

Accuracy and Limitations of Full-Scale Dynamic Shaft Testing

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Dynamic methods of load testing driven piles and bored shafts are in common use throughout the United States and Europe. The complex equations and computer programs used to analyze the data from such tests might lead to the assumption that the results are equally precise. In fact, little is known or has been published about the absolute accuracy of such methods. The potential sources of error that may exist in all phases of the operation, from data collection to correlation with static load tests, are described. The differences between the classical CASE method and the SIMBAT technique are discussed.

Method of predicting the capacity of driven piles using dynamic loading have been available for many years and are well documented and extensively used. When these techniques are used on bored cast-in-place shafts, new problems arise, not the least being that of increased scale. More important, the shaft dimensions and properties are more difficult to quantify than those of precast piles, and these factors influence the accuracy of the predictions.

The Centre Experimental de Recherches et d'Etudes du Batiment et des Travaux Publics (CEBTP) has carried out research in dynamic test methods since 1980 and has participated in Class A prediction trials in the United States and Europe. Working tests have been carried out on shafts ranging in diameter from 8 to 48 in. in a wide range of soil conditions. This research led to the development of a methodology specifically adapted to bored shafts known as SIMBAT (Simulation de Battage). It also made the authors aware of the potential errors inherent in all types of dynamic pile test and the difficulty of obtaining genuine static/dynamic correlations.

This paper has the following aims: to create an awareness of the potential cumulative errors that are inherent in dynamic load testing, to highlight the difficulty of obtaining genuine static/dynamic correlations, and to compare the CASE method of predicting static load test results with the SIMBAT technique.

TEST ACCURACY

The result of a dynamic load test is either a single value quoted as being the shaft capacity or a load settlement plot. How accurate are these results? Plus or minus 5 percent? Plus or minus 50 percent? Most engineers would find the former to be an acceptable possible error but the latter unacceptable. A shaft capacity reported as being 100 tons but that could be

anything between 50 and 150 tons is of little or no practical use.

The problem is that the real accuracy of dynamic testing is not known. It is all too easy to develop complicated formulas and compute results to the n th decimal place, and when the job is done it looks very accurate. It is an easy and fatal step to think that the accuracy of our arithmetic is equivalent to the accuracy of our knowledge about the problem in hand.

This paper does not attempt to answer these problems but instead considers the various sources of error that can arise. The general arrangement of a dynamic test system is shown in Figure 1, and the separate stages of a test are shown in Figure 2.

The potential sources of error in the various phases of the test are given in Tables 1 through 3. Readers might like to insert their own estimates in the right-hand column. Often, some of these errors will be positive and some negative, and they will partially cancel each other out. They may, however, conspire together and produce a cumulative effect.

In a driven precast pile many of the assumed values are interlocking, and there is less room for global error. For example, the pile impedance is calculated from the same terms as is the conversion of strain to force.

$$Z = \rho CA \quad (1)$$

where

ρ = concrete density,
 C = bar wave velocity in pile, and
 A = pile cross-section

$$\text{Force} = \text{Strain} \times EA \quad (2)$$

where

$$E = \text{dynamic modulus of concrete} = \rho C^2 \quad (3)$$

For a bored shaft, however, it must be remembered that the strain to force calculation is based on the properties of the instrumented section of shaft, whereas the impedance calculation requires a knowledge of these parameters for the shaft as a whole. It is unlikely, for example, that the shaft cross-sectional area will be uniform over the full length or that the concrete modulus of the shaft will be identical to that of the instrumented section. It is apparent that even if modest values are inserted in the "estimated accuracy" column of Tables 1 through 3, the net effect on global accuracy will be significant.

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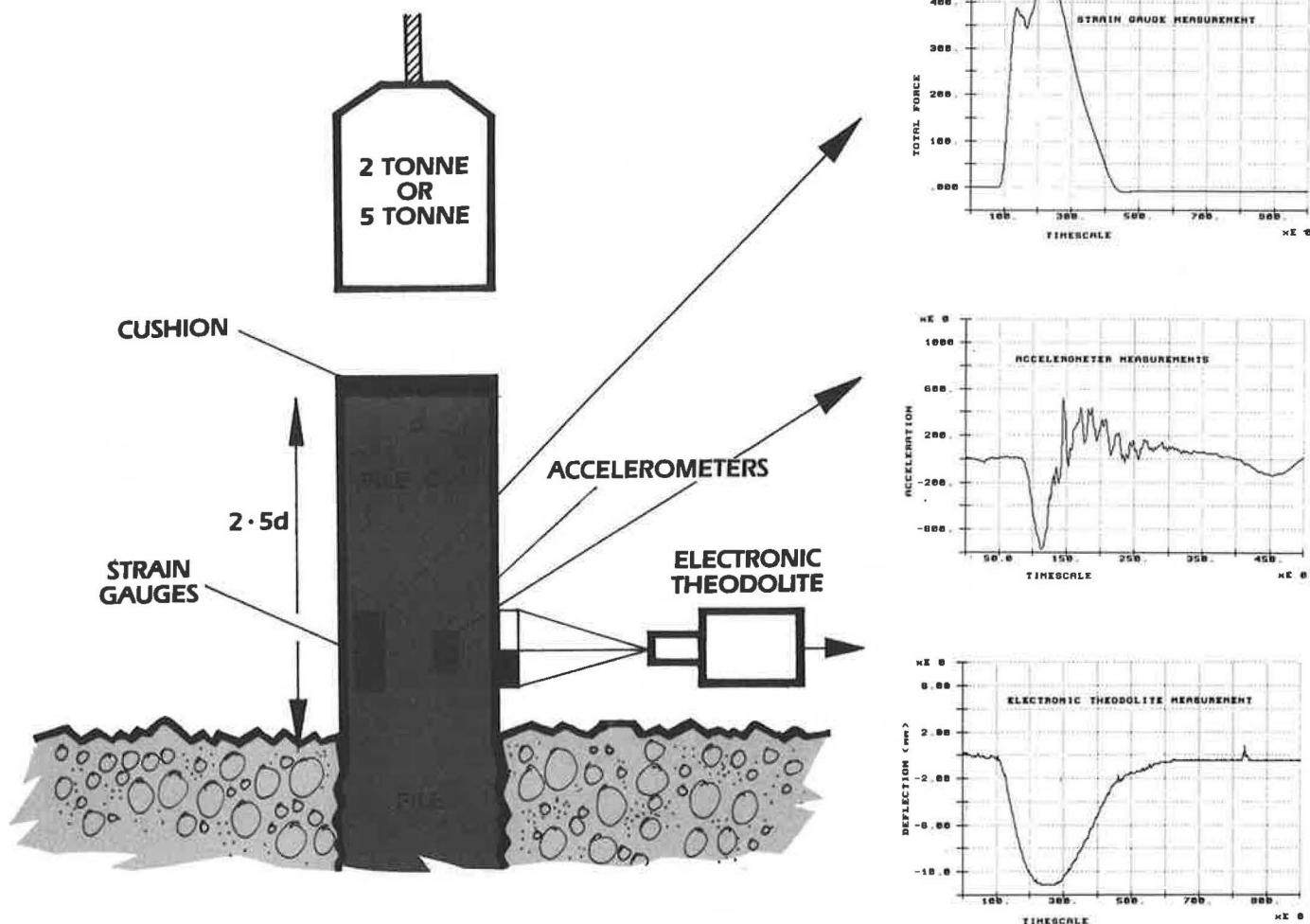


FIGURE 1 General arrangement of system.

A number of measures to improve accuracy are available:

- Low-strain transient dynamic response testing to try to obtain wave velocity and characteristic impedance values for the shaft;
- Ultrasonic testing of a concrete cylinder, representative of the shaft top, to obtain a dynamic modulus value; and
- Use of an electronic theodolite to measure shaft displacement. The shaft top velocity can then be obtained either by integration of acceleration or from the differential of displacement, the two measuring systems being independent.

Finally, construction records of the shaft and a knowledge of the soil conditions are indispensable if useful predictions are to be made.

CORRELATION BETWEEN DYNAMIC AND STATIC LOAD TESTS

The most common form of correlation is a comparison between the predicted "ultimate" capacity from a dynamic test and the "ultimate" capacity as defined by the well-known

Davisson criteria from a static result. Whereas this is a convenient method of comparing results, it does not tell the whole story in the way that a full load/settlement plot does. There is also ambiguity in the term "static load test." Is it a constant rate of penetration test or an incremental test with the load maintained for several hours so that creep and possible short-term consolidation can occur? The situation is not clear, and there are at present no universally accepted correlation procedures.

Many researchers, including the authors, believe that for the present the most satisfactory way of comparing results is by means of full load/settlement plots. In this way, any differences such as creep and consolidation can be identified.

Genuine correlations between dynamic and static load tests are difficult to obtain. Once a shaft or pile has been loaded to failure, either dynamically or statically, it is no longer virgin and cannot be expected on retest to behave in the same manner. This is particularly true in cohesive or silty soils. How then can true correlations be obtained?

The simplest and most common method is by carrying out a dynamic test either before or after static loading. This must be considered unreliable, or, at the least, of limited accuracy. It is of course possible to sandwich a static test between two

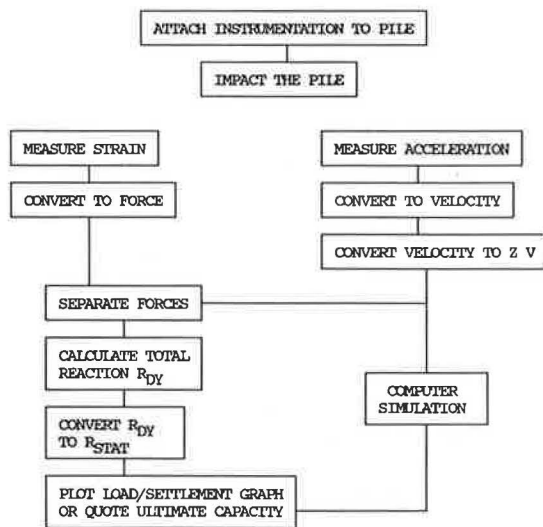


FIGURE 2 Stages of a test.

dynamic tests, one carried out before and one after the static test. This would give a good indication of performance changes brought about by the testing itself—if there were none, the correlation could be considered valid.

An alternative approach, and one which was used on a trial site in Belgium (1), was to construct a series of shafts, each with its own twin a few feet away. Dynamic tests were carried out on the first set of shafts, followed by static loading of the twins. One can never know for certain whether the twins were identical, but encouraging results were obtained.

COMPARISON OF THE CASE AND SIMBAT METHODOLOGIES

The SIMBAT technique is a relative newcomer in the field of dynamic load testing. It was developed in France by CEBTP and is the result of some 10 years of research, both in the laboratory and in the field. The system uses many of the

TABLE 1 TOTAL FORCE MEASUREMENT

OPERATION	POTENTIAL SOURCE OF ERROR	ESTIMATED ACCURACY
Attachment of Strain Gauges to Pile Shaft	Poor Bonding/attachment Non-Verticality	± %
Measurement of Strain	Does strain measured at 2 points on pile surface accurately represent average strain over the full shaft section	± %
	Strain gauge accuracy, temperature effects etc.	± %
	Eccentricity of hammer impact on shaft	± %
	Transmission of strain gauge signal through connecting cables to Data Acquisition	± %
	Accuracy and resolution of Data Acquisition System	± %
Conversion of Strain to Force	<u>Force = Strain x Section x Modulus</u>	
	Accuracy of Modulus Assumption (particularly if pile has steel sleeve)	± %
	Accuracy of Section Measurement	± %
	Global Accuracy of Force Measurement	± %

TABLE 2 VELOCITY MEASUREMENT

OPERATION	POTENTIAL SOURCE OF ERROR	ESTIMATED ACCURACY
Attachment of Accelerometers to Pile	Poor attachment Non-Verticality	± %
Measurement of Strain Acceleration	Accelerometer accuracy, temperature effects etc.	± %
	Transmission of signal to Data Acquisition System	± %
	Accuracy and resolution of Data Acquisition System	± %
Conversion of Acceleration to Velocity	<u>Velocity = Integral of Acceleration</u>	
	Progressive errors, integration constant etc.	± %
	Global Accuracy of Velocity Measurement	± %

TABLE 3 PREDICTION OF ULTIMATE CAPACITY FROM FORCE AND VELOCITY

OPERATION	POTENTIAL SOURCE OF ERROR	ESTIMATED ACCURACY
Multiply Velocity by Impedance (Z)	Assumption of $Z = \rho CA$, where ρ = concrete density C = Bar wave velocity in pile A = Pile cross-section	\pm %
Separation of Forces and Calculation of Total Reaction	Choice of position on Force Separation Diagram (See Fig 3)	\pm %
	Are all the upward forces due to soil effects or, in the case of bored shafts, is there a contribution from shaft enlargements etc.	\pm %
Conversion of Total Reaction to Static Reaction	<u>Choice of Methodology</u> CASE CAPWAP TNO SIMBAT	\pm %
Prediction of Ultimate Capacity Velocity	What is Ultimate Capacity? Choice of definitions.	\pm %
	Have all the soil resistance forces been utilised?	\pm %
	Global Accuracy of Prediction	\pm %

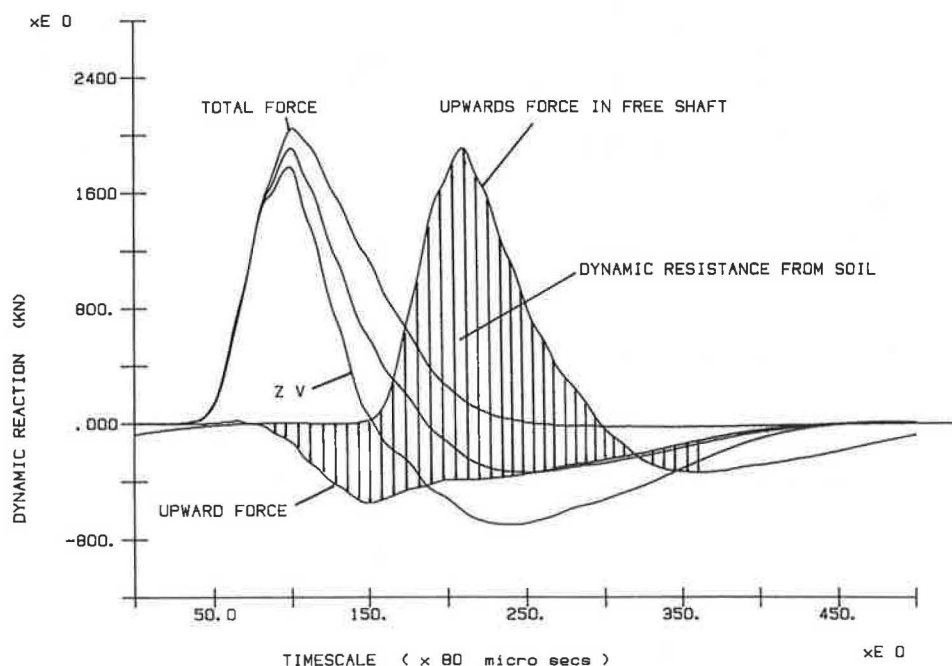


FIGURE 3 Force separation diagram.

original wave equation theories but differs from other systems in a number of areas. These have been described previously by Paquet (2). Probably the most important single difference is the conversion of dynamic total resistance to static resistance.

The classical CASE formula states that the dynamic to static conversion is related to the pile top velocity as described by Hannigan (3):

$$R_{STAT} = R_{DY} - Jc(ZV_1 + F_1 - R_{DY}) \quad (4)$$

where

- R_{STAT} = static resistance,
- R_{DY} = dynamic or total resistance,
- V_1 = velocity at Time 1,
- F_1 = force at Time 1, and
- Jc = dimensionless CASE damping factor.

This assumes that all the damping resistances are concentrated at the shaft toe.

In the SIMBAT method it is proposed that the relationship between dynamic and static resistance is a function of the penetration velocity of the shaft with respect to the soil:

$$R_{\text{STAT}} = R_{\text{DY}} - f(V_{\text{pen}}) \quad (5)$$

where $f(V_{\text{pen}})$ is a function of penetration velocity.

The shaft velocity and the penetration velocity are quite different, as can be seen in Figure 4.

The second important difference between methodologies is that SIMBAT uses a series of impacts on the shaft, often 10 or more, the permanent settlement of penetration being mea-

sured for each blow. The reactions are then plotted against cumulative penetration. Finally, Equation 5 is applied to the set of results as a whole to obtain a static load settlement plot. This procedure does not require the assumption of a soil damping factor.

The two methods were compared using a series of blows on a driven cast-in-place shaft in France. The shaft was 550 mm in diameter and 16.4 m in length and formed in silty sand. The CASE capacity was calculated for four of the blows using a soil damping factor (J) of both 0.2 and 0.4, these being appropriate values for the soil conditions. The results are given in Table 4 and are plotted in Figure 5. The differences between the two predictions are immediately apparent.

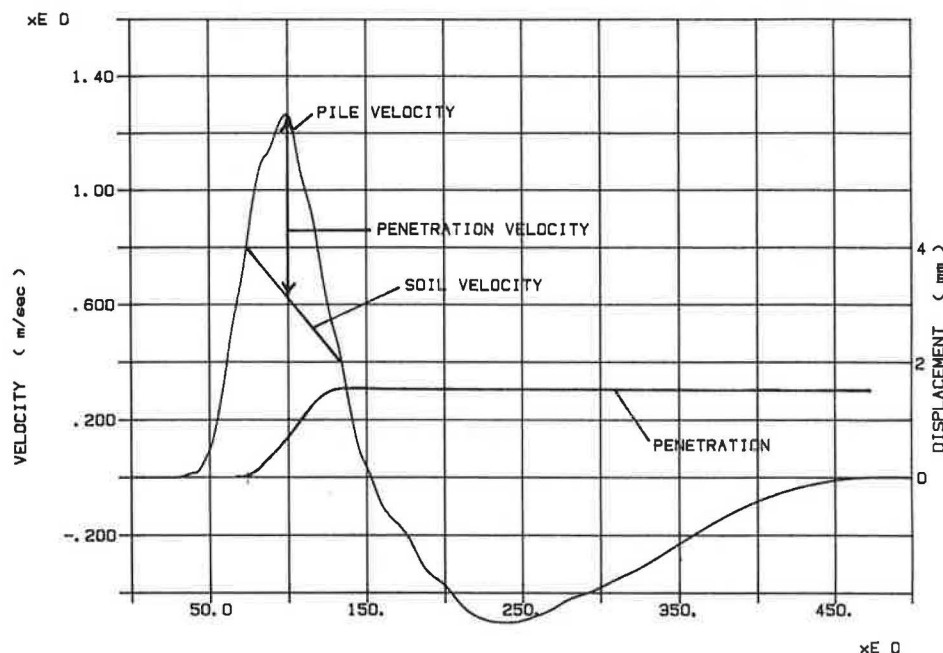


FIGURE 4 Velocities in pile-soil interaction.

TABLE 4 COMPARISON OF CASE AND SIMBAT PREDICTIONS

BLOW No.	DROP HEIGHT (m)	PEN (mm)	DYNAMIC RESISTANCE (KN)	SIMBAT STATIC RESISTANCE (KN)	CASE STATIC RESISTANCE (KN)	
					$J = 0.2$	$J = 0.4$
1	0.3	0.85	2300	2650		
2	0.4	0.96	2900	2166		
3	0.5	0.85	2900	2250		
4	0.6	1.48	3460	2328		
5	0.7	1.73	3755	2432		
6	1.0	2.47	4480	2590	3876	3187
7	0.4	0.44	2900	2563		
8	1.0	2.51	4750	2830	4153	3330
9	0.5	0.81	3360	2740		
10	1.2	3.36	5400	2830	4571	3689
11	0.5	1.00	3680	2915		
12	1.5	3.65	6000	3208	5221	4241

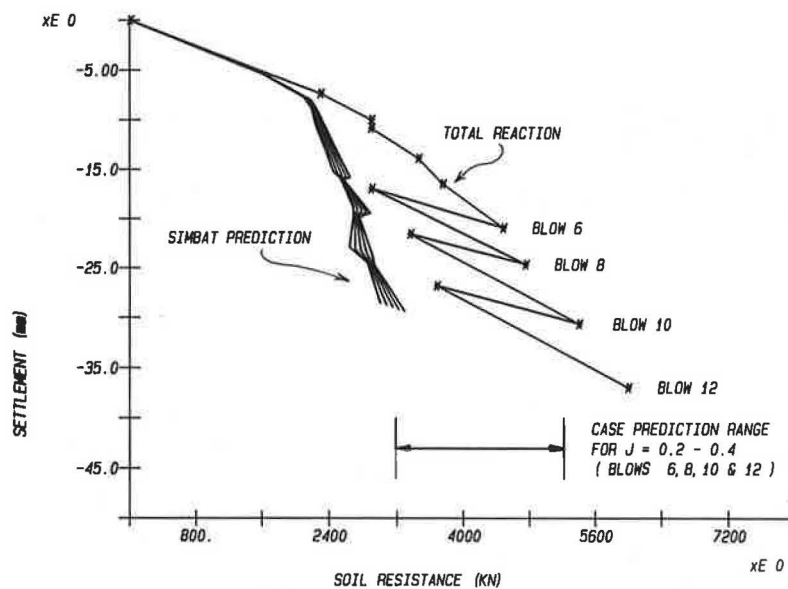


FIGURE 5 SIMBAT and CASE pile capacity predictions.

CONCLUDING REMARKS

It may seem strange that practitioners of dynamic testing should seek to publicize the potential errors and limitations of these methods. The intention is not to discredit such tests, but rather to create an awareness of potential errors and the measures that can be taken to reduce them. Dynamic/static correlations of 1:1 are probably the result of happy coincidence rather than the application of science.

The current Federal Highway Administration program of dynamic testing in California and Texas is providing an enormous data base from which some of the questions raised in this paper may be answered.

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