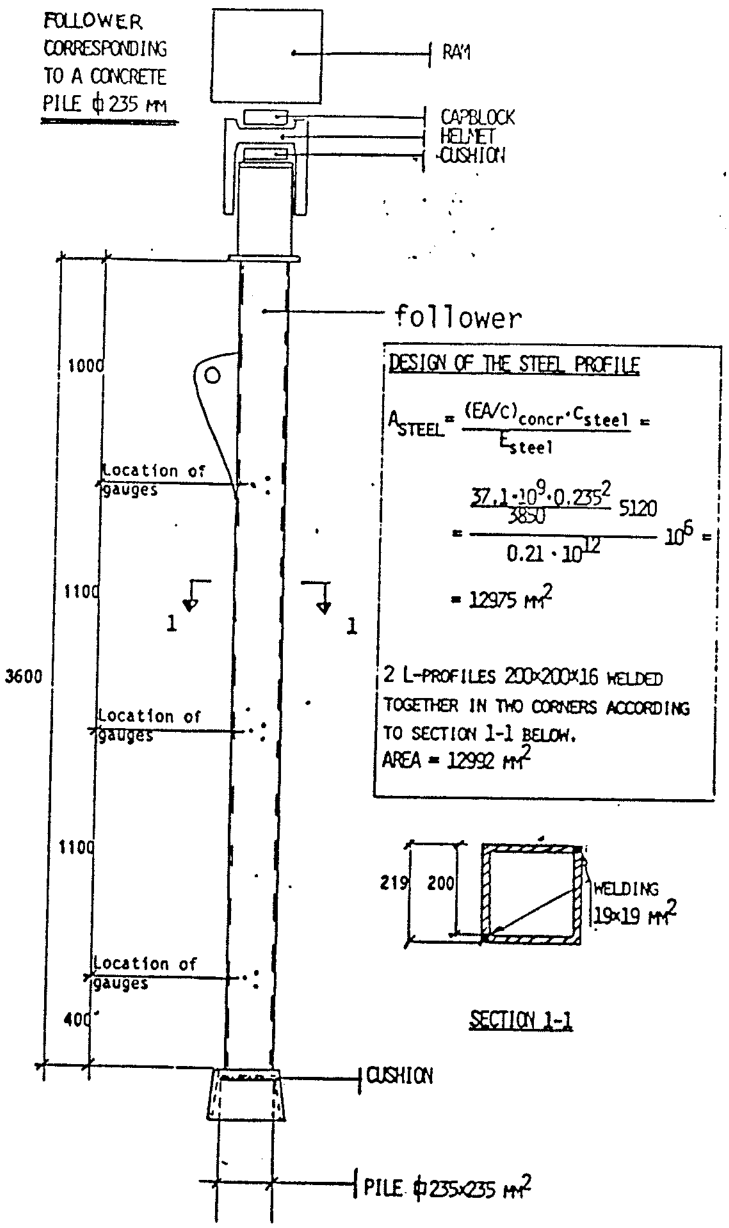

Figure 1. Steel follower corresp. to a pile dimension of ϕ 235 x 235 mm²

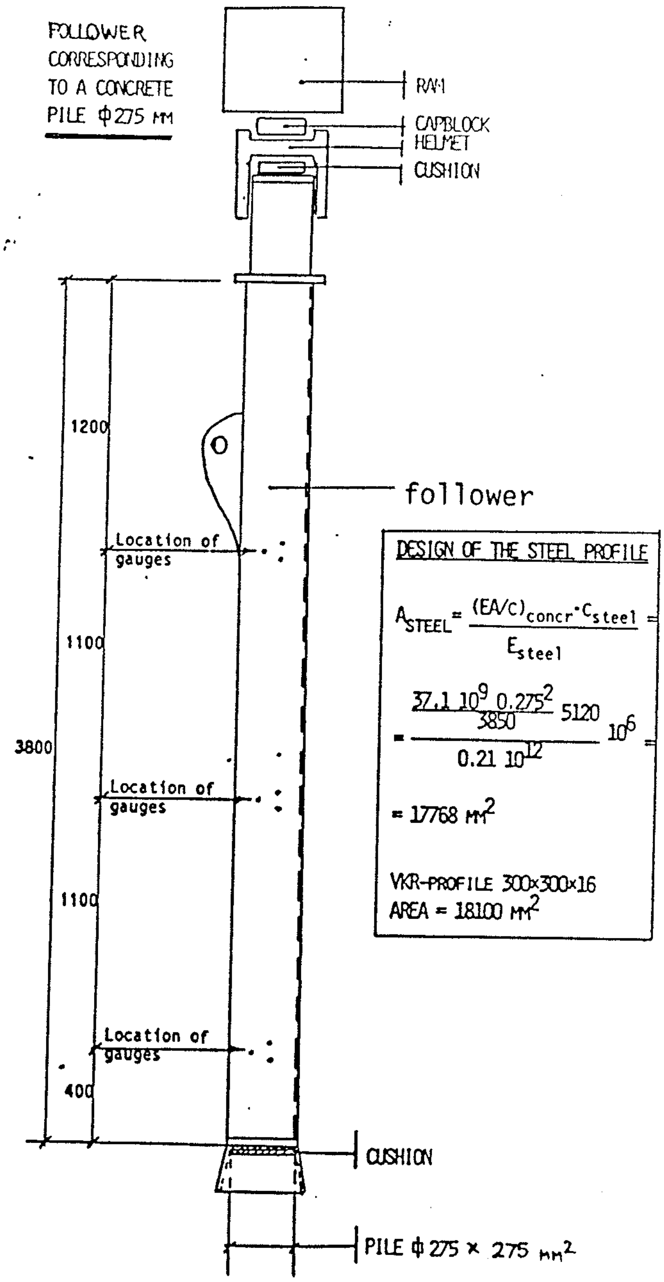

Figure 2. Steel follower corresp. to a pile dimension of ϕ 275 x 275 mm²

An important point is to make the energy loss in the interface between the steel follower and the concrete pile as small as possible. Four different types of cushion materials were therefore tested in order to find out the most suitable ones. The cushion materials used were:

- no cushion
- 6 mm lead
- stiff plywood (cushion material subjected to at least 1000 blows)
- 10 mm PVC-plastic pad

Field testing

Two comparative tests have so far been performed - one for each follower.

Dimension ф 235x235 mm²

The site where the follower was tested was situated in Uddevalla, Sweden, at the building site of Volvo's new car factory. The soil conditions are shown in fig 3 below:

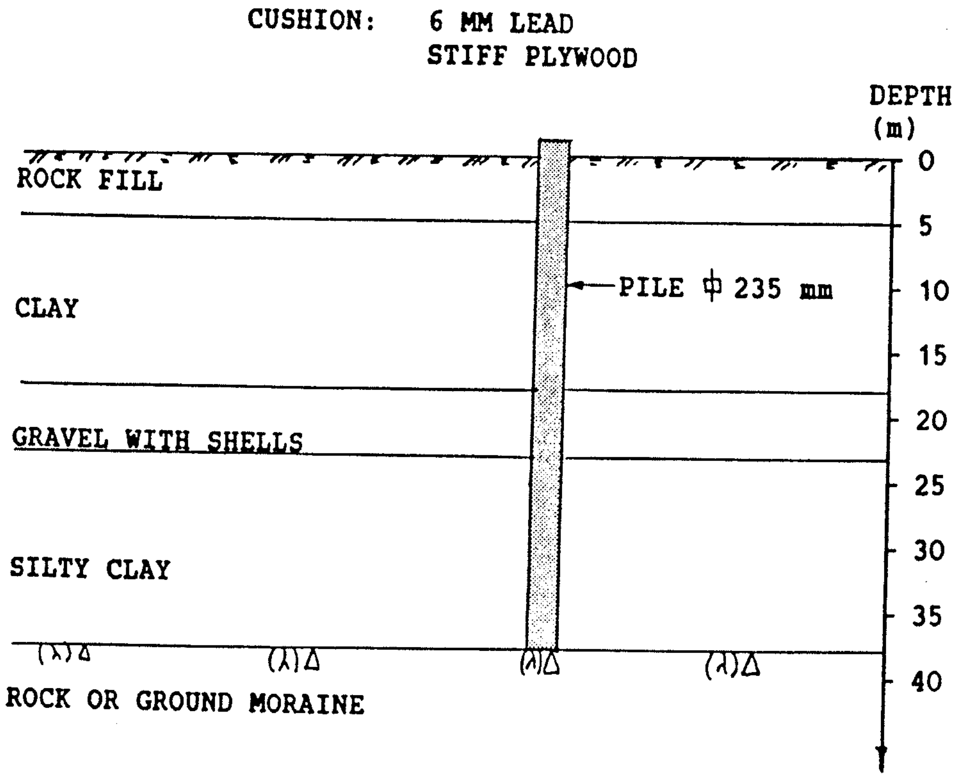

Figure 3 Soil conditions at the Volvo site, Uddevalla, Sweden

The two types of cushion materials tested on the end bearing pile were the 6 mm lead and the stiff plywood. Figures 4 and 6, below, display force-velocity measurements (F-V curves) on a concrete pile and a steel follower for the lead (fig 4) and the plywood (fig 6) cushion. Figures 5 and 7, on the other hand show separately direct comparisons of the force recordings (F-F curves) for pile and follower as well as corresponding velocity recordings (V-V curves). The "follower-curves" in this direct comparison are scaled to the same size as the curves measured on the concrete pile.

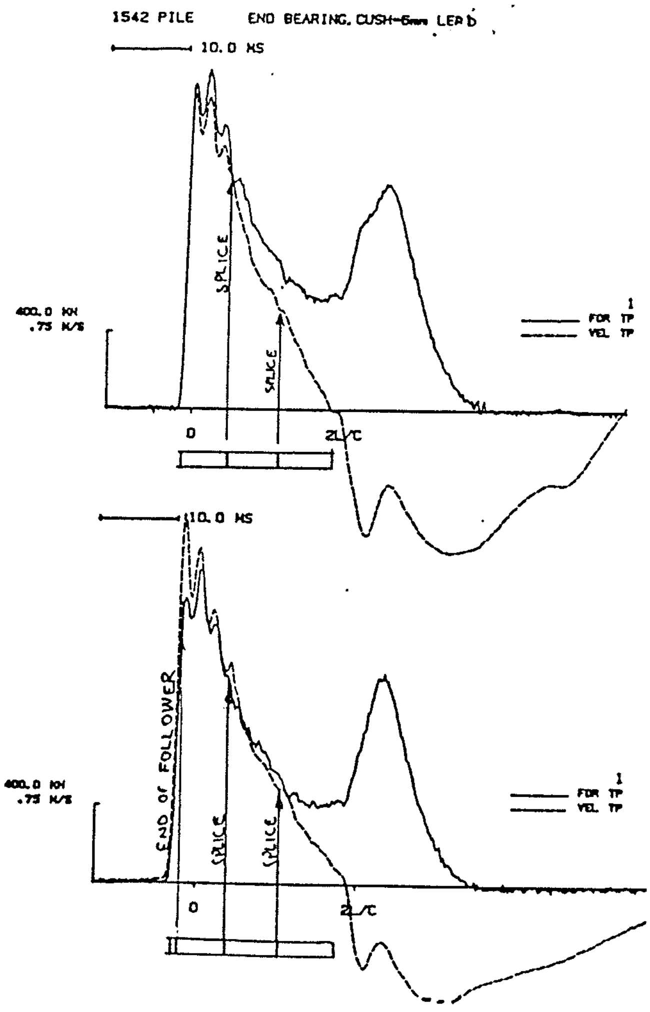

Fig 4 F-V curves. End bearing. Cushion material = 6 mm lead.

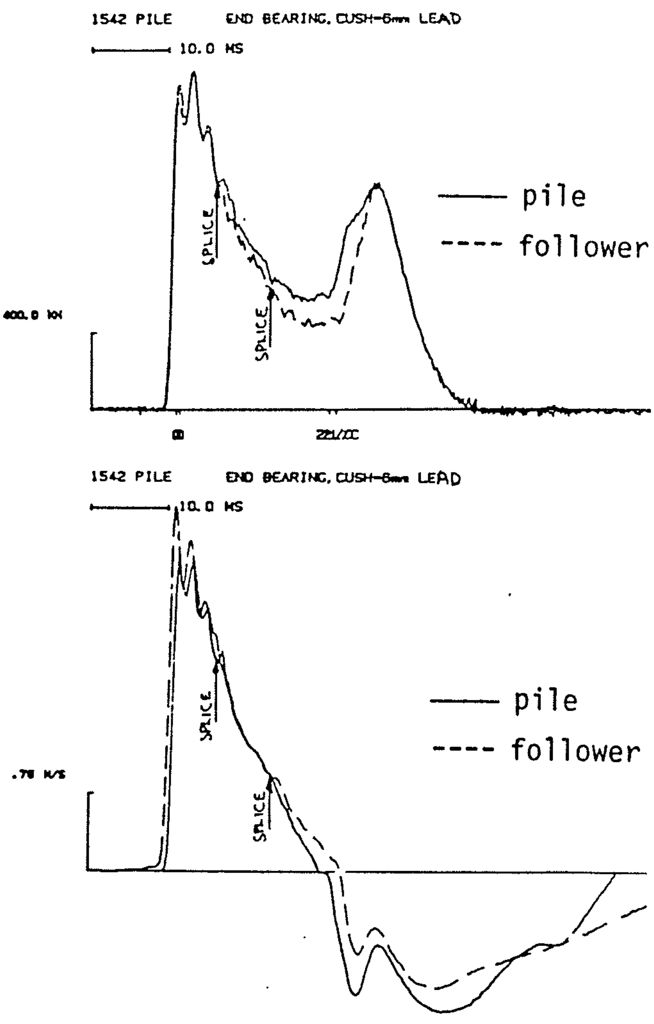

Fig 5 F-F and V-V curves. End bearing. Cushion material = 6 mm lead

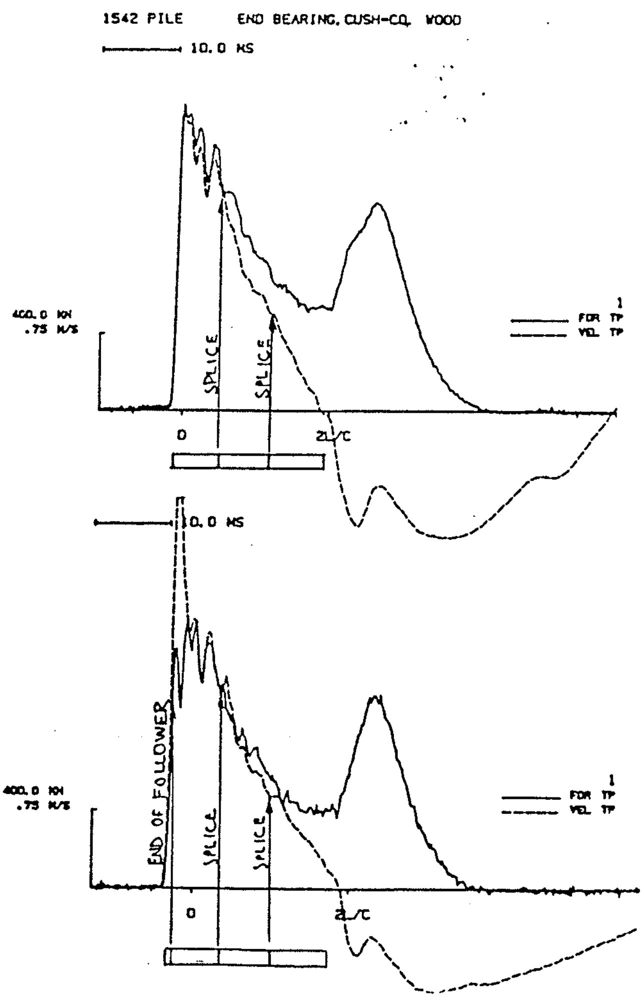

Fig 6 F-V curves. End bearing. Cushion material = Stiff plywood.

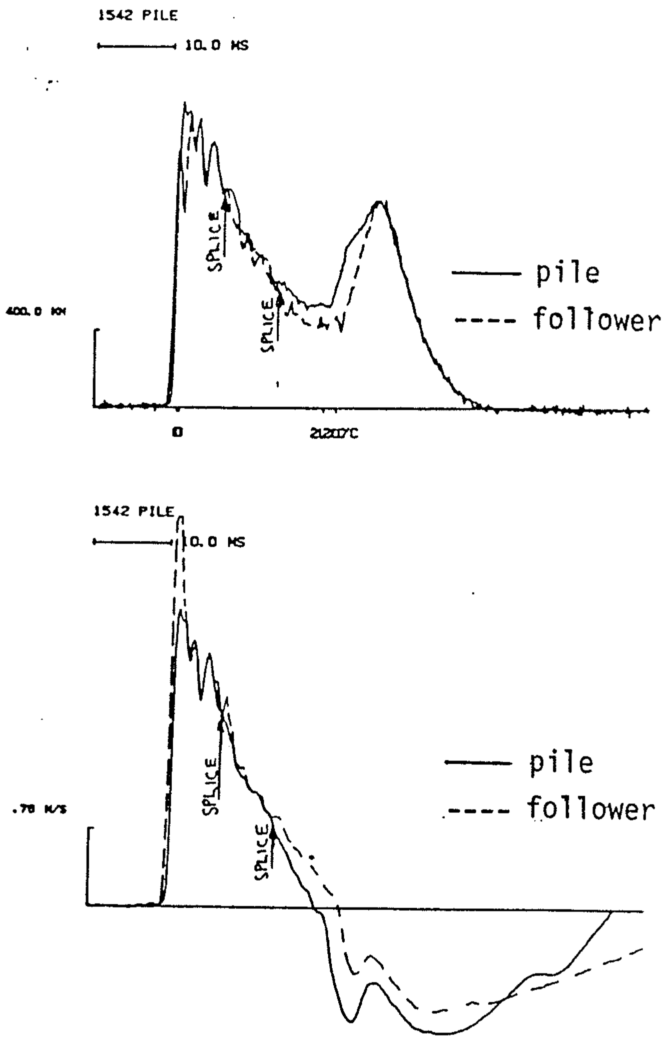

Fig 7 F-F and V-V curves. End bearing. Cushion material = Stiff plywood.

A table comprising the results of the two tests mentioned above (fig 4-7) and five others are shown in table 1.

PILE: CONCRETE ф 235 MM   foll. = follower

Soil conditions at toe	F/V (Peak)		E_{max}	Constant of proportionality*		
	Pile	Foll.		F_{pile}/F_{foll}	V_{pile}/V_{foll}	Cushion
Rock	1.0	0,96	5,6 kNm	1.04	1.0	6 mm lead
Rock	1.0	0.95	14.8 kNm	1.05	1.0	6 mm lead
Rock	1.0	0.95	20,3 kNm	1.05	1.0	6 mm lead
Rock	1.0	0.92	35,0 kNm	1.09	1,0	6 mm lead
Rock	1.0	0.93	6.4 kNm	1.07	1.0	Plywood (stiff)
Rock	1.0	0.93	9.0 kNm	1.08	1.0	Plywood (stiff)
Rock	1.0	0.95	30.1 kNm	1.05	1.0	Plywood (stiff)
AVERAGE	1.0	0.94		1.06	1.0	

* The value of this constant (k) is defined by the scale factor required to make the best possible fit i.e. $k = A_p/A_f$ where A = the area confined by the respective curves and the time axis. For the correlation of the force-curves is the whole lapse valued. For the velocity-curves on the other hand only the lapse up to 2L/c is used.

Table 1   Comparative stress wave measurements on a steel follower and a concrete pile ф 235 x 235 mm^2.

Dimension ф 275 x 275 mm^2

The site for this test was situated in Lilla Edet, Sweden, where a 30 meter high warehouse was being built. The soil conditions are shown in fig 8.

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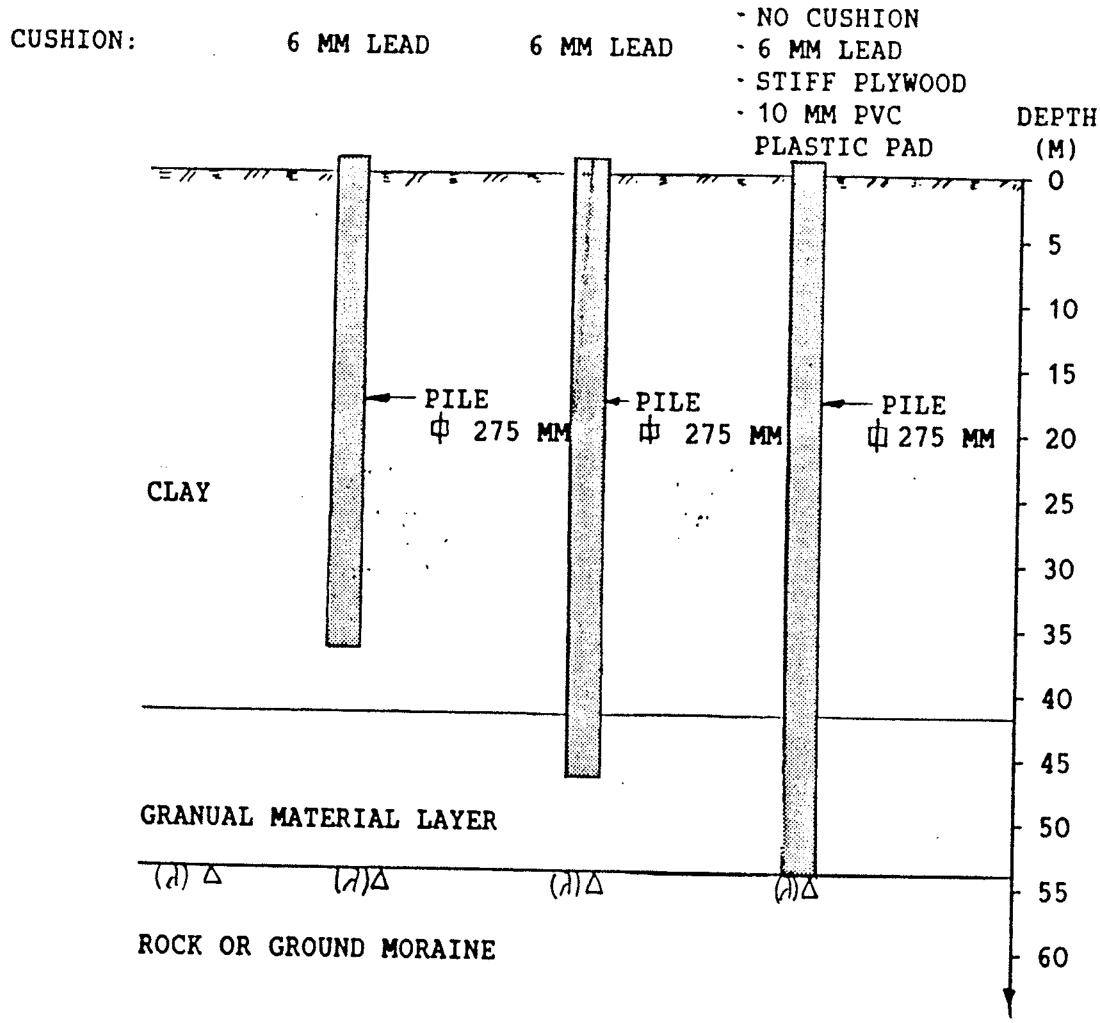

Figure 8   Soil conditions at the site in Lilla Edet, Sweden

Different tests were carried out with the pile toe located in:

- clay
- granular material layer
- rock

Cushion materials used were:

- no cushion
- 6 mm lead
- stiff plywood
- 10 mm PVC plastic pad

The types of curves shown below (Fig. 9-20) are the similar to those described in the previous chapter.

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Notations:

F-V curves	comparison of force and velocity.
F-F curves	comparison of force curves in concrete pile and in steel follower.
V-V curves	comparison of velocity curves in concrete pile and steel follower.

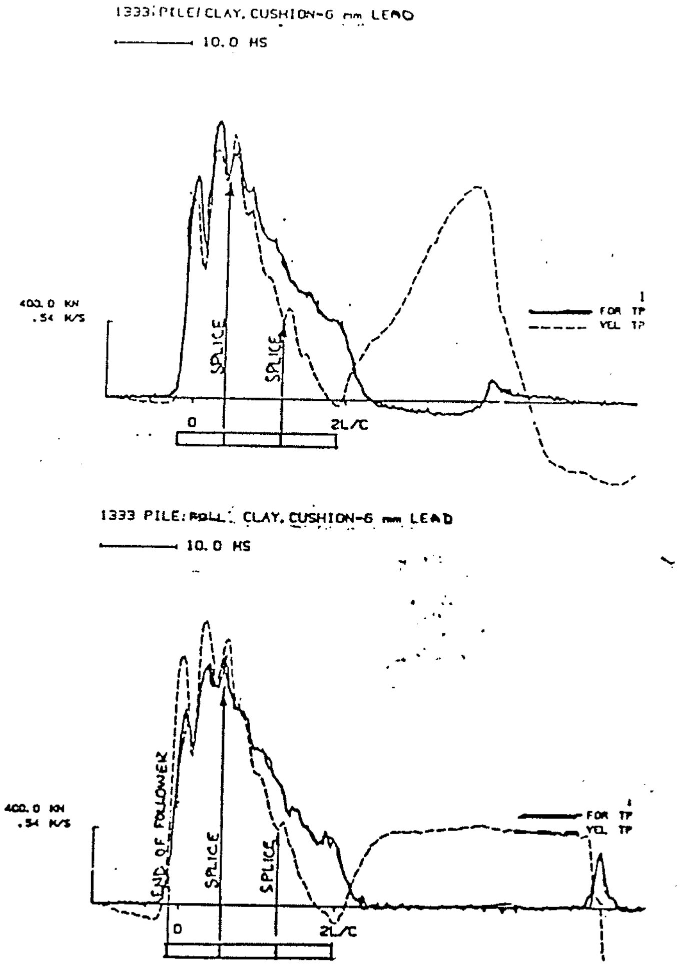


Figure 9. F-V curves. Clay.
Cushionmaterial=6 mm lead

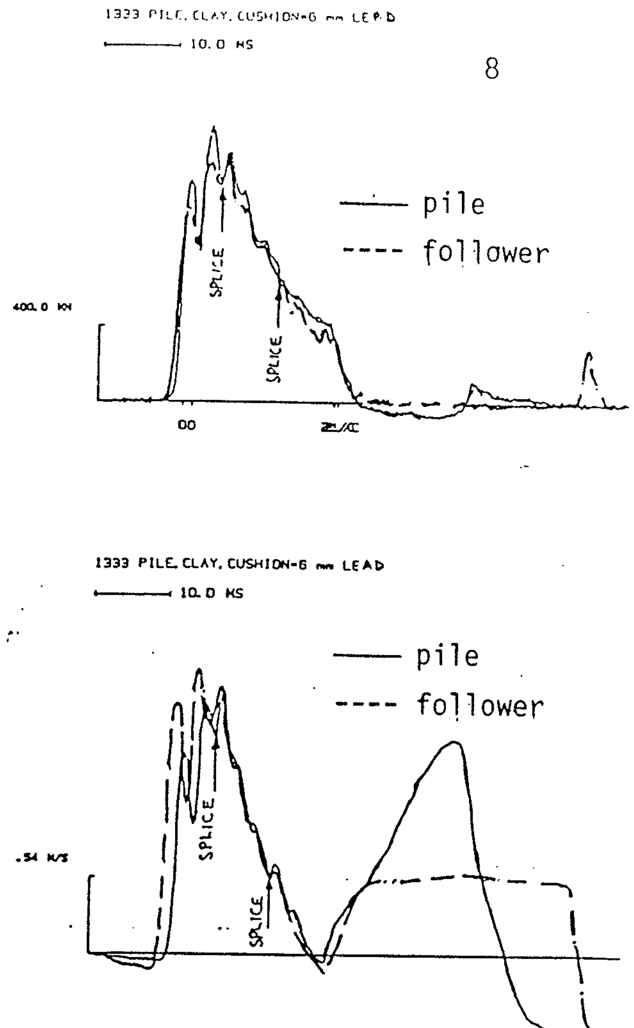


Figure 10. F-F and V-V curves.
Clay.Cushionmaterial=
6 mm lead

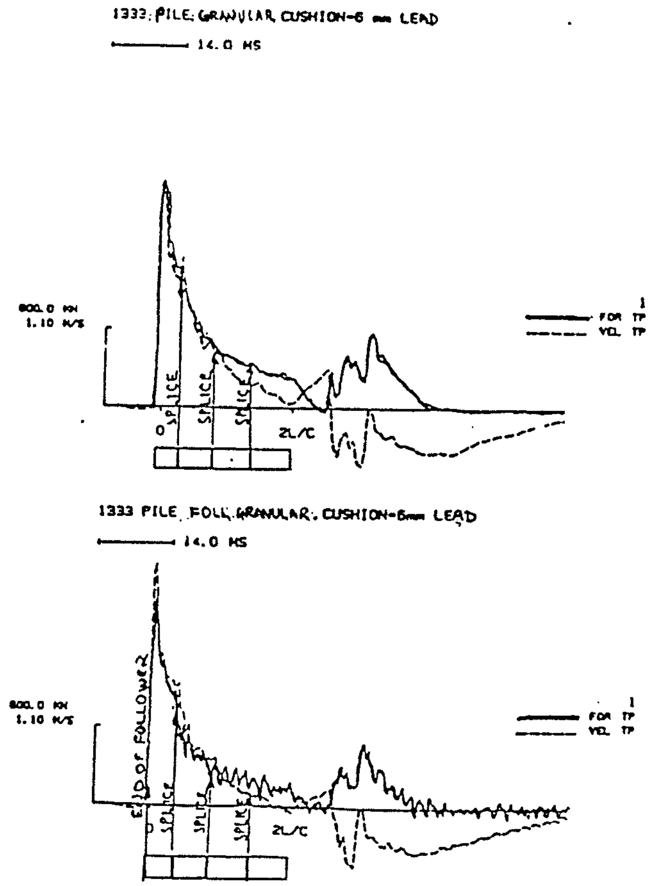


Figure.11. F-V curves. Granular mtrl.

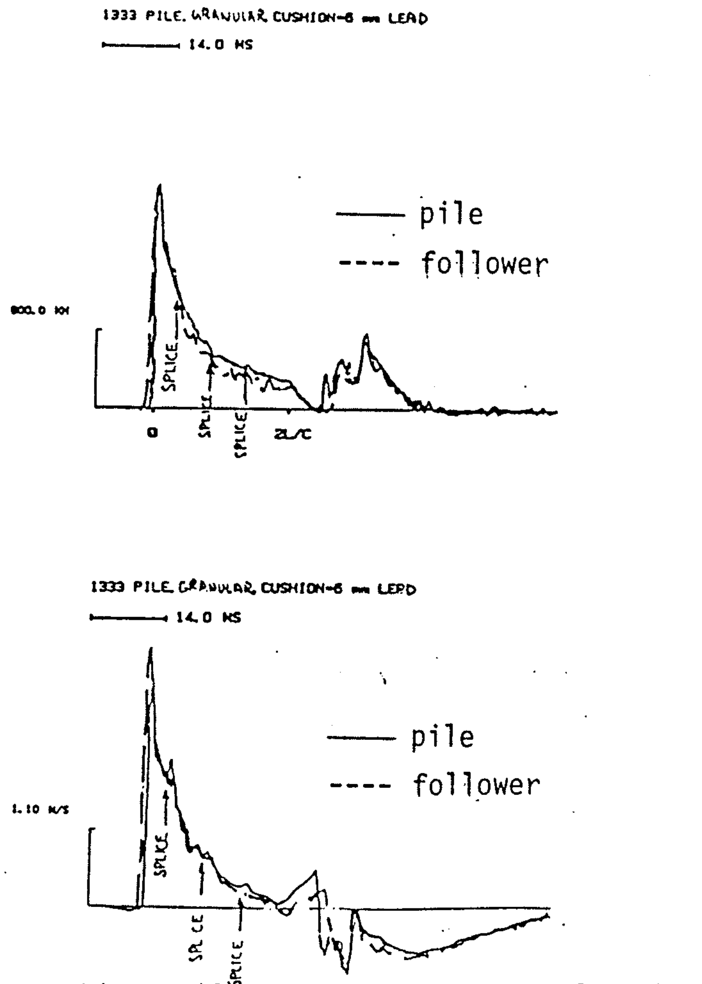


Figure 12. F-F and V-V curves. Granul.m.

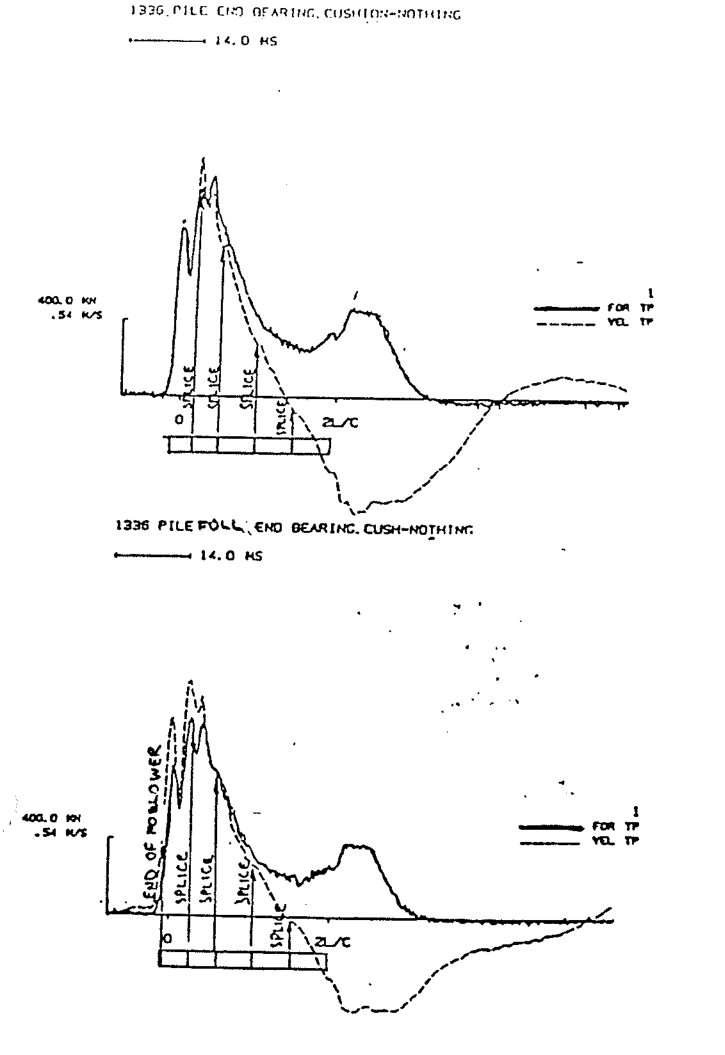


Figure 13. F-V curves. End bearing. Cushionmaterial=no cushion

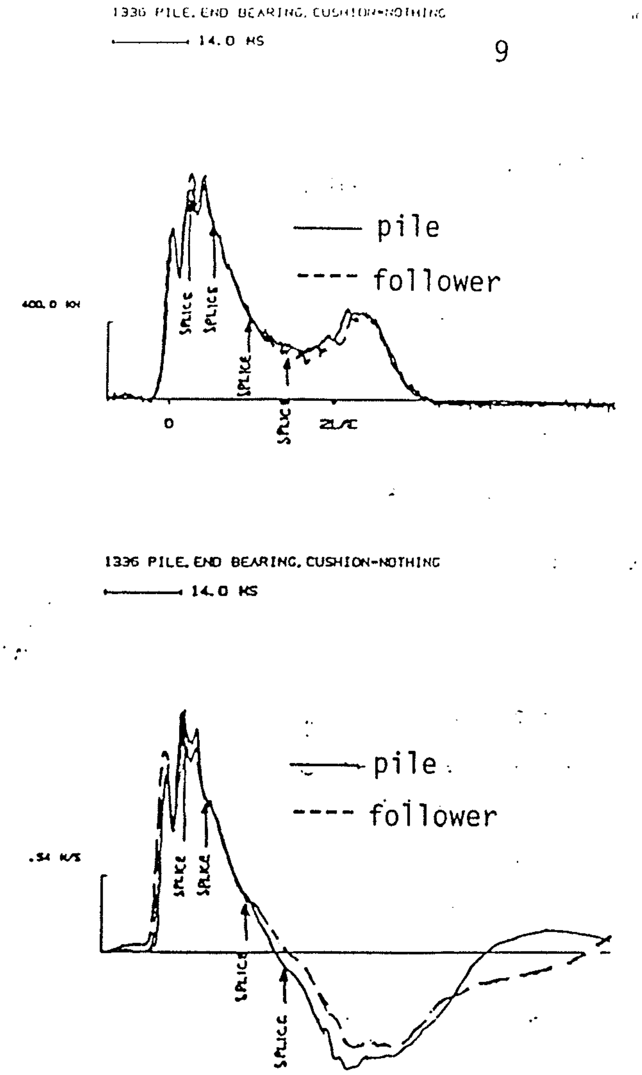
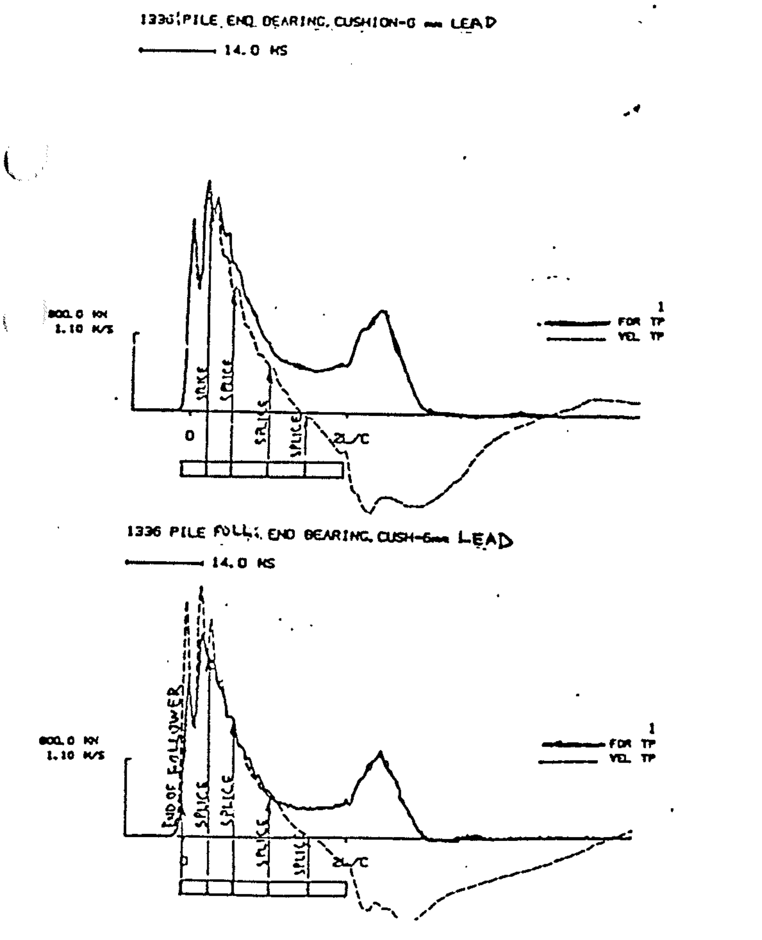


Figure 14. F-F and V-V curves. End bearing. Cushion-material=no cushion



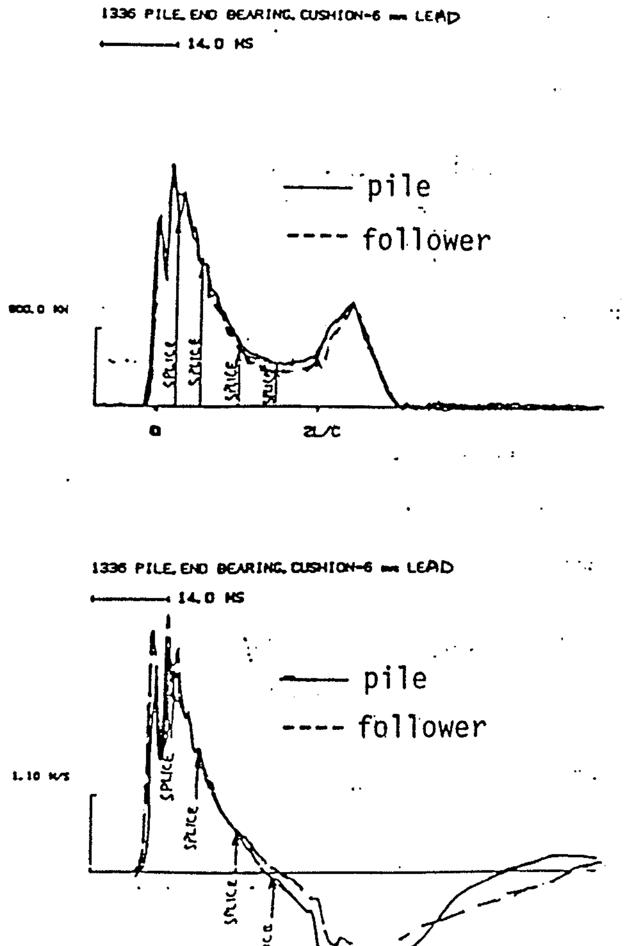


Figure 15. F-V curves. End bearing. Cushion material-6 mm lead .

Figure 16. F-F and V-V curves.End bearing Cush mtrl-6mm lead

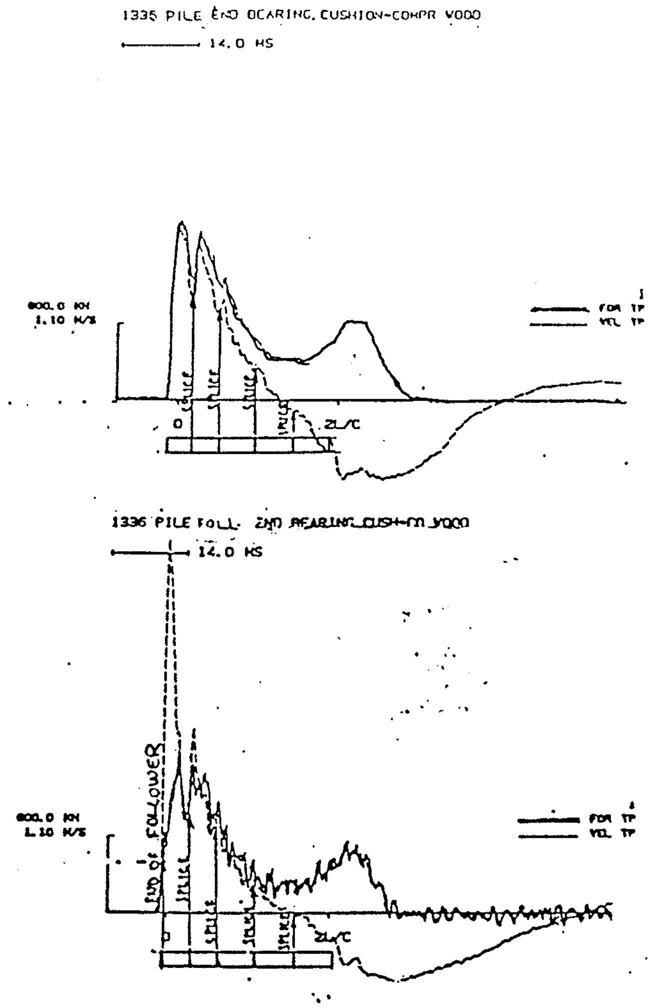


Figure 17. F-V curves. End bearing. Cushionmaterial=stiff plywood.

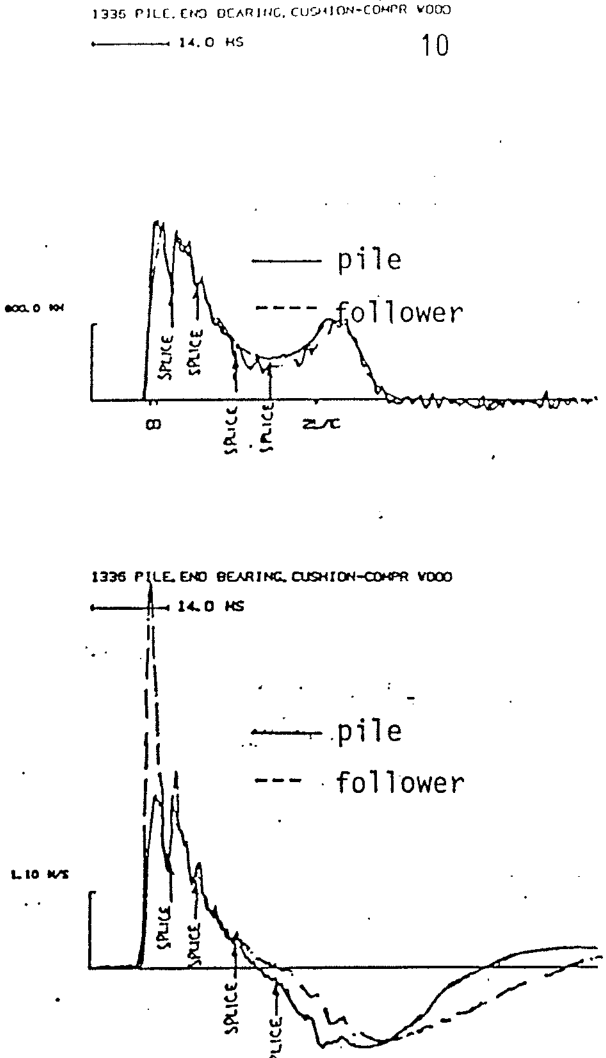


Figure 18. F-F and V-V curves.End bearing.Cushionmtrl= stiff plywood.

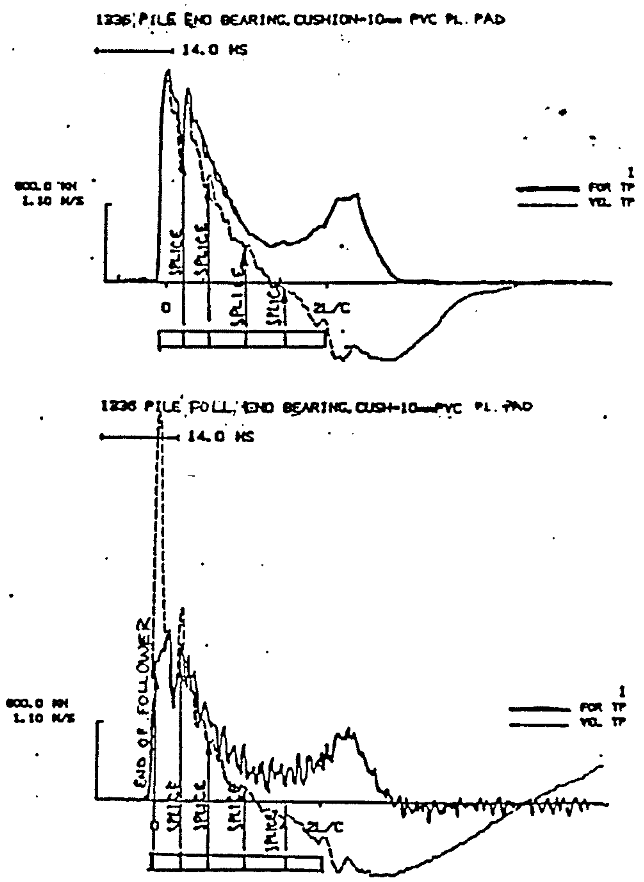


Figure 19. F-V curves. End bearing. Cushionmaterial=10 mm PVC

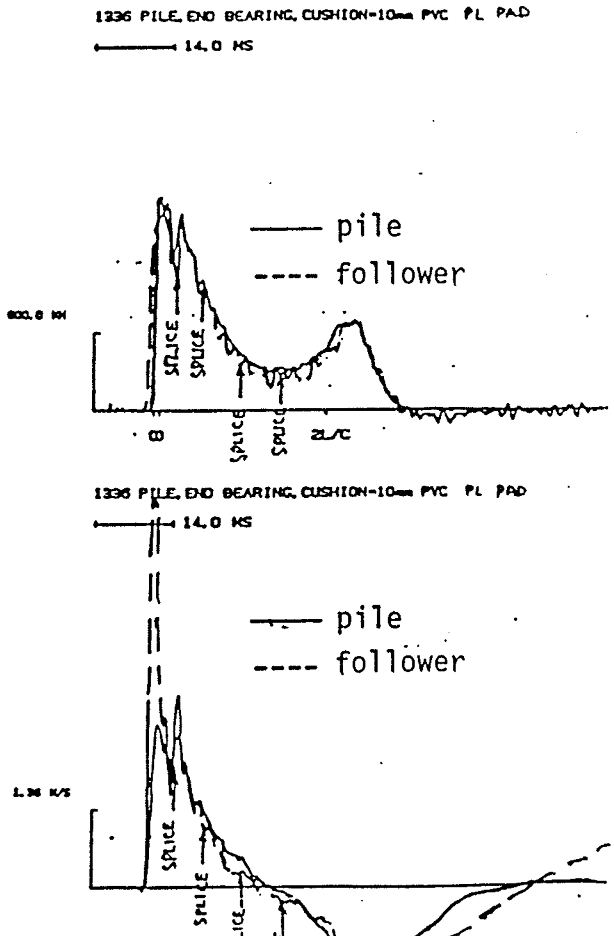


Figure 20. F-F and V-V curves. En bearing.Cushionmateria

A table of the six measurements above are shown in table 2.

PILE: CONCRETE ⌀ 275 MM   foll. = follower

Soil conditions at toe	F/V(Peak)		E_{max}	Constant of proportionality*		
	Pile	Foll.		F_{pile}/F_{foll}	V_{pile}/V_{foll}	Cushion
Clay	1.0	0,94	18,6 kN	1.15	1.15	6 mm lead
Granular material	1.0	0.93	26.0 kNm	1.15	1.08	6 mm lead
Rock	1.0	0.90	13,8 kNm	1.14	1.02	No cushion
Rock	1.0	0.90	49,1 kNm	1.19	1,03	6 mm lead
Rock	1.0	0.88	31.8 kNm	1.20	1.06	Plywood (stiff)
Rock	1.0	0.90	38.7 kNm	1.30	1.23	10 mm PVC plastic pad
AVERAGE	1.0	0.91		1.20	1.09	

* The value of this constant (k) is defined by the scale factor required to make the best possible fit i.e. $k = A_p/A_f$ where A = the area confined by the respective curves and the time axis. For the correlation of the force-curves is the whole lapse valued. For the velocity-curves on the other hand only the lapse up to 2L/c is used.

Table 2   Comparative stress wave measurements of a steel follower and a concrete pile ⌀ 275 x 275 mm^2

Conclusions

The tests show that in many cases it is possible to base the stress wave analysis in a concrete pile by measurements on its steel follower. The results should however be carefully evaluated.

Exploratory test piling should always be carried out by measuring on the pile itself but it seems justified for production control to be performed by using a steel follower according to table 3 below:

Soil conditions	Bearing capacity	Integrity
Clay (driving)	No	Yes
Clay (restrike)	? (Yes)	Yes
Granular material (driving)	(Yes)	Yes
Granular material (restrike)	(Yes)	Yes
End bearing (driving)	Yes	Yes
End bearing (restrike)	Yes	Yes

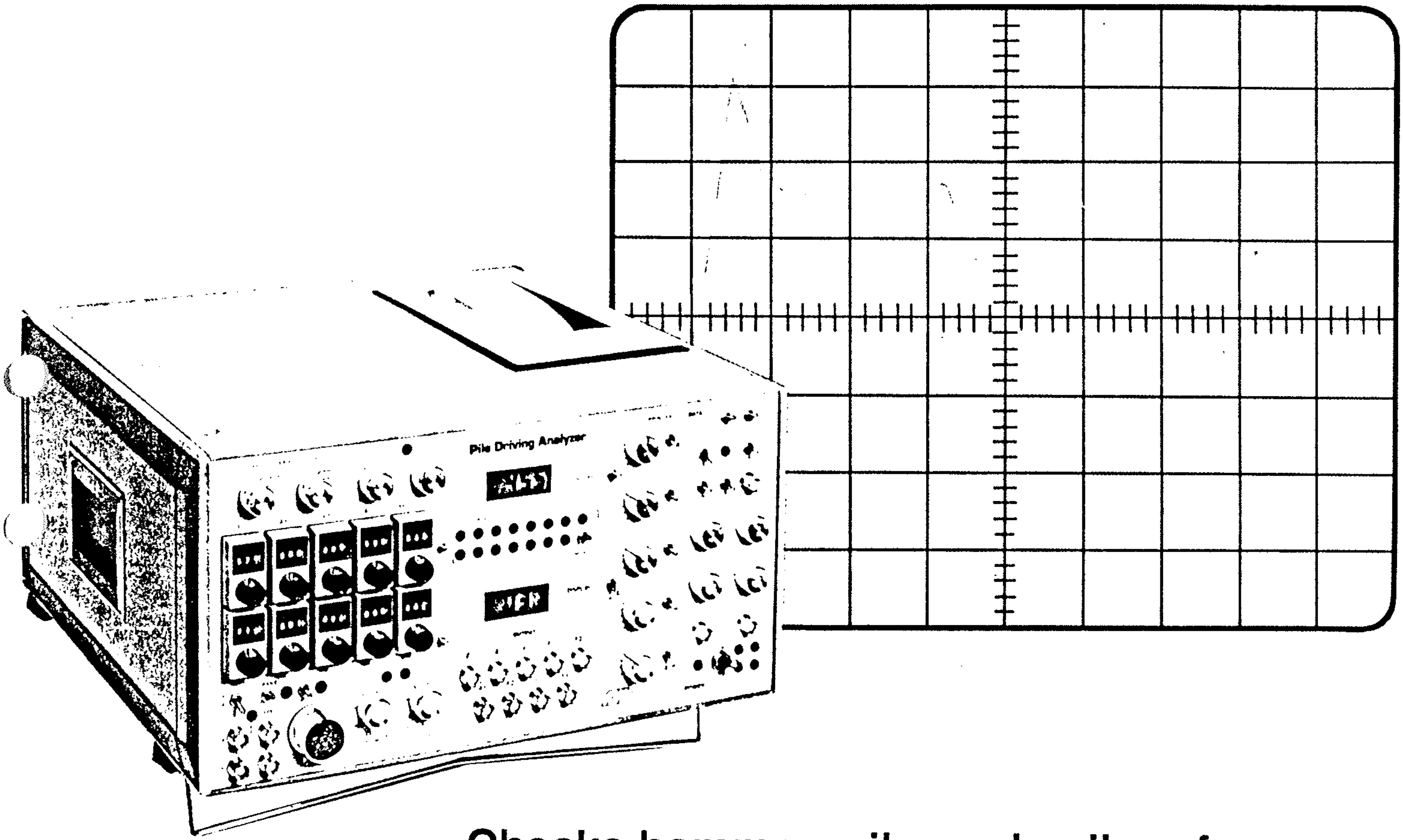
Table 3 Authors expectations with regard to accuracy of correlation between stress wave measurements on a steel follower and simultaneous measurements on the appurtenant concrete pile.

Preferable cushion materials to be used are either no cushion at all or 6 mm lead according to the tests. The other two tested materials i.e. stiff plywood and 10 mm PVC-plastic pad, caused significant disturbance due to reflection waves in the initial phase of the stress wave (Fig 17 and 19). Minor reflection waves were also observed when the two recommended materials were used.
One problem by using a steel follower is that when the compression force is ≤ 0 it is impossible for the stress wave to travel across the transition between the follower and the concrete pile. This will cause errors in the measurements. To overcome this problem it would be possible to equip the pile top and the end of the follower with a splice permitting tensile forces to be transmitted across the interface.

ENCLOSURE

Pile Driving Analyzer™

For Improved Pile Foundations at a Lower Cost



Checks hammer, pile, and soil performance

- Significantly faster and less expensive than static tests
- Improves quality control; dynamically tests many piles in one day
- Immediate results for every hammer blow avoids delays; restrike verifies soil setup/relaxation
- Cost effective in determining best driving criteria or penetration

- Gives soil resistance distribution
- Confirms safe tensile and compressive driving stress
- Detects extent/location of pile damage
- Applicable to piles, drilled shafts or caissons of any size or material
- Reduces legal problems or claims by providing proper documentation and correcting problems early
- Calculates hammer efficiency; assists in detecting malfunctions or comparing different hammers, cushions

- If driving is unusual, determines if problem is hammer, pile or soil
- Checks assumptions of wave equation analysis; bases decisions on measurements, not speculation
- Designed by and for civil engineers with easy-to-understand results; system is simple, quickly assembled and ready to test in minutes
- Backed by over 20 years of proven performance by the developers of dynamic pile testing

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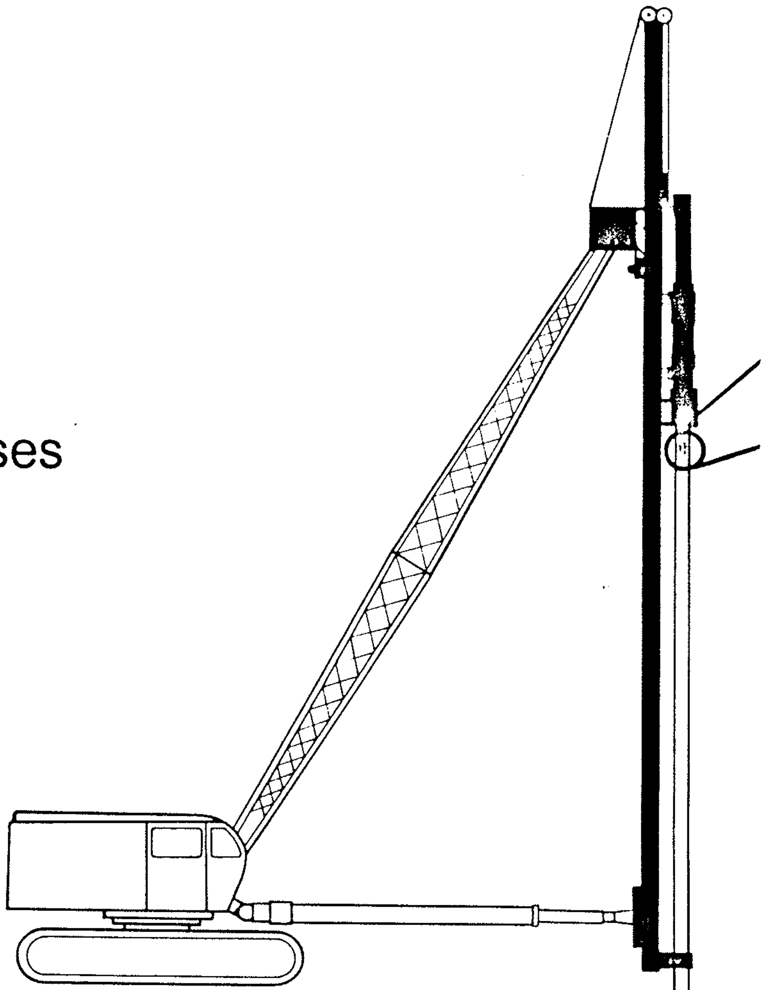
4535 Emery Industrial Parkway
Cleveland, Ohio 44128 U.S.A.
Telephone: (216) 831-6131
Telex: 985662 (PILE DYN)
Facsimile: (216) 831-0916

Dynamic pile testing is not expensive, but problem piles are. Can you afford to just assume that your foundation is safe? Today's higher foundation loads require modern construction control. The Pile Driving Analyzer can quickly verify the entire pile installation and give you greater confidence in your foundation.

Piles no longer have to be overdriven with resulting higher foundation costs. Equally valuable for large or small projects on land or offshore, the Pile Driving Analyzer provides immediate on-sight answers with fast, simple, accurate and inexpensive solutions to your pile problems.

The Pile Driving Analyzer™ Determines:

Bearing capacity
Hammer performance
Tension/compression stresses
Pile integrity or damage



Dynamic Pile Testing – The Better Alternative

Perhaps you have noticed innovation in construction other than pile driving and wondered why blow counts and some 19th century dynamic formulae are still used to estimate pile capacity. Load testing of an arbitrary pile, usually not run to failure, is expensive and causes long construction delays. A quick, inexpensive test on several piles giving much more information may be more attractive.

Begun in 1964, research at Case Western Reserve University under Dr. G.G. Goble resulted in a reliable, theoretically sound, easy-to-use technique to predict pile capacity under dynamic loading (remolded strength during driving or service load including set-up/relaxation by restrike testing). To meet an increasing demand for this capability, Pile Dynamics, Inc. was formed in 1972 and developed the "Pile Driving Analyzer" (PDA), an easy-to-use, preprogrammed field computer designed for civil and geotechnical engineers.

After more than two decades of research and experience, our Pile Driving Analyzer has been proven worldwide at over 2,000 construction sites on over 20,000 piles in over 30 countries on six continents. The results of dynamic testing have been correlated with data from several hundred static load tests.

How the Pile Driving Analyzer Works

Reusable transducers measuring strain and acceleration are quickly attached with bolts or anchors to concrete, steel, or timber piles. The system has also been used for auger piles and drilled caissons. The PDA provides signal conditioning, and converts the measured signals to force and velocity for use in its digital processor. Using closed form solutions to wave propagation theory, the PDA then solves for activated soil resistance, maximum pile stresses, pile integrity and hammer performance. Immediate printout for each hammer blow provides a complete investigation of the hammer-pile-soil system as the pile is driven or during restrike. This fast, simple procedure can be easily applied to several piles, giving more information at a fraction of the cost.

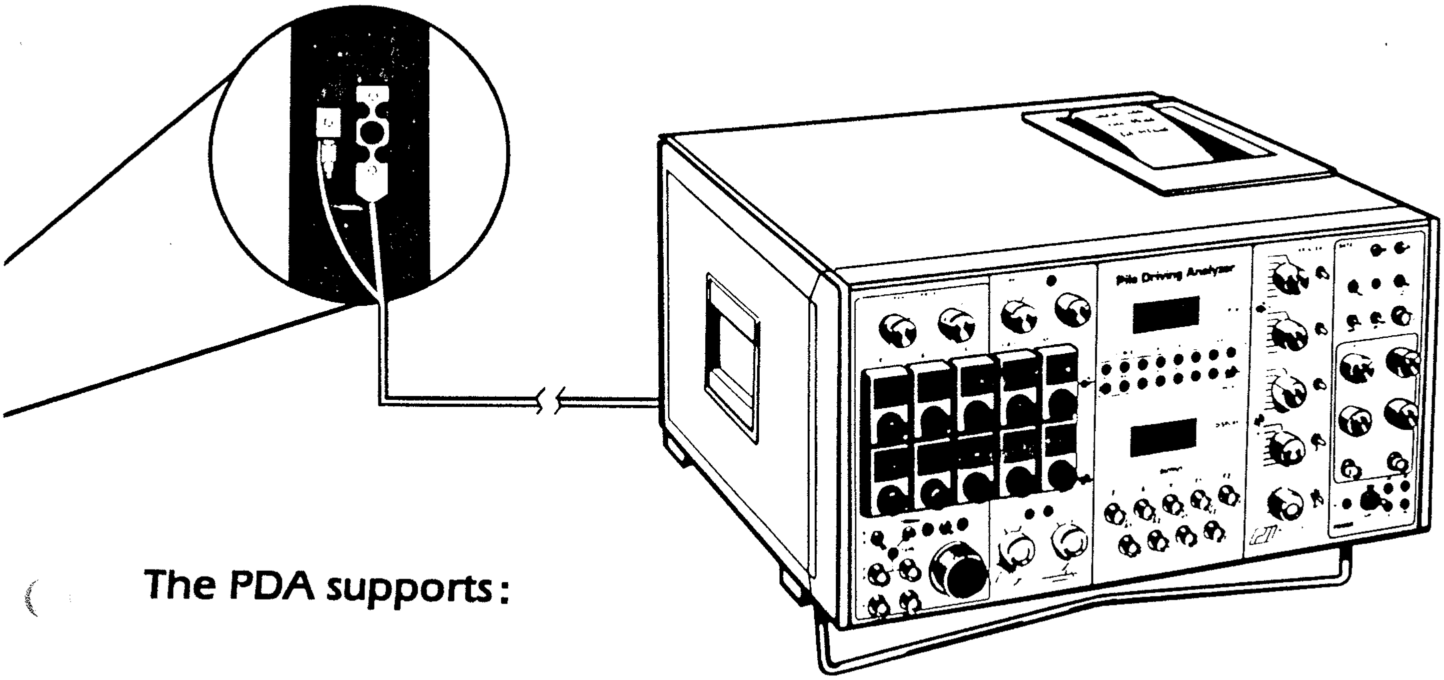
This compact field-portable system was designed by civil engineers to be user-friendly; its automatic operation, self checking and warning features practically insure error-free results. Our rugged device contains no disks or other dust or temperature sensitive components and the real time analysis for every blow eliminates field replay or other interruptions.

Use of the PDA Results

Although an improvement over dynamic formulae, wave equation results are only as accurate as the available soil and hammer input information. Our PDA system can verify the assumed wave equation hammer and soil models or provide the correct data for improved wave equation analysis.

The PDA is often used to check driving stresses or measure hammer performance for qualifying hammers. The system can inspect the pile for structural damage without costly extraction.

With the PDA system, static tests can be reduced or eliminated. For very small projects where no testing is usually performed, or on large piles or offshore projects where testing is prohibitively expensive, PDA tests provide a low cost tool for inspection. For major projects with multiple planned static tests, some static tests can be replaced with several dynamic tests, increasing quality control with substantial savings. Preliminary test programs prior to or at the beginning of a job become both practical and economical using the PDA and have often saved time and money by monitoring stresses



The PDA supports:

Tape Recorder
Oscilloscope
Strip Chart Recorder
Computer
Digital Plotter
Digital Storage
Telecommunication

and preventing pile damage, detecting hidden difficulties in the hammer performance, and improving driving criteria or reducing penetration requirements. Regardless of project size, PDA testing will result in an improved foundation and fewer problems.

> Electronic measurements and computation have revolutionized the world of the civil engineer. With today's higher pile loads and more cost competitive foundations, the Pile Driving Analyzer produces answers . . . for every blow . . . in real time . . . to produce better, safer foundations at a lower cost.
>
> When experience counts . . . The Pile Driving Analyzer, a tool of knowledge.

Case Histories

Reduces Cost—For a sewage treatment plant, dynamic testing indicated that each pile could be shortened by at least 20 feet, later confirmed by static tests. Occasional PDA tests then provided the construction control for this 8,000 pile project, resulting in savings of $2,500,000.

Saves Time—About 120 days construction time were saved by replacing 30 static pile tests with 400 dynamic tests for the replacement of several railroad and highway bridges. The PDA's accuracy was verified by spot checking with static tests.

Saves Money—For a large bridge in Australia, twelve 1.1 to 1.5 meter diameter drilled caissons were tested dynamically. Ultimate capacities exceeding 2,000 tons correlated well with static tests. Dynamic tests then replaced static tests for 70 additional caissons saving $2,000,000.

Investigates Damage—The PDA tested 137 concrete piles in seven days at a sewage treatment plant to determine the extent and location of suspected structural damage.

Hammer Evaluation—During construction of a large processing plant where four air hammers were used, it became apparent that actual efficiencies varied and the blow count criterion was questioned. The PDA found that efficiencies of some hammers were less than half of other supposedly identically rated hammers. Driving criteria were adjusted for each hammer's measured efficiency.

Detects Problems—Testing was compared with the wave equation on H pile bridge foundations. The PDA detected poor hammer performance, resulting in inadequate capacity at the required blow count, a fact later confirmed by a static test. The PDA also found hidden major structural damage in several piles.

Offshore Uses—The PDA has been used on many offshore oil platform installations to check hammer performance and pile stresses and on exploration conductor pipes to obtain soil constants for later driveability analysis with wave equations.

Pile Driving Analyzer™

Model GC

Results for Each Blow

- Bearing capacity from Case Method
- Optional capacity computations for large quakes, variable concrete/timber wave- speed, and long friction piles
- Toe resistance and skin friction
- Maximum compression stress, acceleration, velocity and displacement
- Maximum tension stress in pile
- Pile structural integrity; extent and location of damage
- Maximum energy transferred to pile
- Ram impact velocity
- Hammer cushion stiffness
- Blows per minute for hammer check
- Blow counter
- Input and reflection of force, velocity, upward and downward force waves
- Quakes and damping factors with additional analysis

State-of-the-Art Digital Processing

- Fast Motorola 68000 microprocessor analyzes up to 120 blows per minute
- Analog-to-digital conversion up to 20 kHz for 1, 2 or 4 channels; up to 300 msec total sample time
- Memory: 256 kB
- High accuracy digital integrations
- Easy program upgrades

Output

- Analysis for every blow during driving; no waiting or delays for results
- Immediate printing of inputs, blow count and up to 40 different results for each blow on fast built-in printer
- Analog output of force, acceleration and velocity in real time
- Automatic scope and strip chart setup
- Data storage of every blow on analog FM cassette recorder
- Optional RS232 interface to computers, plotters, modems or other devices
- Report-quality digital plotting of measured and computed quantities vs time; load vs deflection of cushions and of pile toe bearing
- Temporary digital storage in RAM of up to 100 selected blows for transfer to disk for permanent data storage (early 1988)
- Capacity vs blow count

Warning Indicators

- Internal calibration check
- Detects transducer malfunctions
- Comparison of V1/V2, F1/F2, V/F for data quality and/or bending
- Detects high stresses
- Power supply monitors

Specifications subject to change without notice

Automatic Signal Conditioning

- Two strain channels with high accuracy seven wire shielded hookup
- Two acceleration channels with velocity from special purpose integrators
- Automatic selection of transducers
- Automatic trigger and balance; frequency response 1600 Hz (3 dB)
- Reanalysis from tape records

Automatic Oscilloscope Control

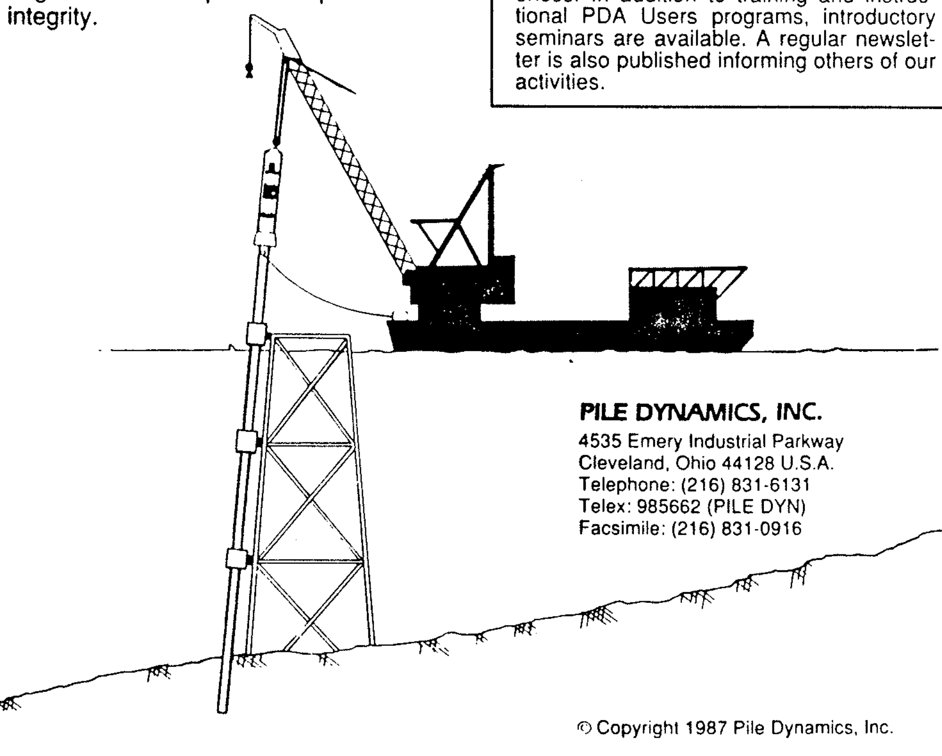
- Continuous bright display on simple X-Y scopes of signals for every blow avoids misinterpretation
- Display force and proportional velocity with time markers for fast evaluation
- Also displays force waves, displacement, energy and resistance vs time
- Pile damage indicator

Environmental/Physical

- User oriented controls
- Power: 90 to 250 volts AC, 44-440 Hz. 250 Watts from portable generator
- Temperature: Operating -10° to +35° C, Storage -10° to +75° C.
- Size: 16 x 18 x 9 inches (410 x 460 x 230 mm)
- Weight: 44 lbs. (20 kg.)

Pile Integrity Tester (PIT)

This method, now an option for the PDA, uses a small handheld hammer to strike the pile. An accelerometer senses reflections from serious discontinuities or the pile bottom. The PDA plots the resulting signals to rapidly allow the engineer to select piles with questionable integrity.



Pile Dynamics - The Developers of Dynamic Pile Testing

You can rely on our commitment to quality products and service, both today and in the future. We are big enough to serve your needs promptly in North America or world-wide, either directly or through our agents. Yet we are small enough to care about you, our valued client.

Warranty/Service

Since the founding of Pile Dynamics in 1972, over 150 PDA units have been placed in operation worldwide through 1987. The PDA is covered by a full one year warranty which can be extended for a modest cost. Service is available in several locations worldwide. Most problems can be isolated quickly by simply contacting our staff. If the problem is not corrected immediately, replacement parts can be shipped promptly and installed quickly due to our modular design.

Technical Support

We are working full time to help find the solutions you need. We have built a strong reputation based on solid engineering, a quarter century of dedicated research as the original developers of dynamic pile testing, and attention to the needs of our clients. We work closely with our clients providing training and further support as requested. Technical advice and opinions are provided promptly and free of charge. Additional analyses by either CAPWAP or WEAP wave equation methods (we also developed both methods) are available by purchase or as a service.

User Seminars and Training

We are constantly learning from our PDA Users and our own experience, and incorporate these findings into our practice. This is further strengthened by our inviting all PDA Users worldwide to gather regularly for further instruction and to share experiences. In addition to training and instructional PDA Users programs, introductory seminars are available. A regular newsletter is also published informing others of our activities.

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