Statistical Analysis of a Large Number of PEM Tests on Piles

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ABSTRACT: The pulse echo method (PEM) is without doubt the most widespread test for pile integrity evaluation. We may say, without exaggeration, that the number of piles tested annually by PEM is measured in millions. Such large numbers invite statistical analysis that can shed light on the testing method in particular and on the piling industry in general.
Our analysis touches a number of items, including probability of flaw occurrence, wave speed selection, actual vs. planned pile lengths and amplification value vs. pile length. In addition we provide some figures regarding the size of the average project, average pile lengths in various countries and even the average time spent to test a pile. Our observations are followed by some insight as to their causes.

1 INTRODUCTION

The pulse echo method is the most prevalent one for pile testing. Many hundreds of such instruments are used all over the world to test many thousands of piles every day. In view of these figures, the method is a very attractive subject for statistical analysis. Some early statistics were already quoted in the early eighties of last century (Fleming et al. 1992), but since then no large-scale surveys have been published.

Using a simple data-mining tool we have collected data of over 80,000 piles tested by seven laboratories in USA, Israel, Vietnam, India and Spain from more than 1500 different projects. All the piles were tested with the PET system by Piletest.com (Fig. 1).

Figure 1 - The PET system

In the following pages we address the two main aspects of PEM testing: Pile integrity and pile length. The sample we obtained is large and diverse enough to show statistical trends, which cannot be reliably seen in a smaller sample or in a sample taken by one user, in one country, on a single project or from one contractor.

2 FLAW OCCURRENCE

A ***flaw*** is any deviation from the planned shape and/or material of the pile (Amir 2002). It may thus involve inclusions of foreign material, necking, bulging and also piles that are too short.

Reliable information regarding the percentage of flawed piles is significant in several ways:

- Knowing the expected ratio of flawed piles helps us develop a statistical model that determines what percentage of the piles on a given site should be tested.
- The expected flaw ratio enables realistic assessment of safety factors on pile groups.
- Comparing the measured flaw percentage on a given site to the industry average is a possible measure of the pile contractor work quality.

Table 1 summarizes the percentage of flawed piles from different sources.

Table 1 - Flaw occurrence ratio

Location	No. of piles tested	Testing method	Piles with flaws		Ref.
			Number	[%]	
United Kingdom	9,550	Sonic (analog)	161	**1.7**	1
California	2,986	Mostly radioactive	-	**20**	2
US site X	470	Visual inspection	-	**64?**	2
US site Y	171	Visual inspection	-	**76?**	2
Asia	300	Visual inspection	-	**>20**	2
Italy	6,865	Ultrasonic	811	**12**	3
Israel site "R"	253	Sonic (digital)	57	**22.5**	4
	40	Ultrasonic	26	**65**	4
Israel site "TA"	65	Ultrasonic	28	**43**	4

1. Fleming et al. (1992)
2. O'Neill & Sarhan (2004)
3. Faiella & Suprebo (1998)
4. Piletest.com files (both sites are good examples of poor construction)

The results quoted in Table 1 cover a very wide range and are therefore of little use. We believe that the results of our present survey, due to its size and non-selective character, are both more reliable and more useful.

3 STATISTICS

The analysis results follow. Factual items are usually followed by observations (which are points of special interest within the data) and speculations (which are a *possible* explanation of the factual data, based on experience and auxiliary knowledge, and are not factual)

◈ Speculations are marked in order to distinguish them from factual data.

In this paper we also introduce some results of more trivial nature. Although these probably do not merit additional discussion they may still be of interest.

3.1 *Assumed wave speed*

The software asks the user to enter the assumed wave speed, which is usually an unknown factor of PEM. The wave speed may be entered in 50m/s (or 100fps) steps with a default value of 4000m/s. The wave speed distribution for all piles in presented in Figure 2.

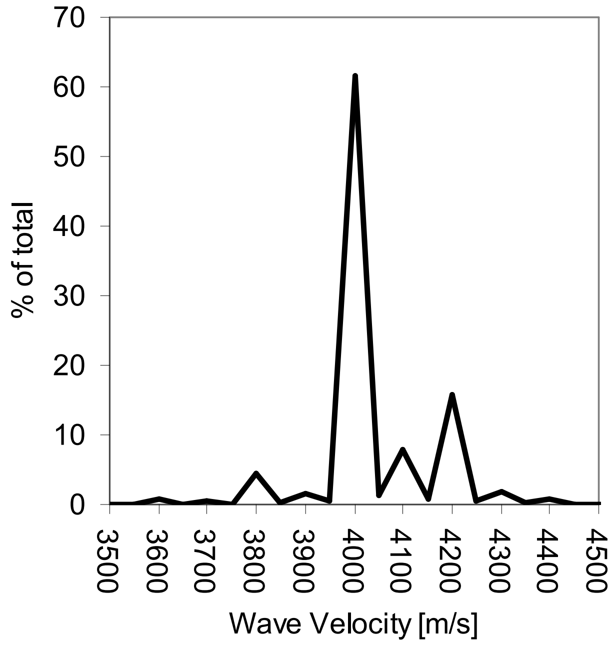

Figure 2 - Assumed wave speed

Observation

In most cases, the default wave speed of 4000m/s was used. 4200, 4100 and 3800m/s follow in this order, although in much lower numbers.

Speculation

◈ Testers do not abuse the wave speed by trying to "chase" the as-made lengths. This gives more credibility to the following data where measured pile length is analyzed.

3.2 *Measured vs. planned ratio*

Besides being an integrity-testing tool, PEM instruments also serve to establish the actual (as distinct from claimed) pile length. In the following, "*ELR*" (Extra Length Ratio) is defined as the amount by which the measured pile length deviates from the planned one (1).

$$ELR = \frac{measured - planned}{planned} \qquad (1)$$

e.g. ELR = -0.1 stands for a pile which is 10% shorter than planned. The term "planned" in this case covers either values read off the drawing or as-made lengths reported by the site supervisor. The software makes no distinction between the two.

Figure 3 shows the cumulative distribution of ELR for all piles.

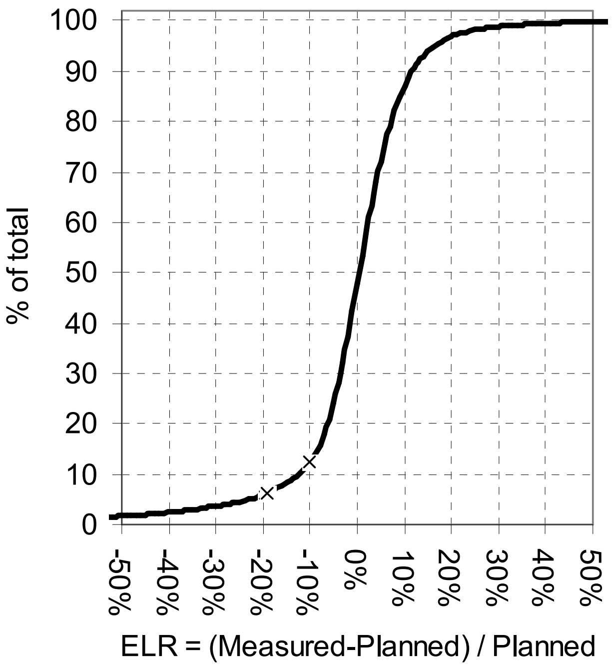

Figure 3 – ELR distribution

Observations

- 50% of the piles are at least as long as planned
- 12% of the piles are shorter than planned by at least 10%
- 6% of piles are at least 20% shorter

Because of the large sample size, we could group the data into several "buckets" and still have enough samples for a smooth distribution curve shape. Figure 4 shows this interesting result.

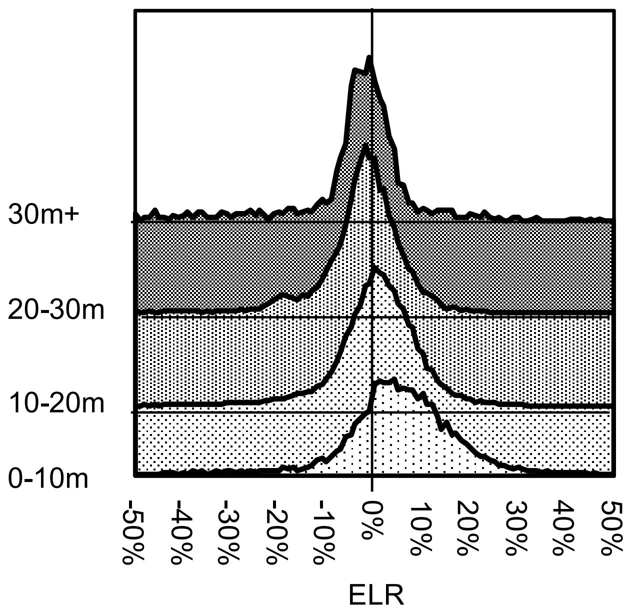

Figure 4 - ELR, by different length baskets

Observations

- The longer the piles, the smaller the relative scatter from planned length
- The curve shifts to the left as the piles get longer.

Speculations

- In shorter piles, direct depth measurement is easier, thus enforcement is tighter.
- Longer piles are more often produced under slurry, which makes depth control by the supervisor more challenging.
- The absolute depth error is probably constant, thus the absolute ELR value gets smaller with depth.
- Longer piles often penetrate harder layers, which contractors try to avoid.

3.3 *Testers' comments*

One of the powerful options the software offers is the ability to enter comments in each pile's file. We have analyzed those comments, facing the following difficulties:

- The comments are free-text and not categorized, often containing private shorthand and context-specific data
- Some laboratories do not use this feature and enter comments only on the final report. Those were excluded.
- We could not analyze Vietnamese comments and those were excluded.

Altogether, we were left with 49000 piles to work with from which ~6000 (12.4%) included any comments. We have done word-by-word (as apposed to grammatically aware) categorization into seven categories: preparation, head-related issues, flaws, necking, bulging, too short and "Other Issue" The results are summarized by Table 2.

Table 2 - Tester's comments

No comment	88.0%	
Other Issue	4.2%	[*********************]
Preparation	4.1%	[*********************]
Head	2.5%	[*************]
Flaw	0.6%	[***]
Necking	0.5%	[***]
Bulging	0.3%	[**]
Too Short	0.05%	[]

Observation

The total percentage of declared flaws (combining flaw, necking, bulging and too short observations) is 1.85%

Speculations

- Some flaws are hidden under other categories. For example, poor head preparation can hide a flaw.
- In many cases testers refrained from declaring piles as "too short" since the measured length was in any case provided.

3.4 *Number of piles per project, per country*

Table 3 - Avg. number of piles per project, per country

Vietnam	87	[*********]
Israel	60	[******]
India	39	[****]
Spain	33	[***]
USA	16	[**]

Observation

In Asia, the average testing project is significantly larger than in Europe, and much larger than in the USA.

Speculations

- Possibly this has to do with the fact that cast-in-situ piles are relatively new in the USA, where driven piles have dominated the market for many years.
- It is quite common in the USA to test only a small proportion of the piles while in Asia PEM testing of all piles is usually specified.

3.5 *What are the chances to find a flaw in a project?*

In section 3.3. we saw that testers observed flaws in 1.85% of the piles. To this we may add the 6% of piles that were 20% or more too short, to get a total of 7.85% flawed piles. This figure is in between the figure quoted by Fleming et al. (1992) and the other sources quoted in Table 1.

Combining the flaw occurrence rate of 7.85% and the average number of piles per project found in Table 3 we can now calculate the probability of finding a flaw in an average project. Figure 5 shows this probability subject to (at least) the following assumptions:

- Uniform flaw distribution across projects (which is typically not the case)
- Uniform flaw distribution across countries (which is not necessarily the case)
- Flaw occurrences are unrelated events hence exponential distribution is suitable. In fact, flaws cluster as a result of many factors such as ground conditions, drilling and casting method, equipment, contractor and supervision skills and more

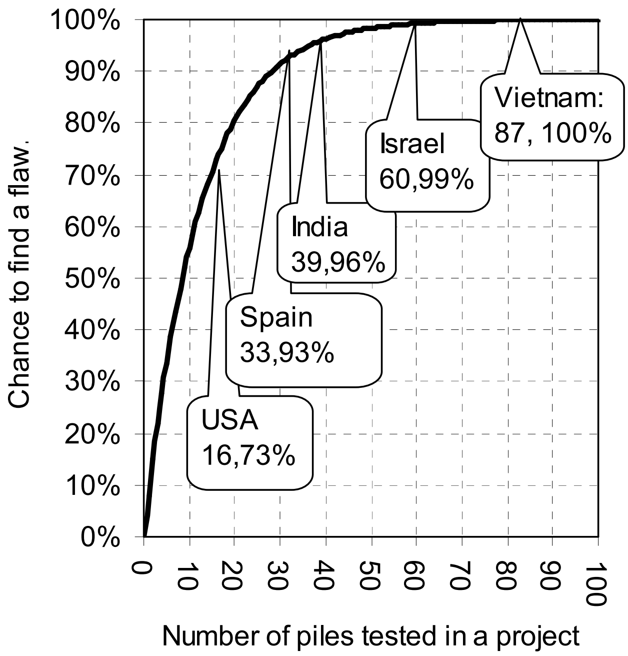

Figure 5 - chances to find a flaw in a project, per country

Observation

It is more common than not to find a flaw in a project.

Speculations

- Bored piles are produced in the ground and subject to soil collapse and to the influence of ground water and drilling mud.
- On the other hand, the process is largely invisible, making adjustment to changing conditions very difficult.
- Considering the above, a perfect pile is almost impossible to produce.

3.6 *Mean length of piles*

The sample contains piles of lengths varying from 1m to 63m. The distribution of lengths is shown in Figure 6. The mean pile length varies considerably from country to country, as shown in Table 4 - Mean length of piles, per country.

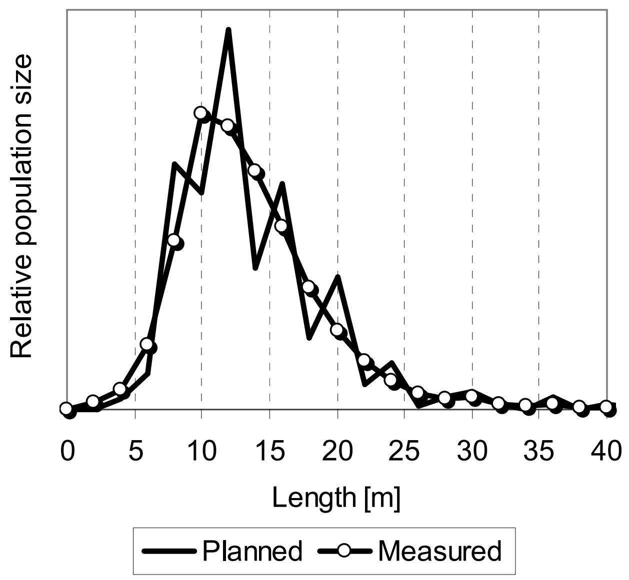

Figure 6 - Planned and measured length distribution

Table 4 - Mean length of piles, per country

Vietnam	37m	[***************]
India	22m	[*********]
USA	20m	[********]
Spain	14m	[******]
Israel	13m	[*****]

Observation
Piles are typically designed in whole meter lengths.

Speculations
- Shorter pile average might mean higher penetration of PEM to the private housing sector, where structures are typically lighter.
- Both India and Vietnam have extensive alluvial plains with soft soils that necessitate longer piles. Spain and Israel have mostly harder soils where shorter piles are quite satisfactory.

3.7 *Amplification vs. measured length*

Exponential amplification serves to compensate for skin friction and accentuate the toe reflection. Theoretically, the amplification depends on the slenderness L/d ratio, but since the software does not require the users to record the pile diameter, we analyzed amplification vs. length (Figure 7).

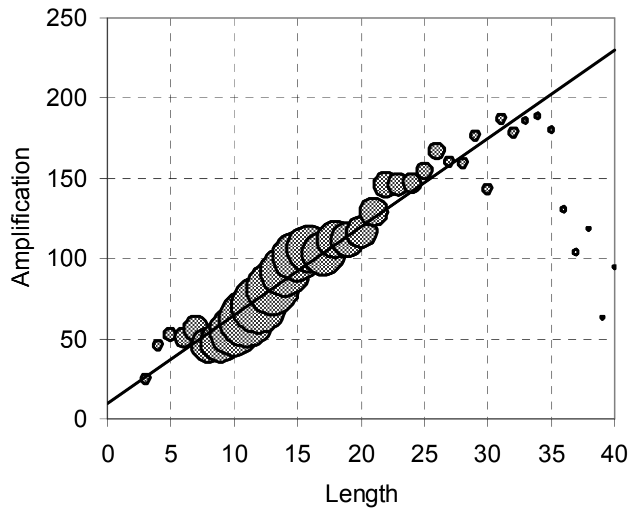

Figure 7 - Amplification vs. length (bubble area is proportional to the sample size)

Observation
- Longer piles need higher amplification

Speculation
- Longer piles are most probably designed with higher slenderness ratios.

3.8 *How long does it take to test a pile?*

The software records the time of the first and last impact applied to the pile. The time difference (test duration) was analyzed. No data is recorded as to the additional "overhead" time. Figure 8 shows the distribution of the test duration.

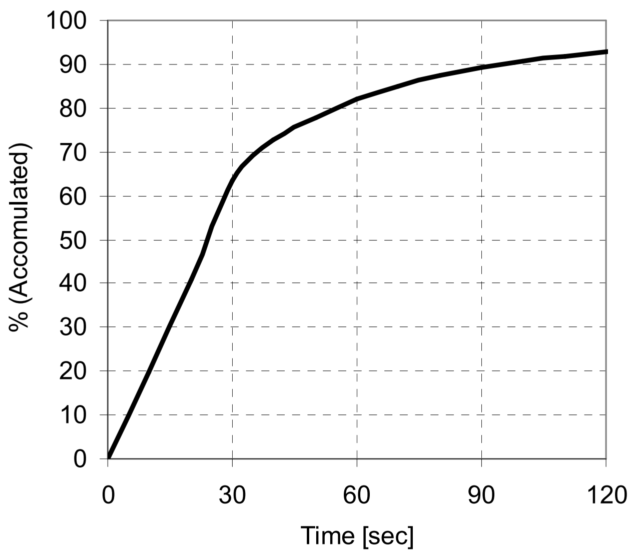

Figure 8 - Test duration distribution (accumulated)

Observations
- 63% the piles are tested within 30 sec
- 82% of piles are tested within 1 minute
- 92% within 2 minutes

Speculation
- Apparently, testers spend most of the time driving to the work site, getting a safety briefing, talking

to the contractor, locating the piles and moving around the work site. Net testing duration is relatively short.

Does the test duration depend on other pile parameters? Figure 9 shows some correlation between duration and planned length.

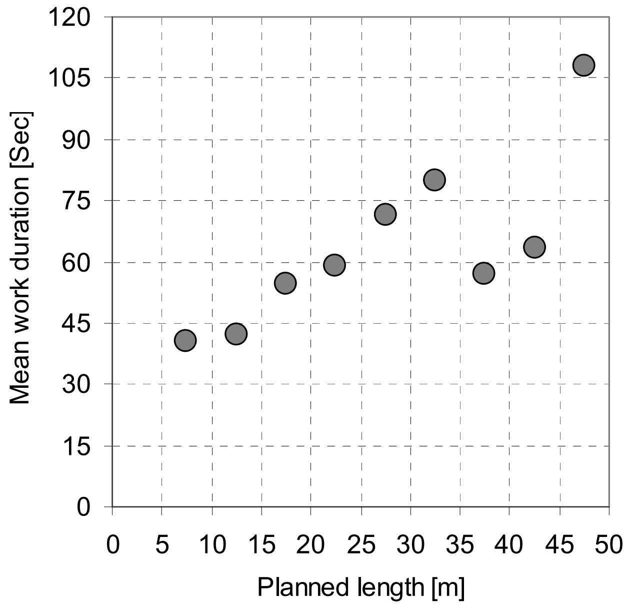

Figure 9 - Average work time vs. planned length

Observation
Longer piles take longer to test

Speculation

- With longer piles, the higher amplification also magnifies noise, making toe reflection less obvious. Thus, more blows are needed to achieve a proper reflectogram.

CONCLUSIONS

- A certain amount of imperfections is an inseparable part of piling.
- PEM is an extremely fast and cost-effective means for pile integrity testing.
- Lacking better data, a wave speed of 4,000 m/s is a satisfactory default value.
- On the average, there is a good fit between planned lengths and those measured by PEM
- Imperfections were observed in less than 2% of the total population. In addition, 6% of the piles were found to be 20% or more shorter than planned.
- In view of its low cost and relatively low flaw occurrence, testing a small percentage of the piles in a project is not a valid strategy.
- Intrusive methods using access tubes have a higher (typically three times) flaw detection probability than PEM.

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