Validity of the Beta Method to determine pile damage

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ABSTRACT

In 1979 the Beta Method of pile integrity was published. The basic idea behind this method is that stress waves propagating through a foundation pile will be reflected on cracks in concrete piles. As the crack becomes more extensive, so do the reflections. In the ultimate situation of a fully cracked pile, no waves will travel through the crack and the stress wave will be fully reflected. The Beta Method is then calculating the reflection rate (reflected as percentage of the original peak force) and the outcome is presented as a reliable integrity indicator. However, from both theory and practical experience it can be shown that applying the beta method to indicate pile damage will give false negative and false positive results. The former is unwanted because sound piles will be rejected, which will cause grief to the piling contractor. The latter will result in the fact that damaged piles are accepted as sound, where that shouldn't be the case, obviously increasing the risk of failure. The paper will once again illustrate this, through theory as well as practical examples, and then conclude by making suggestions for a practical pile damage assessment on a job site using low strain dynamic testing.

Keywords: Beta Method, pile damage during driving

1 INTRODUCTION

When driving concrete foundation piles the objective is to have a sound deep foundation element in place at the end of pile driving. To achieve this objective it is essential that pile damage is minimized during pile driving as invariably some damage will occur (if only due to the fact that the small cracks present in the concrete before the start of pile driving will grow as a result of the pile driving stresses), but this damage should not affect the integrity of the foundation, which the pile will be part of.

Given that objective it is logical that the pile driving industry desires to have a method that allows for real-time assessment of potential pile damage, similarly to the real-time indication of the pile capacity as it is driven into the ground. The latter is achieved by applying a simplified algorithm (such as the CASE Method or the TNO Method) to provide an indicative capacity value based on the measured acceleration and strain values at the pile top during pile driving (the so-called pile driving analysis process). In 1979, a paper was published by Rausche and Goble describing a method that would provide a similar real-time pile damage assessment, using the same measurements of pile top acceleration and strain, the so-called BETA Method.

2. BETA METHOD

When an axial load is applied on the pile top a stress wave is generated in the pile that will travel through pile. As it travels downwards, upward acting stress waves are generated by changes in pile impedance (whenever they occur), by the soil resistance along the pile shaft (continually for that the part of the pile that is already below grade), and finally by the pile toe. This upward wave signal can be analyzed for abrupt changes and these changes generate a so-called alpha value:

$$\alpha = \frac{\mu_\Delta}{2(F_i - R_\Delta)} \qquad (1)$$

where μ_Δ is the relative increase of the proportional velocity at the point of damage, F_i the impact force, and R_Δ the resistance force when the relative velocity increase due to the defect becomes noticeable. The α is then used to calculate β using the following equation:

$$\beta = \frac{1-\alpha}{1+\alpha} \qquad (2)$$

This Beta is assumed to be the impedance ratio

$$\beta = Z_{new} / Z_{old} \qquad (3)$$

where Z_{new} is the impedance of the pile with the anomaly and Z_{old} the original pile impedance. Assuming that the pile originally had a uniform cross section over the entire length, Beta is then assumed to reflect damage that has occurred in the concrete pile and in their paper Rausche and Goble even suggested a damage classification scale (see Table 1), which is widely used in the industry, despite the fact that the authors clearly stated in their paper in 1979 that "there is no experimental proof available justifying the (…) classification".

Table 1. Beta Method Damage Classification

B (%)	Severity of damage
100	Undamaged
80 – 99	Slight damage
60 – 79	Damage
< 60	Broken

The equations listed above are from the original Rausche and Goble paper, and while over the years various alternate equations have been published for Beta, the basic claim remained the same: that Beta has a specific value, which can easily be determined based on the measurements at the top of the pile during pile driving, and that it provides a deterministic and accurate assessment of pile damage during pile driving.

2. REASSESSMENT OF THE BETA METHOD

Once it had been published, the BETA method was not universally adopted. It was recognized that the value of Beta was derived from the upward acting stress waves, which are not solely due to changes in pile impedance. For as soon as even a part of the pile has entered the soil, the soil friction will also cause upward acting waves. This means that if the upward acting waves are used to assess potential changes in pile impedance the soil interaction component would have to be known. And if that could be easily and directly deducted from the strain and acceleration measurements at the top of the pile, the analysis of the dynamic load testing data would not require any signal matching (i.e., the process to determine the soil model that will generate the soil interaction component that allows the best match between the calculated signals and those measured at the pile top during the test). Since this is obviously not the case, the fallacy of simply calculating the value for Beta to assess potential changes in pile impedance for any part of the pile where there is a soil interaction component should be obvious.

While the above was widely discussed among practitioners, the fallacy was not addressed in technical papers or formally presented at conferences until 2011, when Verbeek and Middendorp published a paper in the DFI Journal, where they discussed the initial findings of their review of BETA Method. The paper was based on data from more than 400 concrete piles driven in Florida with not only the traditional external acceleration and strain sensors at the pile top, but also embedded sensors at the pile toe. It raised serious questions regarding the reliability of any damage assessment method based solely on the change of pile impedance (such as the Beta Method), especially to detect damage near the pile toe. The paper also suggested the need to re-assess the damage classification used for the BETA Method, as they reiterated the point made by Rausche and Goble in their original paper that "there is no experimental proof available justifying the (…) classification".

Verbeek and Goble took this suggestion to heart and together reviewed the method in detail (covering both the theoretical and practical aspects of the method), the findings of which were presented during the 9th International Conference on Testing and Design Methods of Deep Foundations in Japan in 2012. The theoretical review of the method revealed flaws in the original paper and demonstrated that the basic equation of the BETA Method was incorrect for any part of the pile where there was interaction between the soil and the pile. While the theoretical review of the method showed clearly that the BETA Method cannot be a reliable indicator of pile damage, the practical review reinforced this. Using the more than 400 data sets for piles driven in Florida with both internal and external gauges (the same data used by Verbeek and Middendorp), the review focused on piles with toe damage and showed that the BETA Method is not a reliable indicator for such damage. On that basis the paper presented by Verbeek and Goble concluded that the Beta method, derived by Rausche and Goble himself some 30 years earlier, should not be used any longer to protect against pile toe damage.

This conclusion has been misinterpreted over the years. In the original draft of the paper Verbeek and Goble stated that the method should not be used any longer to protect against pile damage. The reasoning behind this conclusion was straightforward: the theoretical review showed that the method was incorrect for any part of the pile where there was interaction between the soil and pile, and while the practical review only covered piles with toe damage, there is no reason to constrain the conclusion to pile toe damage only. However, the reviewers of the draft paper felt differently and thus the conclusion was reworded. However, the data reviewed by Verbeek and Middendorp and subsequently by Verbeek and Goble merely supported the outcome of the theoretical review, which in and of itself clearly demonstrated the fallacy of the BETA Method.

The second misinterpretation has been that the paper would imply that the upward acting stress waves would not reflect any defects in the pile. Obviously stress waves propagating through a foundation pile will be reflected on cracks (as well as other anomalies) in concrete piles that cause a change in impedance. However, in a prestressed concrete pile a crack in the concrete may not immediately result in a change in impedance. Only when the tensile stress is exceeded repeatedly crack degradation will occur, which will prevent the prestressing to close the generated crack entirely, and thus will result in stress wave reflections. However, these reflections may not be visible at the sensor location at the pile top, as they are damped out by the shaft friction. The extent of this damping obviously depends on how far the crack is below the soil surface (the deeper it is located, the more it gets damped out) and the extent of the shaft friction (the higher the shaft friction, the more the reflection is masked). To makes matters even more complex, as the pile gets driven deeper into the soil (which in and of itself would diminish the extent of the stress reflection at the surface) the crack may increase in size (which would enhance the stress wave reflection) depending on the stress levels in the pile. Based on the above it should be obvious that there will be situations where there is a crack in the concrete pile that will not result in a stress wave that can be detected by the sensors at the pile top.

As the crack becomes more extensive, the generated reflection will begin to become visible at the pile top and at that time analysis of the upward acting stress wave can be used to assess the source of the reflection: whether the reflection is due to a change in soil stiffness or a crack in the pile. As the location is at a fixed distance from the pile head, the reflection of the crack will reach the pile head at the same amount of time after each blow. This is different from the responses of soil layers. As the pile penetrates deeper and deeper into the soil, a particular soil layer moves closer and closer to the pile head and therefore the wave response of that particular layer will reach the pile head earlier in subsequent blows. This means that by comparing the sensor recordings at the pile top for subsequent blows (and possibly by applying signal matching in case of relatively small impedance changes) the presence of a crack and even the growth of that crack as the pile is driven deeper can (possibly) be identified. But this can only be done through a signal matching process of various blows, but not automatically using the data from a single blow as suggested by the BETA Method.

3. USE OF THE BETA METHOD

Despite the publication of the papers by Verbeek and Middendorp, and by Verbeek and Goble, the BETA Method continues to be widely used. Some of those that advocate the use of the method do point out some limitations, such as that very short impedance changes may not be assessed properly and that due to measurement inaccuracies false PDA damage diagnostics are possible. Nonetheless, so the argument goes, a beta value of less than 80 % generally indicates a pile integrity issue, and therefore a value of more than 80 % must reflect that the pile has no integrity issues.

This argument is flawed for a number of reasons. First, it completely ignores the warning of the authors that presented the BETA Method in 1979. As stated above, Rausche and Goble clearly stated in their paper that “there is no experimental proof available justifying the (…) classification”, and more than 40 years later there is still no experimental proof.

At the same time there is evidence that piles with a beta value as high as 100 % can be seriously damaged. In their paper Verbeek and Goble presented an example of a 18 m long, 0.75 m x 0.75 m square concrete pile (with embedded strain and acceleration sensors in both the pile top and the pile toe) was placed in a 6 m deep pre-drilled hole, after which the pile was driven further into the ground using a diesel hammer. Initially pile driving was uneventful (with just 11 blows required to drive it 0.3 m further into the ground). However, around blow 85 the change in pre-stress level in the reinforcement (the so-called pre-load delta) at the pile toe began to increase, and right around blow 100 the pre-load delta exceeded 50 microstrain. It was decided to continue, in part because the Beta value indicated no damage whatsoever (value was still at 100 %) until the pile had been driven to refusal less than 6 ft (1.8 m) from the start of driving. As the pile had not been driven to the required depth, the contractor decided to pull the pile (which was seemingly undamaged based on the Beta value of 100 %) to pre-drill the hole further so the pile could be installed as specified. When the pile was pulled the pile damage indicated by the pre-load delta became apparent: vertical cracks extended 10 ft (3 m) up from the pile toe as noted by the visible ends of the tape measure (see Figure 1). While the damage shown in this figure was obviously aggravated due to the 600 additional blows after the initial damage occurred, it nevertheless provides evidence that the beta value cannot be relied

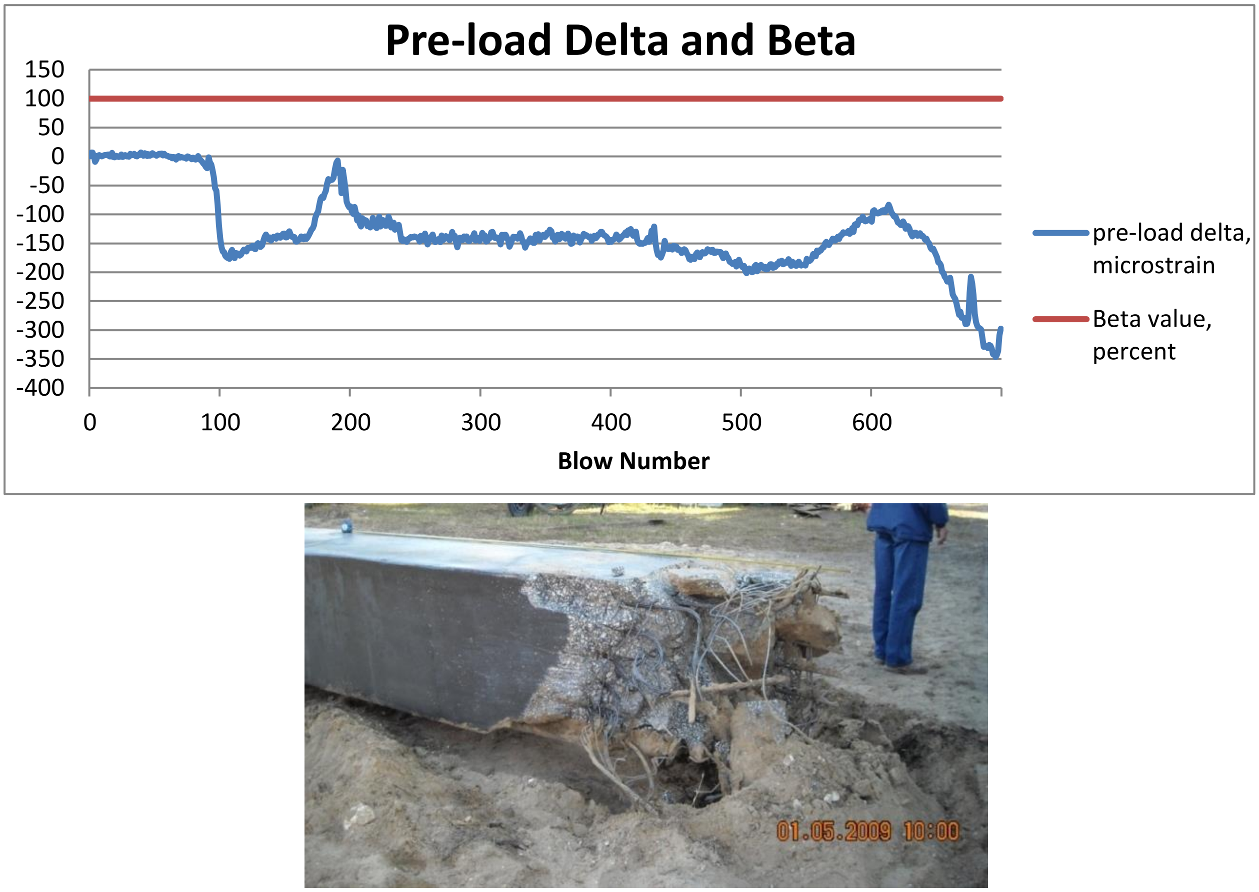

Fig. 1. Measured pre-load delta and Beta values in the 60 ft long 30 inch square concrete pile during pile driving.

upon to identify pile damage. This should be of concern as it may result in the fact that damaged piles are accepted as sound where that should not be the case, obviously increasing the risk of failure.

But the opposite, i.e. false positive results, may also be the case, in which case sound piles will be rejected, which will cause grief to the piling contractor. A reflection caused by a soil layer may be misinterpreted as a reflection due to a loss in pile impedance and thus imply that there is pile damage. Based on these possible false positive and false negative results alone the use of the BETA Method should at a minimum be reevaluated.

Another argument to support the continued use of the beta method is the fact that the papers by Verbeek and Middendorp and by Verbeek and Goble only included examples of pile toe damage that was missed by the beta method. Thus the argument goes that the method is still valid for damage assessment of the remainder of the pile. Obviously this argument completely ignores the theoretical review included in the paper by Verbeek and Goble, which showed that the method is flawed for every part of the pile that is buried, and it also glances over the reasons for including examples with pile toe damage only. As mentioned earlier the examples were drawn from more than 400 data sets for piles driven in Florida with both internal and external gauges. Since for all these piles the internal sensors were positioned in the pile top and the pile toe, only pile toe damage examples could be obtained.

4. ALTERNATIVE TO THE BETA METHOD

Simply suggesting that the BETA Method should not be applied is not a very satisfactory recommendation, since the fact remains that it is important that pile damage can be determined reliably. Some have suggested to use the average wave speed as an indicator of pile damage, based on the fact that in a damaged area the wave propagation becomes more cumbersome and therefore the average wave speed decreases. But determining the wave speed requires a clear identification of the pile toe reflection, which is not always easy, especially when the pile penetration increases. Consequently while this may approach may provide another input when the potential for pile damage is assessed, it cannot be used by itself as a reliable indicator.

As mentioned before it is possible to perform signal matching on various blows for each pile to assess potential damage. However, not only is this a very labor-intensive exercise, the accuracy of the assessment may not be all that high as the soil response component in the upward wave may mask a defect. More practical would be to subject the piles to low strain dynamic testing (in accordance with ASTM D5882), whereby a stress wave is generated by simple hitting the pile top with a hand-held hammer and recording the stress wave with an accelerometer placed on the pile top. Since a pile driving project typically involves the installation of a number of identical piles in relatively near proximity, the traces recorded with the accelerometer can be averaged. Assuming that most piles are undamaged (which is a realistic assumption, especially if the pile driving process is simulated in advance to ensure that the driving stresses are within acceptable limits) and also that the soil profile is basically the same for each pile, the average trace (the so-called site characteristic trace) then reflects the soil response to the stress wave. Any pile with a trace that deviates from this site characteristic should then be analyzed further as this deviation may reflect pile damage. By applying this approach a large number of piles can be tested with a minimal effort and the data analysis can be largely automated, thus providing a efficient quality control method for pile damage.

It must be stated, however, that the use of low strain dynamic testing has limitations as well. Since it uses a uniaxial approach the method becomes less suitable as the pile diameter increases. Similarly, as the pile length increases the energy of the stress wave is reduced more and more (through soil damping) to the point that the upward wave can no longer be registered.

5. CONCLUSION

When installing a driven pile it is important that the pile remains sound and therefore a reliable method to assess pile damage is an essential element of the quality control effort. Unfortunately there is no simple method that can provided an accurate assessment of the pile condition in real time. As the part of the pile where the damage is likely to occur is buried, the assessment has to be based on the analysis of stress waves, whether generated as part of a high strain or a low strain dynamic test. But as pile damage begins to occur during pile driving the damage may not generate any reflections or the damage is simply too small that the reflects are masked by those generated by shaft friction. And when the reflections are visible it requires analysis to determine their origin as a change in the soil conditions may create the same type of reflection as a defect. Consequently the beta method cannot be used to assess the pile condition. Instead recorded stress wave data should be carefully reviewed and interpreted, making full use of all available data to compare the results for individual piles in close vicinity of each other and to correlate these results with soil investigation data. But most of all it is important that the notion that a simple equation, such as suggested by the beta method, can generate a reliable assessment of the pile condition is viewed for what it is: a pipe dream.

REFERENCES

1) Rausche, F., Goble, G. G. (1979). "*Determination of pile damage by top measurements*", American Society for Testing and Materials, 1979: Philadelphia, PA; 500-506.
2) Verbeek, G., Goble, G. (2012). "*Re-evaluation of t he Method to Determine Pile Damage Using the Beta Method*," Ninth International Conference on Testing and Design Methods for Deep Foundations, Kanazawa, Japan.
3) Verbeek, G., Middendorp, P. (2011). "*Determination of Pile Damage in concrete piles*", DFI Journal, Vol. 5 (2), pp 23-29.

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