Alternative facts in pile testing

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ABSTRACT

For many in the foundation testing industry it is not always clear which 'fact' is truly a fact, or merely an opinion (which could be classified as an alternative fact). This paper will discuss a number of 'facts' associated with high strain dynamic testing and review most of them using the stress wave theory. This stress wave theory applied to foundation piles is over 70 years old, and is a great tool to assess 'facts'. Some of the 'facts' have been debunked in the past, but remain popular because of they are easy to apply and because practitioners are simply unable to keep up with the sheer number of papers and articles about the subject. Instead they often limit themselves to reading what is in line with expectations, thereby perpetuating these alternative facts. By providing telling examples this paper hopes to break that cycle.

Keywords: Beta Method, pile damage during driving

1 INTRODUCTION

In the 1860s a Frenchman, A.J.C. Barre de Saint Venant, applied the principles of conservation of mass and momentum to the water flow in an open channel. The application resulted in two quasi-linear differential equations, for which de Saint Venant produced a theoretical solution, the so-called method of characteristics. This method was then used for a variety of hydrology related issues, such as to predict the propagation of tidal waves, based on the work of J. Massau and J.C.Schonfield.

Starting in the 1930's Saint Venant's equations were applied to pile driving around the world, such as by L.H. Donnell in the United States, D.V. Isaacs in Australia, and W.H. Glanville in England. In 1938 the latter directed the first comprehensive study aimed at understanding cracking in concrete piles at both the top and the bottom during pile driving. As part of this work, measurements were taken during pile driving using what was considered at that time portable equipment in a construction trailer. As such Glanville is truly the pioneer in the field of pile driving analysis (PDA), as it would take some 18 years before similar work was done in the Netherlands (by A Verduin in 1956) and some 25 years before it was done in the United States (by G.G. Goble in 1964). Just as Glanville can be considered the father of PDA, Isaacs can be considered the first to ever use wave equations for modeling pile driving. But apart from that, he should also be remembered for his insights on the issue of safety factors. In an article published in 1931 in the Journal of the Institution of Engineers Australia, Isaacs wrote the following on this subject:

> It should be remembered, however, that these are not true factors of safety, but include a "factor of ignorance." The author suggests that when the ultimate resistance of any pile has been determined, in fixing the factor of safety the most unfavorable conditions possible in the supporting strata should be judged (the range of conditions possible being narrowed with better knowledge of the subsurface conditions and of the possibility of disturbance from extraneous sources) and a proportion of the factor of safety - a "factor of ignorance" - then allowed in respect to these possible conditions, the manner of determining the ultimate load, and the type of loading to be borne. The remaining proportion of the factor of safety - or true margin of safety - should be approximately constant for all classes of loading and foundation conditions involving the same value of loss in case of failure; and the overall factor

> of safety will then be equal to the product of the true factor of safety with the "factor of ignorance." (p. 305)

Another interesting view on test methods was expressed by Huw Williams in 1987 in a paper he wrote for the International Conference on Piling and Deep Foundations, in which he stated:

> It is now some 20 years since non-destructive tests were first used as a means of quality control for piled foundations. During this time new methods have evolved and old methods have developed, largely due to advances in micro-processing. But despite these undoubted technical advances and the increasing popularity of such methods, many engineers are unaware of their inherent limitations and cannot therefore choose the technique best suited to their requirements. All too often the choice of method will be dictated by cost alone. All test methods, however, have limitations and it is only by being aware that the engineer can specify an appropriate test programme.

While Isaacs refers to “ignorance” and Williams to “unawareness”, another aspect may actually be in play as well: the reliance on “alternative facts” in pile testing. The term “alternative facts” has been described in many ways, such as untruths or delusions. But a fact is something that actually exists (a reality), while an alternative is one of the choices in a set of given options; typically opposites of each other. Therefore “alternative facts” refer to the opposite of reality (which is delusion), or the opposite of truth (which is untruth). Unfortunately when it comes to High Strain Dynamic Testing (HSDT) of foundations there are a number of these “alternative facts” that are widely held as realities as a result of the way they are presented. Some of them will be addressed in this paper, with the aim to create a better awareness of this test method.

2. THE OUTCOME OF HIGH STRAIN DYNAMIC TEST DATA ANALYSIS

When it comes to the outcome of High Strain Dynamic Test (HSDT) data analysis, the general perception is that the analysis outcome is the capacity of the foundation, just as a static load test would provide, thereby ignoring among others the basics of the analysis process, the subjective element in the data analysis, established accuracy of the results and the dynamic effects of the test.

2.1 The Test Analysis Method

The process to analyze HSDT results is generally referred to as “Signal Matching”. As the name suggests, the process aims to determine an analytical "match" to a measured pile driving signal. As shown in Figure 1, the process begins when the measured signal obtained during the test is introduced as input to the pile-soil system at the instrumentation level. Next the analytical signal is calculated and compared to the measured signal. Since the properties of the pile are generally assumed to have been modeled very accurately, any difference between the measured and calculated signal is due to the soil model used for the calculations. Consequently the soil parameters throughout the soil profile are changed until good agreement is obtained between the measured and calculated signal. Once a good match has been established, the static and dynamic model parameters for the soil resistance along the pile (shaft friction) and underneath the pile (toe resistance) are determined, with which actual values of the mobilized resistances can be estimated. This allows then the estimation of the mobilized static bearing capacity of the pile, which is the sum of all static contributions of the soil to the pile, since the dynamic soil resistance occurs during driving only.

The main difficulty with this process is that it has no unique solution. While the Method of Characteristics itself has a unique solution, the soil model with an unknown number of layers and different strength, quake and damping values for each layer is simply too complex to allow for a closed form solution. As a result the final match depends on the interpretation of the analyst and hence the analysis results, which are not necessarily the pile capacity, but rather the analysts best assessment of that capacity, are clearly subjective.

A completely different issue is the fact that the derived capacity estimation does not necessarily address the serviceability requirements of the overall foundation. It may well be that the allowable settlement is less than the settlement associated with the derived capacity and therefore in the opinion of the authors the outcome of a HSDT (or any load test for that matter) should never be single number, but rather a load-displacement curve. However, since this aspect is not specifically related to HSDT it will not be addressed in detail in this paper.

2.2 The Subjective Element

The consequence of the fact that signal matching does not have a unique solution is best illustrated by the outcome of load testing events supervised and analyzed by independent parties. Tables 1 and 2 are generated from the report on the International Prediction Event on the Behavior of Bored, CFA and Driven Piles in CEFEUP/ISC’2 experimental site in Porto, Portugal in 2003, a typical class A prediction event. The tables present the capacity predictions (shaft Rs, end bearing

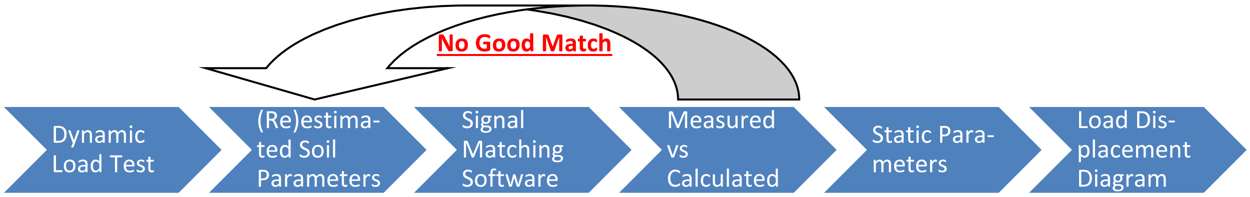

Fig. 1. Signal Matching Process.

Table 1. Predictions based on HSDT methods for pile E0 (bored).

Predictor	Blow	Capacity (kN)			R/ Q_{SPLT}	R/R_{max}
		Rs	Rb	R		
1	B1	549	902	1451	1.44	0.75
	B2	591	910	1501	1.49	0.78
	B3	610	993	1603	1.59	0.83
	B4	542	1099	1641	1.63	0.85
2	B1	844	650	1494	1.48	0.78
3	B2	1170	180	1350	1.34	0.70
4	B1	644	915	1559	1.55	0.81
5	B1	1149	289	1438	1.43	0.75
	B2	1828	72	1900	1.89	0.99
	B3	1828	72	1900	1.89	0.99
	B4	1828	58	1886	1.87	0.98
6	B1			1716	1.70	0.89
	B2			1632	1.62	0.85
	B3			1865	1.85	0.97
	B4			1922	1.91	1.00
7	B1	730	682	1412	1.40	0.73
	B2	952	567	1519	1.51	0.79
	B3	1217	427	1644	1.63	0.86
	B4	1377	284	1661	1.65	0.86
Q_{SPLT} = 1007 kN						

Table 2. Predictions based on HSDT methods for pile C2 (driven)

Predictor	Blow	Capacity (kN)			R/ Q_{SPLT}	R/R_{max}
		Rs	Rb	R		
1	B19	496	986	1482	1.00	0.78
	B21	636	815	1451	0.98	0.76
	B23	563	894	1457	0.98	0.76
2		729	653	1382	0.93	0.72
3	B3	815	615	1430	0.96	0.75
	B12	700	610	1310	0.88	0.69
	B28	790	740	1530	1.03	0.80
4	B30	928	632	1560	1.05	0.82
5	B22			1877	1.26	0.98
	B23			1884	1.27	0.99
	B24			1900	1.28	1.00
	B25			1909	1.28	1.00
6	B3	971	510	1481	1.00	0.78
	B6	992	592	1584	1.07	0.83
	B11	645	743	1388	0.93	0.73
	B15	742	627	1369	0.92	0.72
	B20	804	606	1410	0.95	0.74
Q_{SPLT} = 1481 kN						

Rb, as well as total capacity R) of very experienced predictors for a drilled shaft (Table 1) and a driven pile (Table 2) using DLT results. In the tables the values of ultimate resistance obtained by a Static Pile Load Test (QSPLT) are presented as well. Different blows are used by predictors, so the values are grouped by predictor's number.

The parameter R/R_{max} (the ratio between the prediction in question and the maximum predicted value) clearly illustrates the subjective element in the analysis results. For both bored and driven piles pile the value of this parameter ranges from approx. 0.7 to 1, which means that the highest capacity prediction is more than 40 % higher than the lowest. This range would even be wider if the predictions for the end bearing or the shaft friction were analyzed. The tables also show that for bored piles the analysis results clearly overstated the static load test results, with R/Q_{SPLT} ranging between 1.34 and 1.91. For driven piles this parameter is somewhat better, ranging between 0.88 and 1.28.

These test results clearly illustrate the subjective nature of the analysis results, which is only a logical consequence of the fact that there is no unique solution. However, this subjective nature would harm the credibility of the test results and therefore test results like those shown above are sometimes presented in a different way. For if the results from Predictor 5 were excluded, then the results in table 2 suddenly would appear a lot better. But the selective use or presentation of only some test data is misleading and could only be appropriate if it were obvious that those data were an anomaly. However, very similar results were reported by Maertens and Huybrechts (2003), where driven concrete piles and various types of screw piles were subjected to both static and dynamic load tests. And in 2014 the German Federal Waterways Engineering and Research Institute BAW published an article entitled "Evaluation of dynamic load tests of drilled shafts". That article included the outcome of a comparison to illustrate the subjectivity associated with the dynamic load test result analysis, as shown in Figure 2. Is summarizes the analysis results when 4 analysts analyzed the same data sets for 5 different piles and reflects not only a substantial spread (in one case the highest capacity prediction is almost 50 % higher than the lowest), but it also shows that there is seemingly no consistency in how an analyst ranks in the prediction results for the various piles (e.g. analyst C3 gave the highest prediction for pile 5 and the lowest for pile 8).

Taken together it shall be clear that the analysis results are not only subjective, but also that this subjectivity cannot be addressed with a simple correction factor for a particular individual.

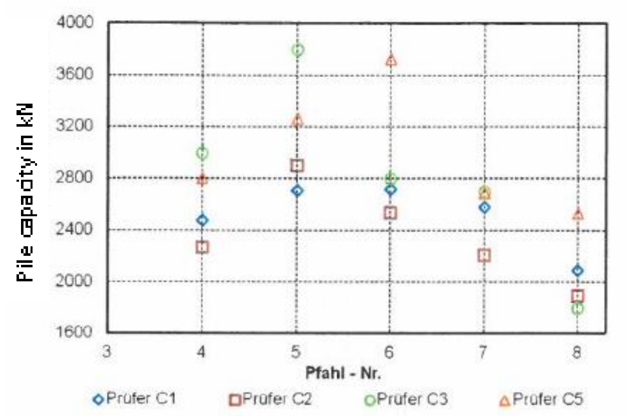

Fig. 2. BAW Evaluation of dynamic load tests of drilled shafts.

2.3 The Accuracy of the Results

Apart from ignoring the subjective aspect, the analysis outcomes are generally presented as very accurate. As mentioned above, this is sometimes done by the selective use or presentation of test data, and sometimes in a manner that is not all that evident. In a paper presented at the Seventh International Conference on the application of Stress Wave Theory in 2004, Likins and Rausche reported on a study using data from a company database that includes results from SLTs and HSDTs performed on a variety of pile tests, pile sizes and soil types. They stated that the correlation of the dynamically calculated capacities with static load test capacities was good with a Coefficient of Variation (i.e. the ratio of the standard deviation and the mean value) of 0.16. They also presented Figure 3 below, implying that the results are not only generally accurate, but that they are conservative as well.

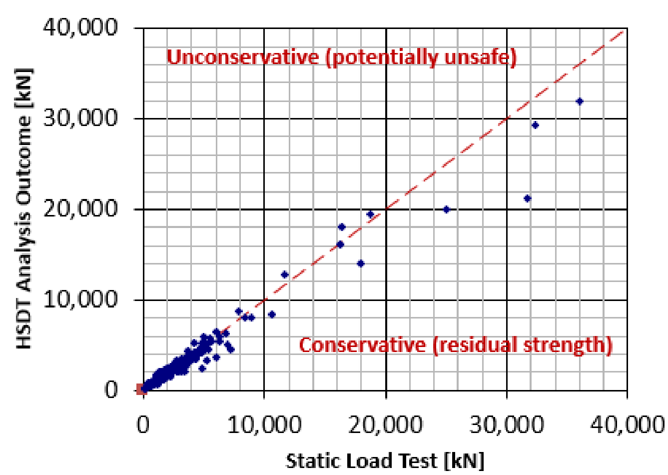

Fig. 3. Suggested Accuracy of HSDT Results.

TABLE 10 Statistical parameters of the ratio between static capacity (Davisson's Criterion) and signal matching analysis (CAPWAP) categorized according to soil type, time of driving and driving resistance

	Clay & Till				Sand & Silt				Rock			
Mean	1.352				1.517				0.930			
Standard Deviation	0.723				1.085				0.172			
Number of Cases	100				265				15			
Time of Driving	EOD		BOR(last)		EOD		BOR(last)		EOD		BOR(last)	
Mean	1.634		1.133		2.068		1.193		0.968		0.925	
Standard Deviation	0.899		0.444		1.765		0.391		0.132		0.203	
Number of Cases	45		40		77		116		7		7	
Blow Count (BPcm)	< 5	≥ 5	< 5	≥ 5	< 5	≥ 5	< 5	≥ 5	< 5	≥ 5	< 5	≥ 5
Mean	1.127	1.725	0.750	1.315	2.191	1.458	1.126	1.283	1.070	0.952	0.671	0.879
Standard Deviation	0.637	0.807	0.241	1.160	1.901	0.512	0.386	0.355	-----	0136	0.163	0.230
Number of Cases	35	35	11	10	64	13	74	40	1	6	3	3

NOTES: EOD = End of Driving; BOR(last) = Beginning of the last restrike; BPcm = Blows per centimeter

Fig. 4. Paikowsky's results regarding the suggested accuracy of HSDT Results

There are numerous sources to strenuously dispute the claims made by Likins and Rausche. In his report "Load and Resistance Factor Design (LRFD) for Deep Foundations" issued in 2004, Paikowsky presented statistical parameters of the ratio between the SLTs and HSDTs performed on various pile types in various soil conditions. The outcome of his findings for driven piles, the pile type that is easier to analyze given the lack of uncertainty regarding the pile shape, is shown in Figure 4 and it shall be obvious that the Coefficient of Variation is substantially higher than 16 %, except for piles driven into rock. Regarding the conservative nature of the analysis results, Tables 1 and 2 clearly reflect that this is not the case as many analysis results clearly overstated the static load test results.

Another aspect that deserves to get mentioned it that claims regarding the accuracy of the HSDT analysis results are sometimes based on the number of foundation failures. It is true that foundation failures occur very seldom, but the main reason for that is the safety factor that is incorporated in the foundation design. However, since there is currently a tendency in the industry to reduce this safety factor (resulting in a smaller foundation that is cheaper and more sustainable), it is increasingly important to have an accurate understanding of the accuracy and the spread of the analysis results of HSDT.

2.4 The Dynamic Effects of the Test

The potential overstatement of the pile capacity, mentioned earlier for both driven piles and cast in-situ piles, points to another alternative fact, which would suggest that aspects that affect other types of load testing do not apply to HSDT. When HSDT is performed the outcome is generally seen as reliable as the outcome of a static load test, and many even consider it (much) more reliable than the outcome of a Rapid Load Test (RLT), given the uncertainty about the rate effects. These rate effects were introduced in the analysis process for RLT since the most commonly adopted analysis method, the unloading point method (which uses a constant damping coefficient and only requires the raw data measured during the test for a closed form solution) works well in coarse grained soils, but overpredicts the static pile resistance in fine-grained soils. The reason for that is that the method assumes that the soil viscous damping is linear with velocity. While this acceptable for granular soils, in cohesive soils, where the soil damping is highly non-linear, which leads to overpredicting the pile capacity, which is addressed by introducing the rate effects correction factor.

These rate effects have been studied extensively and are now generally accepted, and yet when it comes to HSDT the rate effects are seldom addressed, even though in the analysis method for that test method the same assumption is made regarding viscous damping. It only seems logical that when rate effects are required to correct the soil-visocus damping assumptions for one test method, the same applies to the other, much more dynamic, test method with a much higher loading rate. And yet, as mentioned before, this aspect is rarely covered in the analysis of HSDT data. But when it is done, as in a paper presented by Rodriguez et al., it is used to explain the reason why HSDT overpredicted the pile capacity, which in the case studies presented in that paper was 11 and 23 percent, respectively. Taken together is clearly indicates that rate effects should be considered when analyzing HSDT results and that HSDT results can overpredict the capacity of the pile being tested, which conflicts with alternative facts of HSDT.

3. THE USE OF HSDT

When faced with the actual facts mentioned in the preceding paragraphs, the response is often that it suggests that HSDT should not be used at all. This is at best a misrepresentation. Performing load tests provides additional information and thus reduces uncertainty, or to use Isaacs' formulation, it reduces the factor of ignorance. As such any test is beneficial, as long as the test method is properly understood so the analysis results are interpreted correctly. It is therefore important that practitioners reflect this understanding in their reporting and refrain from making unwarranted claims, such as stating that the signal matching results they have generated equate to the capacity of the pile that was tested.

Another important aspect where practitioners should be more upfront is how the type of the pile that is tested may affect the analysis results. In case of a premanufactured concrete pile the dimensions and the Modulus of Elasticity are known along the pile length, but in case of a cast-in-situ pile that is unlikely the case. As a result the pile model for such piles is generally less reliable and hence the accuracy of the analysis results for the latter pile type is generally less than that for the former (as also reflected in the results summarized in Tables 1 and 2). It is therefore unfortunate that a paper by Alvarez et al. claims that auger cast-in-place (ACIP) piles can be reliably tested using HSDT (as illustrated in Figure 3). As part of their conclusions it is stated that a comparison of the static and dynamic loading test results of 47 ACIP piles showed that the mean of the ratio of dynamic to static tests was 1.04, which implies a slight overestimation of static load test capacity by the dynamic tests, and a COV of 11 %. It should be noted that this COV value is even less than the value reported by Likins and Rausche for all types of piles combined. While these values may have been the outcome of the piles included in this sample that was presented, in the opinion of the authors the conclusion cannot and should not be applied to ACIP piles in general, especially given the uncertainty regarding the actual shape of such piles. And presenting a paper with such alternative facts does not benefit the industry.

4. CONCLUSIONs

The objective of this paper is to create a better understanding of the HSDT process and to debunk alternative facts that are common in the foundation testing community, not to discredit HSDT as a testing method. By clearly describing these alternative facts at the Stress Wave conference, an event that specifically deals with foundation testing, a discussion may be initiated that will ultimately result in fewer publications that contain such alternative facts.

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