Prediction of unknown deep foundation lengths using the Hilbert Haung Transform (HHT)

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ABSTRACT: Prediction of unknown deep foundation embedment depth is a great deal nowadays, especially in case of upgrading or rehabilitation of old structures. Many old bridges and marine or pier structures in the United States are established using deep foundations system of timber piles and their foundation records do not exist. Non-Destructive Testing (NDT) method for a great variety of materials and structures has become an integral part of many tests. However, the process of testing long piles, deeply embedded in the ground, is more complex than (NDT) of the other structural materials. This paper presents a new method called the Hilbert Huang Transform (HHT). This method is used now by a wide range in a different health monitoring of many systems. In this paper, some field tests on the timber Piles of one bridge at North Carolina was performed to verify the using of (HHT) method for predicting the embedded depth of the unknown piles. Percentage of the accuracy achieved using HHT method for pile length compared to the actual pile length data was performed. Finally, a recommendation is presented for the limitation of using this new method as a new non-destructive method for deep foundations.

INTRODUCTION

Timber piles are still used widely as the primary means of support for many structures. More than 6500 bridges in North Carolina State are supported at least in one part by the timber piles. Thus more than one million of those piles are founded all-over the United State for bridge foundations. This huge number of piles does not include the other piles for other structures such as: marine fender systems, pier structures, fishing piers, and mountain chalets or beach cottage. With so many timber piles used across all the United States, it is important to inspect them to get their overall and embedded length. Determining their embedded lengths represents a major problem. Years of scour have taken place after most of the timber piles in use today were installed and their embedment is no longer the same. The fear is that if a pile's overall length is not known because pile records are incomplete or nonexistent, then the effect of scour on its embedment cannot be determined. There needs to be a way determining the in-place length of timber piles nondestructively while the structure to which they belong remains in service. Then, with such measurements, a pile's embedment and load bearing capacity can be evaluated. The present research study describes a new nondestructive testing method which employs dispersive stress wave propagation and special signal processing techniques to find the embedment length of installed timber piles. This new method is the Hilbert Huang Transform (HHT) method. This method was studied and developed using field tests of the nondestructive pile testing performed for timber piles of one of the bridges in North Carolina State. Four piles of Bridge No.129 at Johnston County were chosen as a case study for applying the method of Hilbert Huang transform (HHT). Those four piles were chosen due to their known of the total overall pile length which will helping to verify the used technique. Finally, the computed pile lengths are compared with the actual data recorded for those piles to judgments of the using of the Hilbert Huang Transform for pile length detections.

HILBIRT HAUNG TRANSFORM METHOD

The Hilbert-Huang transform (HHT) is an empirically based data-analysis method. Its basis is adaptive, so that it can produce physically meaningful representations of data from nonlinear and non-stationary processes. The advantage of being adaptive has a price: the difficulty of laying a firm theoretical foundation. The HHT consists of two parts: empirical mode decomposition (EMD) and Hilbert spectral analysis (HSA). This method is potentially viable for nonlinear and non-stationary, especially for Timefrequency-energy representations. It has been tested and validated exhaustively, but only empirically. In all the cases studied, the HHT gave results much sharper than those from any of the traditional Υ analysis methods in time-frequency-energy representations. Additionally, the HHT revealed true physical meanings in many of the data examined. The development of the HHT was motivated by the need to describe nonlinear distorted waves in detail, along with the variations of these signals that naturally occur in nonstationary processes. As is well known, the natural physical processes are mostly nonlinear and non-stationary, yet the data analysis methods provide very limited options for examining data from such processes. The available methods are either for linear but non-stationary, or nonlinear but stationary and statically deterministic processes, as stated above. To examine data from real-world nonlinear, non-stationary and stochastic processes, new approaches are urgently needed, for nonlinear processes needed special treatment. The past approach of imposing a linear structure on a nonlinear system is just not adequate. Other then periodically, the detailed dynamics in the processes from the data needs to be determined because one of the typical characteristics of nonlinear processes is their intra-wave frequency modulation, which indicates the instantaneous frequency changes within one oscillation cycle. In the past, applications of the Hilbert transform have been limited to narrow band data; otherwise, the results are only approximately correct. Even under such restrictions, the Hilbert transform has been used by Haung et al 1988, to examine the local properties of ocean waves with detail that no other method has ever achieved. Later, it was also used by Haung et al 1988, to study nonlinear wave evolution.

For general application, however, it is now obvious that the data will have to be decomposed first, as proposed by Haung. Independently, the Hilbert transform has also been applied to study vibration problems for damage identification. In all these studies, the signals were limited to "monocomponent" signals, i.e. without riding waves. The real value of the Hilbert transform had to wait to be demonstrated until Haung et al introduced the empirical mode decomposition (EMD) method, which is based on the characteristic scale separation. The EMD method was developed to first operate on the data being processed and to then prepare it for the Hilbert transform. Therefore, we will discuss the time scale problem next, since this concept is central to this new approach.

The Empirical Mode decomposition method, EMD, (the sifting method)

As discussed by Huang et al.[1988], the empirical mode decomposition method is necessary to deal with data from non-stationary and nonlinear processes. In contrast to almost all of the previous methods, this new method is intuitive, direct, and adaptive, with posteriori-defined bases, from the decomposition method, based on and derived from the data. The decomposition is based on the simple assumption that any data consists of different simple intrinsic modes of oscillations. Each intrinsic mode, linear or nonlinear, represents a simple oscillation, which will have the same number of extrema and zero–crossing. Furthermore, the oscillation will also be symmetric with respect to the "local mean." At any given time, the data may have many different coexisting modes of oscillation, one superimposing on the others. The result is the final complicated data. Each of theses oscillatory modes is represented by an intrinsic mode function (IMF) with the following definitions:

(1) in the whole dataset, the number of extrema and the number of zero-crossing must either equal or differ at most by one, and

(2) At any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.

An IMF represents a simple oscillatory mode as a counterpart to the simple harmonic function, but it is much more general: instead of constant amplitude and frequency, as in a simple harmonic component, the IMF can have a variable amplitude and frequency as function with time. With the above definition for the IMF, one can then decompose any function as follows: take the test data as given in the recording signal data; identify all the local extrema, then connect all the local maxima by cubic spline. Repeat the procedure for the local minima to produce the lower envelope. The upper and lower envelopes should cover all the data between them. Their mean is designed as m1, and the difference between the data and m1 is the first component h1, i. e.,

$$h1 = x(t) - m1$$
 (1)

The procedure is illustrated in Huang et al. (1998). Ideally h1 should satisfy the definition of an IMF, for the construction of h1 described above should have made it symmetric and have all maxima positive and all minima negative. However, even if the fitting is perfect,

a gentle hump on a slope can be amplified to become a local extremum in changing the local zero from a rectangular to a curvilinear coordinate system. After the first round of sifting, the hump may become a local maximum. New extrema generated in this way actually reveal the proper modes lost in the initial examination. In fact, with repeated sifting, the sifting process can recover singles representing low-amplitude riding waves. The sifting process serves two purposes: to eliminate riding waves, and to make the wave profile more symmetric. While the first purpose must be achieved for the Hilbert transform to give a meaningful instantaneous frequency, the second purpose must also be achieved in case the neighboring wave amplitudes have too large a disparity. Toward these ends, the sifting process has to be repeated as many times as required to reduce the extracted signal to an IMF. In the subsequent sifting processes, h1 can be treated only as a proto-IMF. In the next step, it is treated as the data; then,

After repeated sifting in this manner up to k times, h1k becomes an IMF; that is,

$$h1k=h1(k-1)-m1k$$
 (3)

Then, it designated as,

$$c1=h1k, (4)$$

The first IMF component from the data is shown in sifting c1. Here, the critical decision must be made: the stoppage criterion. Historically, two different criteria have been used: The first one was used in Huang et al. (1998). This stoppage criterion is determined by using a Cauchy type of convergence test. Specially, the test requires the normalized squared difference between two successive sifting operations defined as:

$$SD_{k} = \frac{\sum_{t=0}^{T} \left| h_{k-1}(t) - h_{k}(t) \right|^{2}}{\sum_{t=0}^{T} h^{2}_{k-1}(t)}$$
(5)

If this squared difference SDk is smaller than a predetermined value, the sifting process will be stopped. This definition seems to be rigorous, but it is very difficult to implement in practice.

Using HHT method for the Prediction of the unknown Foundation

In this paper, prediction of the pile lengths of unknown foundations was evaluated using the HHT method. Many bridges allover the Unites Stated of America were built in the last century and no data are available for most of pile lengths. In this study, one bridge was chosen as a case of study for evaluating the overall pile depths under the bridge bents. Bridge No. 129 (located on road 1006) in Johnston County at NC State was chosen because there are available data for pile lengths to investigate the used method. This bridge consists of five bents. Two edge bents and three in the middle. All bridge piles were timber piles with concrete caps, and heavy cross bracing. Each bent have six piles. Four piles were chosen for the application of the HHT method for prediction of their lengths. Two middle bents of the bridge were chosen, and tests were done on the two edge piles in each one of the two bents. The field tests were done as shown in figure (1) which shows the typical test set up. There are two locations, where the time records from two accelerometers for receiving signals data (A and B) as mentioned before in the SKM method of this study. The distance between the two accelerometers and between them and the above bent and also between the thump and the bent was determined according to the available distance between the bent and the exposed length of the pile(EL) above ground level(or water level if available). The following piles were chosen to predict their overall length (OL), B1P1, B1P6, B2P1, and B6P1. Where, P refers to the pile number and B refers to the bent number. For each pile a number of tests were done by changing the time steps for recording the signal data or the position of the thump (above or below the two accelerometers). Figure (2) illustrates the general signals achieved from the two accelerometers.

Examples of Using HHT Method for predicting pile depth

As mentioned above, four piles were tested for two bents of Bridge No.129 at Johnston County, NC state. Table (1) illustrated the data and the tests done for the four piles.

Bent	Pile	Field	Exposed	Average Pile	Depth of	Depth of
No.	No.	Tests	pile length	diameter	Accelerometer	Accelerometer
			Above	(inch)	(A) from top	(B) from top
			ground in		of pile	of pile
			inch (EL)		(inch)	(inch)
		B1P1T1				
1	1	B1P1T2	73	11.5	24	60
		B1P1T3				
		B1P6T1				
1	6	B1P6T2	88	12.0	30	65
		B1P6T3				
2	1	B2P1T1				54.5
		B2P1T2	66	13.3	18.5	
		B2P1T3				
2	6	B2P6T1	40	12.1	12 75	12 75
		B2P6T2	47	12.1	12.73	43.75

Table 1: shows the data of the tested piles

Figure (3) to Fig.(5) show the four testing pile signal figure data achieved form the data collecting from the two accelerometers of each test. Using the computer tools program, the intrinsic mode function (IMF) for each signal data is done. Figure (6) shows the intrinsic mode functions for two pile tests, B1P1T1 (A &B) and B2P6T2 (A & B) as an examples of using this method. And By using the first intrinsic mode function, as shown in Figure (7) for the same two piles B1P1T1, the signal speed wave Cp was computed using the time difference between the two signal data of each test as mentioned before. Then by using the Hilbert Huang Transform Method (HHT), the overall pile length could be evaluated by drawing the phase angle of each test. Fig., (8) and (9) illustrate the phase angle-time figures for the two pile tests B1P1T1 (A &B) and B2P6T2 (A & B) as an examples of using the HHT to evaluated the overall pile length.

The data evaluated for all the four piles B1P1, B1P6, B2P1, and B2P6 and their predicted data of each pile length are illustrated in Table (2). In this figure, the percentage of the error in pile length compared to the actual pile length is computed to get the accuracy in using the Hilbert Huang transform method for the evaluation of the unknown pile length.



Fig. 1: Typical Field Test Set Up



Fig. 2: Time records from a two accelerometer



Fig. 3: Time Records Taken from Two Accelerometers A and B for pile test B1P1T1



Fig. 4 : Time Records Taken from Two Accelerometers A and B for pile test B1P6T2



Fig. 5: Time Records Taken from Two Accelerometers A and B for pile test B2P6T2



Fig. 6: The IMF components of the Accelerometers (A) for pile test B1P1T1A

Table 2: Prediction of Pile length using HHT Compared to the Actual Length

Bent	Pile	Field	Ср	Npts	Npts	Predicted	Actual	Percentage
No.	No.	Tests	ft/sec2	(Å)	(B)	pile length	Length	Of Error%
						(ft)	(ft)	
1	1	B1P1T1	2140	1491	1302	18.46	19	-3
		B1P1T2	1875	960	911	21.10	19	11
		B1P1T3	2727	1394	1167	20.95	19	10
1	6	B1P6T1	2651	1100	1030	18.08	15.83	14
		B1P6T2	2580	1372	786	16.63	15.83	5
		B1P6T3	1560	1716	1062	14.79	15.83	-7
2	1	B2P1T1	1240	2159	1575	14.61	14.50	1
		B2P1T2	3260	482	207	14.25	14.50	-2
		B2P1T3	2255	1246	1161	16.60	14.50	14
2	6	B2P6T1	3150	1427	1366	11.90	14.10	-15
		B2P6T2	1050	2502	1916	14.25	14.10	2

Fig. 7: The first IMF from the two Accelerometers A and B for pile test B1P1T1

Fig. 8: The computed phase angle $\theta(t)$ for two Accelerometers A and B for pile test B1P1T1

B1P6T2

CONCLUSIONS

For Timber piles which depend upon embedment and shear forces to carry load, the proposed wave propagation method for determining the overall lengths, using the stress bending waves and digital signal processing of dispersive signals by the Hilbert Huang Transform (HHT), has been demonstrated in this research to hold promise as a field test. The percent difference between computed values and pile records are varied from -15% to +14%. Thus with using this new technique, the embedment pile length could be estimated with a reasonable value, which is more convenient for the estimation of the unknown pile data. Also, as a recommendation, by increasing the field test data for each pile a nearest value could be detected for the pile embedded length due to having an average of the result data which gives a reduction in the percentage of error.

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