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Research Paper

Study of the Effect of Source Application on Sonic Echo Tests in Timber Piles

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ABSTRACT: The long-term effects of scour have been identified as one of the primary reasons for bridge failure. To evaluate the performance of the bridges against scour, it is essential to assess the conditions of the bridge foundation including the depth of the piles. Sonic Echo (SE) has been a favorable nondestructive method to evaluate the condition of unknown bridge foundations in the recent decades. Previous studies have shown that the results obtained from SE tests can be affected by a variety of factors such as the pile-to-soil stiffness ratio, length-to-diameter ratio of the pile, presence of defects and anomalies near the pile head, striking method, and hammer type. Although previous studies have discussed such affecting factors, there is a lack of comprehensive investigation regarding the effect of striking method and hammer tip type specific to wood piles supporting bridge decks. In the current study, the effect of striking method and hammer type on the success of SE tests conducted on wood piles has been scrutinized by investigating various options of striking methods and hammer tip types. After comparing different options, superior ones were identified and recommendations for better conducting the SE tests on unknown wood bridge foundations were presented. Numerical simulations were also performed to support some of the conclusions.

Keywords: Pile, Sensor, Signal, Sonic Echo, Superstructure, Wood.

INTRODUCTION

Studies have shown that the long-term effects of scour have been one of the most common reasons for collapse of bridge foundations (Deng and Cai, 2009). Thus, it is crucial to evaluate the bridge foundation characteristics, especially the type and depth of foundations, in order to determine the susceptibility to scour. Such evaluations are not viable for many bridges since no design plans or as-built plans exist to reveal foundation type, depth, or geometry (Coe et al., 2013).

Various Non-destructive Testing (NDT) techniques have been used and developed in

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the past decades to assess the condition of civil infrastructure (Amir and Amir, 2012; Barkavi and Natarajan, 2019; Du et al., 2016; Ghasemzadeh and Abounouri, 2013; Rashidyan et al., 2019a,b). The Sonic Echo (SE) is an economical NDT method with a wide range of applications including characterizing unknown bridge foundations. This method was have been used to evaluate the characteristics of unknown bridge foundations supporting bridge decks (Chai and Phoon, 2012; Huang et al., 2010). A common SE test setup to assess piles underneath a bridge is indicated in Figure 1. Upon applying an impact near the top of the pile, the generated stress wave travels down the pile and reflects at the interface of the pile toe and foundation soil. The propagated wave is recorded through a sensor (a geophone or an accelerometer) (Davis, 1995).

Figure 2 shows a typical velocity amplitude-time graph obtained by a sensor from one of the successful field tests carried out in this study. The indicated impulse and echo points show the moments in which the generated wave passes the sensor location while traveling down and returning towards the pile top respectively. Once the propagated wave velocity is known, the total and buried length of the pile (see Figure 1) can be calculated using Eqs. (1-3).

$$L_{tr} = \frac{v \times \Delta t}{2} \quad (1)$$

$$L_{total} = L_{tr} + L_a \quad (2)$$

$$L_b = L_{total} - L_e \quad (3)$$

where L_{tr}: is distance between sensor location and pile toe, L_{total}: is total length of pile, L_b: is buried length of pile, Δt: is time difference between the impulse and first toe echo and v: is the propagated wave velocity

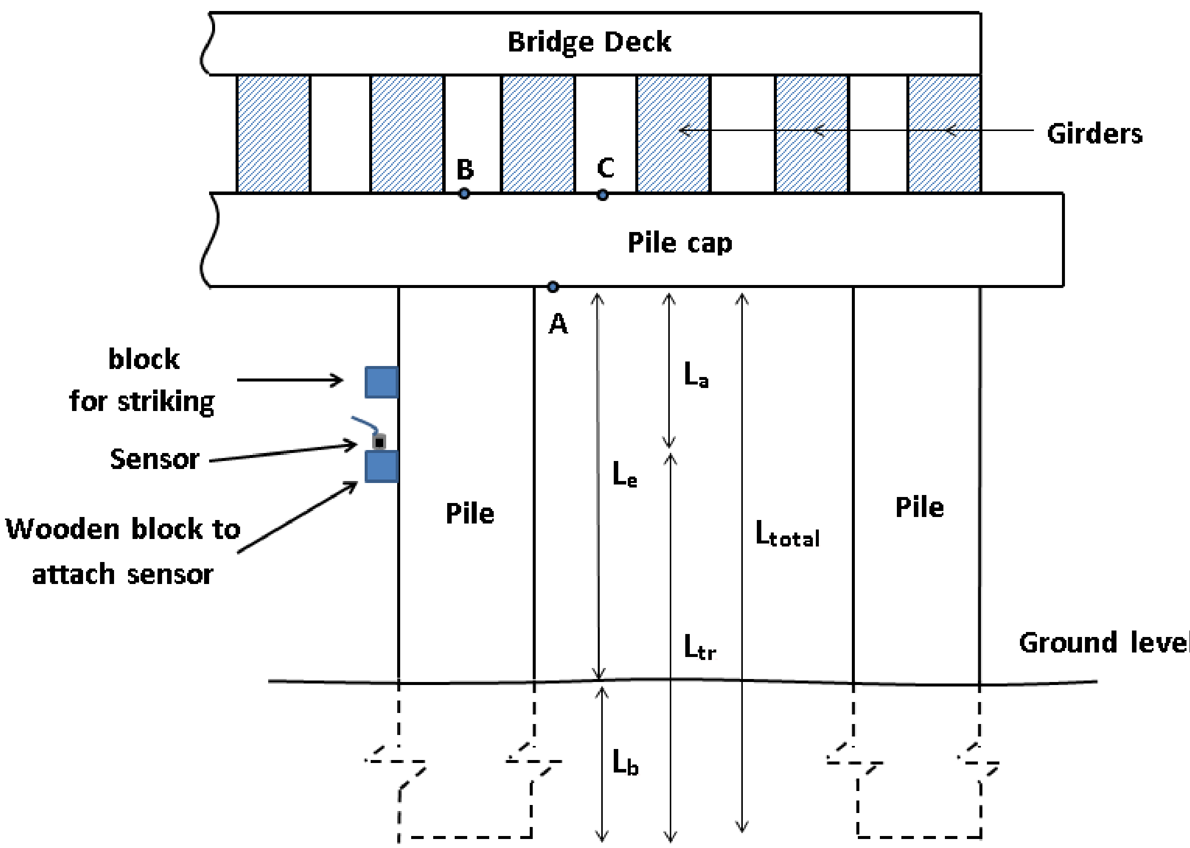


Fig. 1. Sonic echo test setup for piles underneath bridges

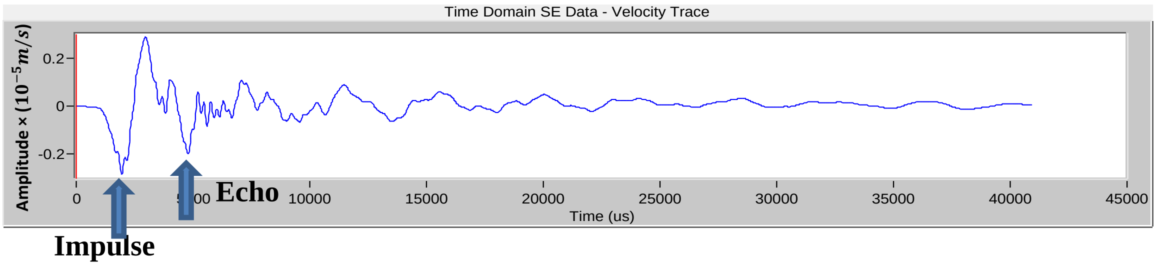


Fig. 2. A typical velocity amplitude-time graph obtained by a sensor from a successful field test

Previous studies have shown that, factors such as the pile-to-soil stiffness ratio, length-to-diameter ratio of the pile, presence of defects and anomalies near the pile head, striking method, and hammer type are major factors affecting the success of the SE test (Yin et al., 1999). Ni et al. (2006) showed that since the impact force energy is radiated from the piles into the surrounding soil, it is difficult to determine the length of a long pile with a high slenderness ratio. The maximum detectable pile length-to-diameter ratio reported in the literature varies from 10 to 30, depending on the stiffness ratio of the pile and the surrounding soil. It was also found that the SE method can be applied on drilled shafts if the shaft to soil stiffness ratio is more than 77 (Kim and Kim, 2003). In addition, the determination of the length of a pile is affected by the presence of anomalies such as bulges and necks along the pile.

A study showed that the defects with sizes greater than 10-30% can be identifiable by SE method (Huang et al., 2010). The striking method and hammer tip type can also affect the success of SE tests. Yin et al. (1999) shown that incorrect hammering can generate poor longitudinal waves. They also indicated that too small hammers with a stiff head generates high frequency waves which attenuates fast and cannot reach the deeper part of the pile. In contrast, too large hammer with a soft head generates a wave with a large content of low frequencies and a large pile which may mix up with reflections from small defects in shallow depth of the pile. Anthony and Pandey (2005) conducted SE tests on 33 piles in four states. They investigated signals obtained from striking the bridge deck as well as an inclined lag screw inserted at 45 degrees to the side of the piles. They showed that using the lag screw had a better performance compared to striking on the top of the bridge deck. They have also showed that a sledgehammer with a medium density plastic tip provided reasonable results.

In another study, the effect of striking method and hammer type on a bridge foundations composed of reinforced concrete pier walls was investigated (Rashidyan et al., 2017). They compared the field tests results with numerical analysis results and provided instructions to use proper hammer tips and striking methods. Although previous studies have discussed various aspects of the affecting factors, there is a lack of comprehensive investigation regarding the effect of striking method and utilizing proper hammer specific to wood piles supporting bridge decks. In the current study, the effect of striking method and hammer type on the success of SE tests conducted on wood piles has been scrutinized by investigating various options of striking methods and hammer tip types. After comparing different options, recommendations for better conducting the SE tests on unknown wood bridge foundations have been presented. Numerical simulations were also performed to support some of the conclusions. The results of this study also can help engineers to identify and characterize unknown wood bridge foundations more effectively.

METHODOLOGY

To achieve the goals of this research, SE tests were carried out on 16 wood piles of three highway bridges located in New Mexico, USA. The foundation plan of the investigated bridges is shown in Figure 3. During testing, the depths of the piles were determined and the selected factors affecting the SE tests were investigated. The selected factors were the striking method and hammer tip type. The correctness of the determining the depth of the piles was confirmed in Bridge 3 for which the foundation information was available.

In addition to the field tests, Finite Element simulation of a foundation comprising a pile cap and multiple piles (similar to bent C at Bridge 3 in Figure 3c) were carried out to study the nature of the velocity signals obtained from the sensors when various striking methods were applied on the foundation. ABAQUS Finite Element software was used to analyze the models.

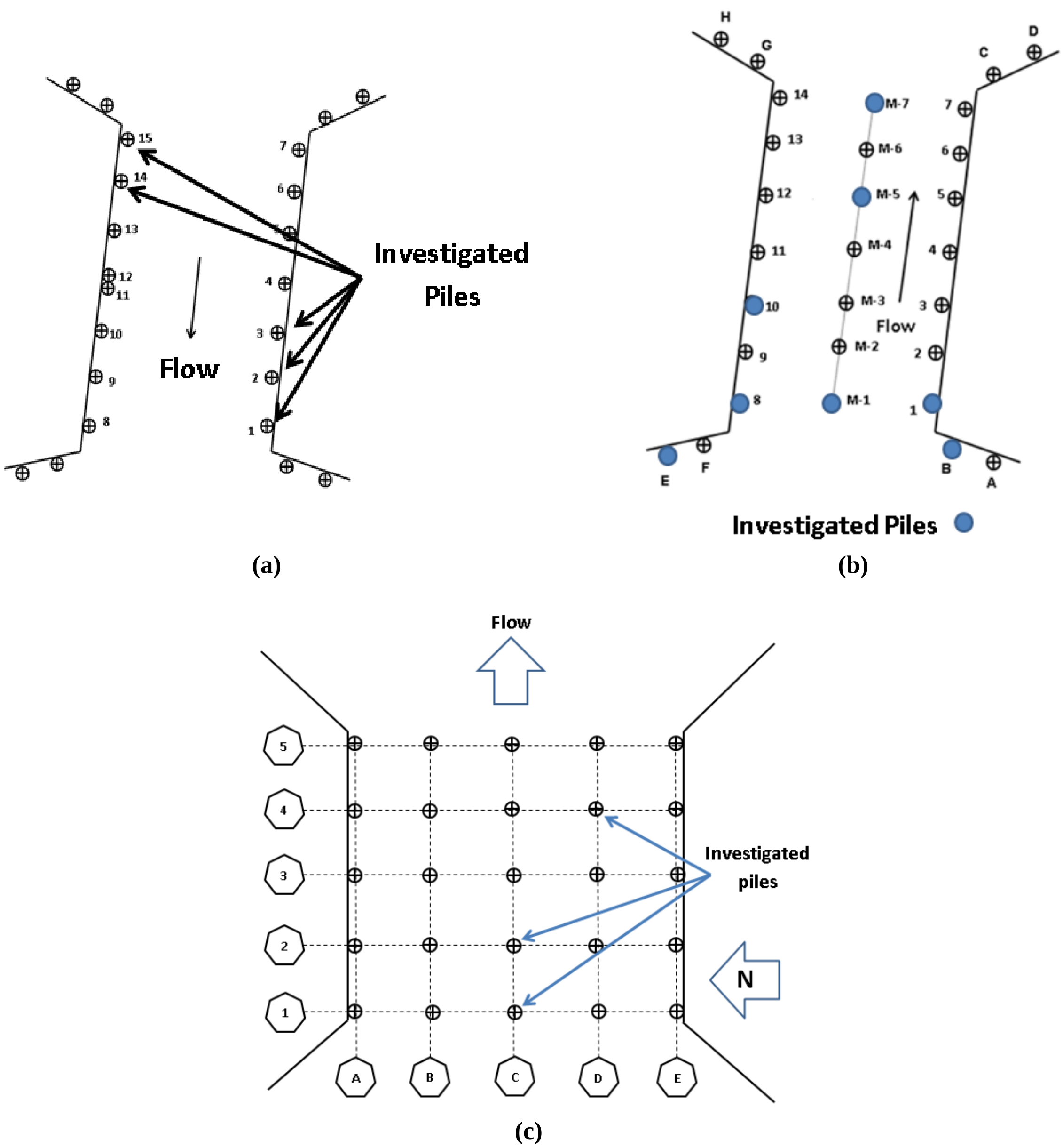


Fig. 3. Foundation plan and investigated piles of Bridges: a) 1; b) 2 and; c) 3

SE test procedure was developed and pursued step by step in conducting the field tests. An SE test procedure includes the selection of striking method, accelerometer placement, equipment assemblage, and data acquisition. Before proceeding to the results of field tests, the SE test procedure is described here.

Striking Setup

In SE tests, sonic waves are generated by striking a hammer on a surface of the foundation. Depending on the accessibility of the pile top, different striking methods can be used to generate sonic waves along the pile. In this research, multiple striking options are examined for both piles with accessible and inaccessible tops and the best options have been recognized. The results will be discussed later.

Striking Setup for Piles with Accessible Top

When either the entire or a portion of the pile top is accessible, a vertical strike can be applied on the top surface of the pile as shown in Figure 4. In wing piles above which there is no superstructure, the vertical strike can be easily applied due to the absence of superstructure (Figure 4a). In some bridges, a part of the pile top becomes accessible due to the difference in the dimensions of the pile and pile cap (Figure 4b), therefore, a top striking is viable although the superstructure exists atop the pile. In both cases, the longitudinal P-waves travelling down the pile is generated directly.

Piles without Accessible Top

When the top of a pile is inaccessible, the longitudinal wave can be generated by other methods. Three options for applying the source are shown in Figure 5. Options 1 to 3 include vertical striking on top surface of pile cap above the pile (point B), eccentric vertical striking on top surface of pile cap (point C), upward vertical striking on bottom surface of pile cap (point A).

A wood or metal block attached to the side of the pile can also be utilized for striking. The blocks can be cubic or wedge in shape. When a striking block is employed, the block should be properly secured by nails and screws to prevent any detachments during striking. The only requirement of the dimensions of the striking block is that they must be greater than the size of the hammer tip to prevent any contact between the pile side and the hammer during striking. The striking block is usually located between the first accelerometer and the top of the pile.

(a) **(b)**

Fig. 4. Striking on: a) pile top and; b) pile top edge

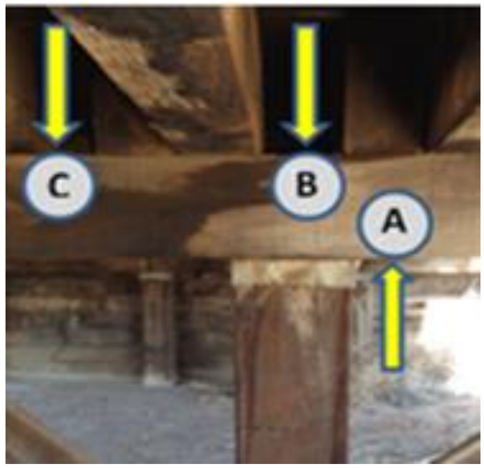


Fig. 5. Vertical striking on top surface of pile cap above the pile, eccentric vertical striking on top surface of pile cap, upward vertical striking on bottom surface of pile cap

Receivers Setup

The sensor (accelerometer) is placed atop the piles with accessible top surface (mainly wing piles). If the pile top is inaccessible, the accelerometers will be vertically mounted on wooden blocks attached onto the side of the test pile with nails, screws, or glue. Examples of accelerometer attachment onto the pile surface is indicated in Figure 6.

Hardware Assembly

The utilized equipment was acquired pursuant to ASTM D5882-07-2013 (ASTM, 2013) and ACI 228.2R-13 (ACI, 2013) and consisted of the FDPC platform, two 100 mv/g accelerometers, a hammer with force transducer and various tips. The assembled SE test equipment is shown in Figure 7. The hammer tips were hard, medium hard, medium soft, and soft as indicated in Figure 8. The contact time for hard, medium hard, medium soft and soft tips were approximately 1200, 2400, 3600 and 4800 microseconds respectively. The contact time increased with the degree of softness of the hammer tip.

Fig. 6. Accelerometers mounted on piles using wooden blocks

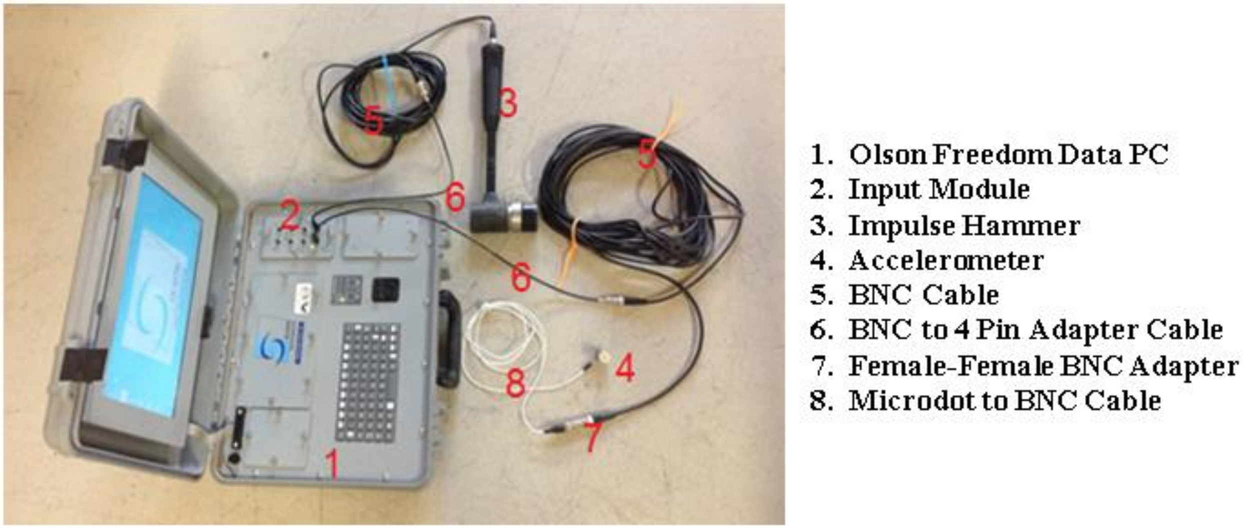


Fig. 7. SE/IR test equipment

Fig. 8. Utilized hammer and four different tips

SE Data Acquisition and Processing

The velocity amplitude-time graphs obtained from the accelerometers were used to determine the pile lengths. An example of obtained velocity graphs from a vertical downward striking on an accessible pile top with the location of the impulse and echo was previously indicated in Figure 2. The pile lengths were calculated based on the differences between the location of the impulse and echo on the velocity graphs. The wave velocities in wood were calculated from measuring the time lapse between two accelerometers mounted on the side of the pile in the piles.

OBSERVATIONS AND RESULTS

SE tests were carried out on 16 piles with known and unknown depths to study the various practical aspects of the method. The depths of 15 piles were measured successfully using SE tests results. The success rate of the tests in each pile, however, depended on factors influencing the obtained signals such as striking specification, sensors location, hammer tips, environmental and foundation conditions. In the current study, the effect of two main factors including striking method specification and hammer tip types are scrutinized. The results of each factor are described in the sequel.

Striking Methods

Piles with Accessible Top

This method was used only when the pile top was fully accessible (2 piles out of 16 investigated piles). The pile length was determined successfully in most of the cases.

The impulses and echoes were clearly recognizable on the velocity graphs in successful tests. Successful SE tests were obtained even for foundations for which only a small part of the pile top was exposed but large enough for applying a hammer strike (6 piles out of 16 investigated piles). An example of a good velocity amplitude-time graph obtained from pile top striking with clear impulse and echo was previously indicated in Figure 2.

The success rate of the all SE tests performed by pile top and pile top edge striking methods on piles with fully or partially accessible top is indicated in (Table 1). The data show that vertical downward striking on the pile top transmits the impulse energy directly to the pile, whereby the most consistent results have been obtained compared to the pile top edges. It is expected that the absence of superstructure result in the lack of adverse reflections from the superstructure boundaries.

Table 1. Success rate of SE tests for different striking methods on piles with accessible top

Striking point	Pile top	Pile top edge
Success rate (%)	83.3	52.4

Piles without Accessible Top

Points B and C: When the pile top was totally covered with the pile cap and superstructure, striking was applied at points B and C as indicated in Figure 5. However, we were only able to apply the impact by striking at point C due to the location of the girder in some cases. In cases where the downward striking at point C was used, the striking point was selected as close as possible to the pile center to maximize the input energy imparting into the pile. In general, higher rate of successful SE tests were observed at point B than at point C due to the greater distance between the striking point and the center of the pile in striking on point C. The results will be further discussed later.

Point A: Upward striking on the bottom surface of the pile cap, adjacent to the test pile, were considered as an effective alternative mean to generate a longitudinal wave through the test pile. Figure 9 depicts examples of velocity graphs obtained from applying upward striking on the bottom surfaces of the wood pile caps. The graphs show that, the upward striking at point A produces tensile wave instead of compression waves generated by downward striking (compare Figure 9 to Figure 2). The field study indicated that fewer successful SE tests were produced than striking at point B.

To identify the best striking methods in piles with inaccessible pile, comparisons were carried out based on field tests and numerical simulation results. The results are explained in the sequel.

Comparison of the striking methods for piles with inaccessible top based on field tests results: Table 2 lists the success rate of SE tests performed by different striking methods on piles with inaccessible top. The results show that vertical downward striking on a point inside the projected pile cross section on pile cap top surface (point B in Figure 5) transmits the most impulse energy directly to the pile, whereby the most consistent results were obtained. Consequently, this method is the best to conduct SE tests. If direct striking at the top of the pile is not feasible, downward eccentric striking on the top of the pile cap (point c in Figure 5) or upward striking on the bottom of the pile cap next to the pile (point A in Figure 5) are alternative options with less expected success rate.

Table 2. Success rate of SE tests performed by different striking methods for piles with inaccessible top

Striking point	Point A	Point B	Point C
Success rate (%)	54.1	81.3	37.5

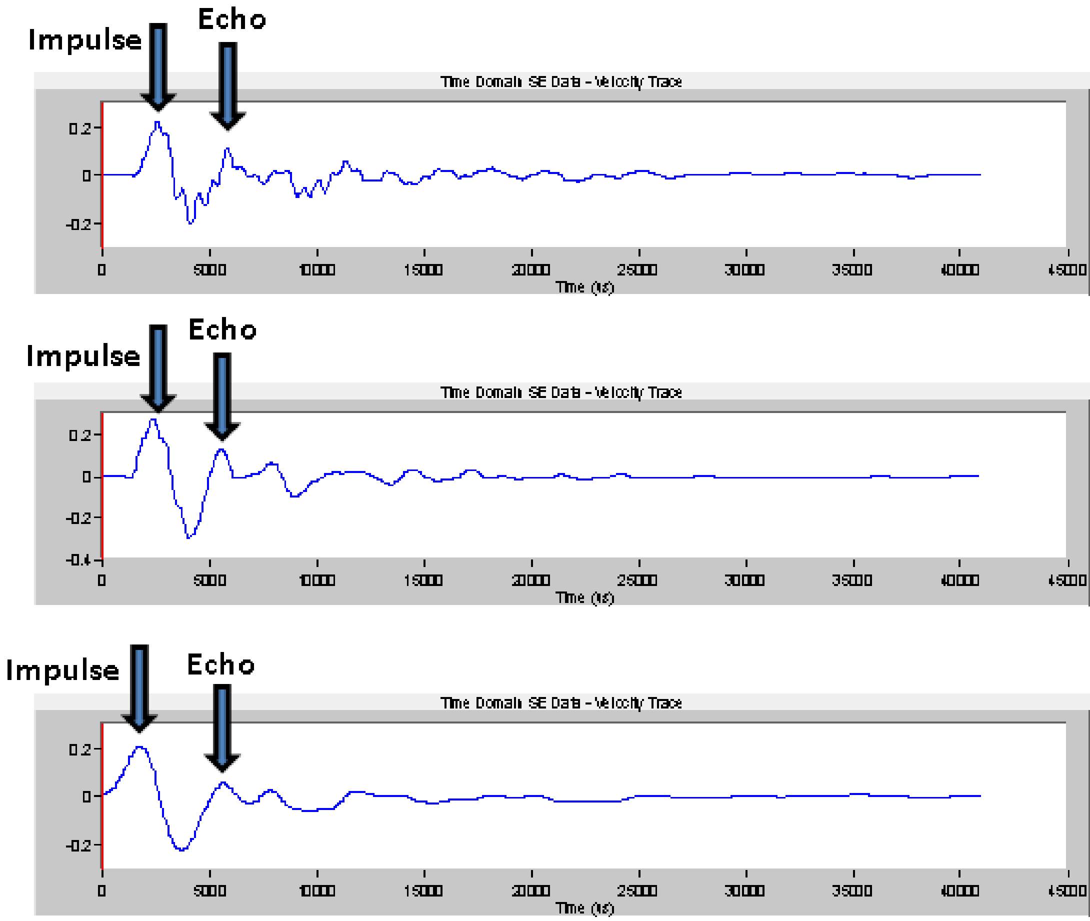


Fig. 9. Examples of velocity graphs obtained from applying upward striking on pile cap

Comparison of the striking methods for piles with inaccessible top based on FEM results: To study the nature of the velocity signals obtained from the sensors in the presence of pile cap, it was decided to investigate a foundation comprising piles and pile cap similar to one of the bridge foundations indicated in Figure 3. The selected FEM model had the same dimensions as the foundation on bent C at Bridge 3. The FEM model provided means to compare signals obtained from different striking methods and determine the best method. The properties of the FEM model are indicated in Table 3. The assumed wave velocity is 3048 m/s which is the same as the velocity utilized to calculate the lengths of piles C-1 and C-2 (see Figure 3c) using field tests results. This velocity was calculated from measuring the time lapse between two accelerometers mounted on the side of the pile in the field.

Other utilized properties are in accordance with the Wood Handbook (USDAFS, 2010). It should be noted that, in the wave propagation problems, the element size should be less than about 1/8-1/10 of the wavelength of the highest frequency in order to capture the proper response (Lin et al., 1991). The maximum frequency of the propagated stress wave is about 2.5/τ (Carino et al., 1986); where τ is the duration of impact. Since the wave velocity is 3048 m/s, throughout this study, the maximum sizes of the elements were selected 0.15 m to satisfy the above-mentioned limitations. Moreover, the actual waveform detected in field tests is subjected to damping inherent in the wood and surrounding material which absorbs the wave energy.

To investigate the effect of material damping, the Rayleigh damping coefficients (Spears and Jensen, 2009) α=8.19 and β=0.0001 were considered in modeling. The effect of surrounding soil is also neglected in the study since the effect of material damping suffice to compare the results of striking methods.

Table 3. Specifications of FEM model of the investigated foundation

V (wave velocity)	3048 m/s
E (modulus of elasticity)	7.43 GPa
ρ (density)	800 kg/m^3
ν (Poisson's ratio)	0.3
Impulse amplitude	1 MPa
Impulse shape	Parabola
Impulse duration	1.2 ms
Simulation time duration	20 ms
Elements type	C3D8R (8-node linear brick)

Figure 10 shows the simulated FEM model. Downward strikes at points B and C and upward strike at point A were applied as the source. The velocity signals obtained from Node 1 (corresponding to accelerometer 1 in the field) located 0.3 m below the pile top are investigated here. The signals obtained from numerical simulations are compared to field results for each striking method in Figures 11 to 13. The results show that all strikes can produce interpretable results leading to determining the pile's length. The impulse and echoes were completely detectable on the graphs. The lengths corresponding to the time differences between the impulse and echo are very close to the actual length and the errors are less than 10%. The results are summarized in (Table 4).

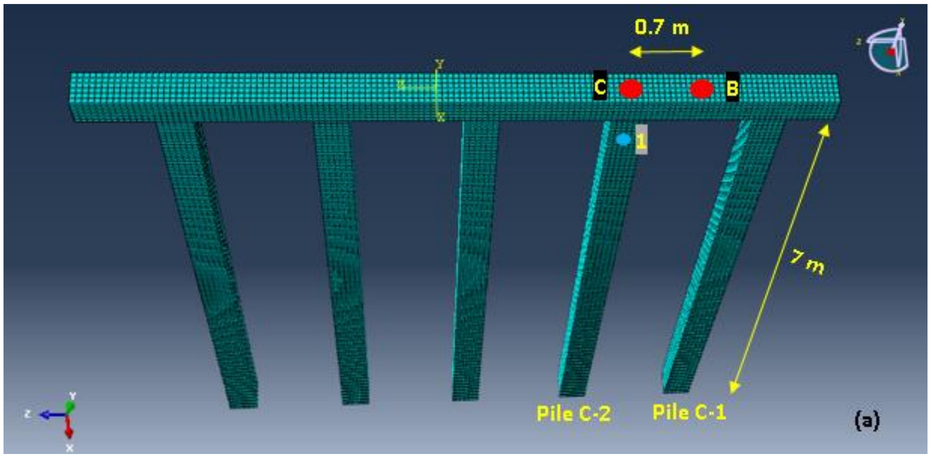
The results also show that, among these three striking methods, the signals' amplitudes for striking at point C (center) is maximum whereas they are minimum for point B (eccentric strike). This can be one of the main reasons for superiority of striking at C over striking at points A and B and superiority of A over B in the field tests results. The amplitudes of the impulses and echoes are indicated in (Table 5) for all striking methods. It should be noted that the actual waveform is affected by multiple reflections from the superstructure boundaries in the field. However, we only tried to compare the signals obtained from different striking methods and identify the most efficient one. The discrepancy between the field test and numerical simulation arises from the neglection of the effect of superstructure and environmental noise which is present in the field.

Table 4. Lengths calculation results for different striking methods

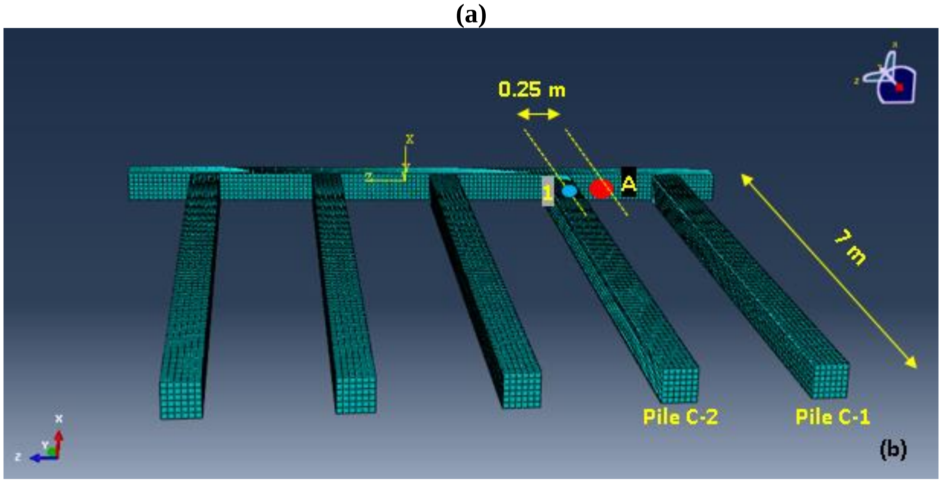
Striking method	**Δt (s) from numerical simulation**	**L_{tr} (m) from numerical simulation**	**L_a (m)**	**Error (%)**	**Δt (s) from field**	**L_{tr} (m) from field**
Striking at point C	0.00485	7.31	6.70	9.1	0.00432	6.58
Striking at point B	0.0045	6.86	6.70	2.36	0.00474	7.22
Striking at point A	0.0046	7.01	6.70	4.63	0.00440	6.71

Table 5. Amplitudes of the source signals for different striking methods

Striking method	**Impulse amplitude**	**Echo amplitude**
Striking at point C	-0.003694	-0.002231
Striking at point B	-0.002421	-0.001712
Striking at point A	0.002925	0.001943



(a)



(b)

Fig. 10. FEM model of foundation at Bent C in Bridge 1 showing striking points: a) B, C and; b) A

It should be noted that, in the FEM section we only provided comparison between different striking method using a simple model comprising pile cap and piles. We acknowledge that a more comprehensive model shall include the effect of surrounding soil, girders, bridge deck and pavement. However, it was impossible to take the effect of all these elements into consideration since the investigated bridge is an old bridge with many deteriorated elements having defects and anomalies with poor attachments between both the pile cap and girders and the girders and bridge deck. Therefore, the conclusions of the FEM section will only be valid for the wave propagation mechanism in our model comprising pile cap and piles.

In addition, as mentioned before, modeling the entire bridge was impossible due to the abovementioned reasons, therefore, we assigned an arbitrary impulse amplitude of 1 MPa (see Table 3) to examine the wave propagation mechanism in our investigated model. Since the amplitude of the signals received by the sensors in the field (which depends of the effect of surrounding soil, girders and bridge deck and their connections) is basically different from those obtained from the FEM model, graphs of Figures 11-13 have different amplitudes. In contrast, these figures and Table 4 show that good agreement exists between the FEM and field tests results in determining the depth of the piles when time difference between the impulse and echo is sought. The graphs indicated in Figures 11-13 show that although the signals obtained from FEM model and field tests have different amplitudes, the time difference between the signals and echoes and consequently the measured lengths are very close to each other (error less than 10 percent).

Striking Block: In this method, the impulse is introduced by striking a block with a hammer. The block is attached to the side surface of the pile using proper nails and bolts. Blocks of different materials (aluminum and wood) and shapes (cube and wedge) were tested in the current study. The aluminum block was specifically machined with a curved surface in order to provide a better contact with the side of the round piles. The utilized wood and aluminum cubic blocks are shown in Figure 14. It should be noted that this method introduces additional costs for attaching a striking block on the pile surface. The method also introduces additional uncertainty due to the problems related to the attachment of a striking block onto the pile surface.

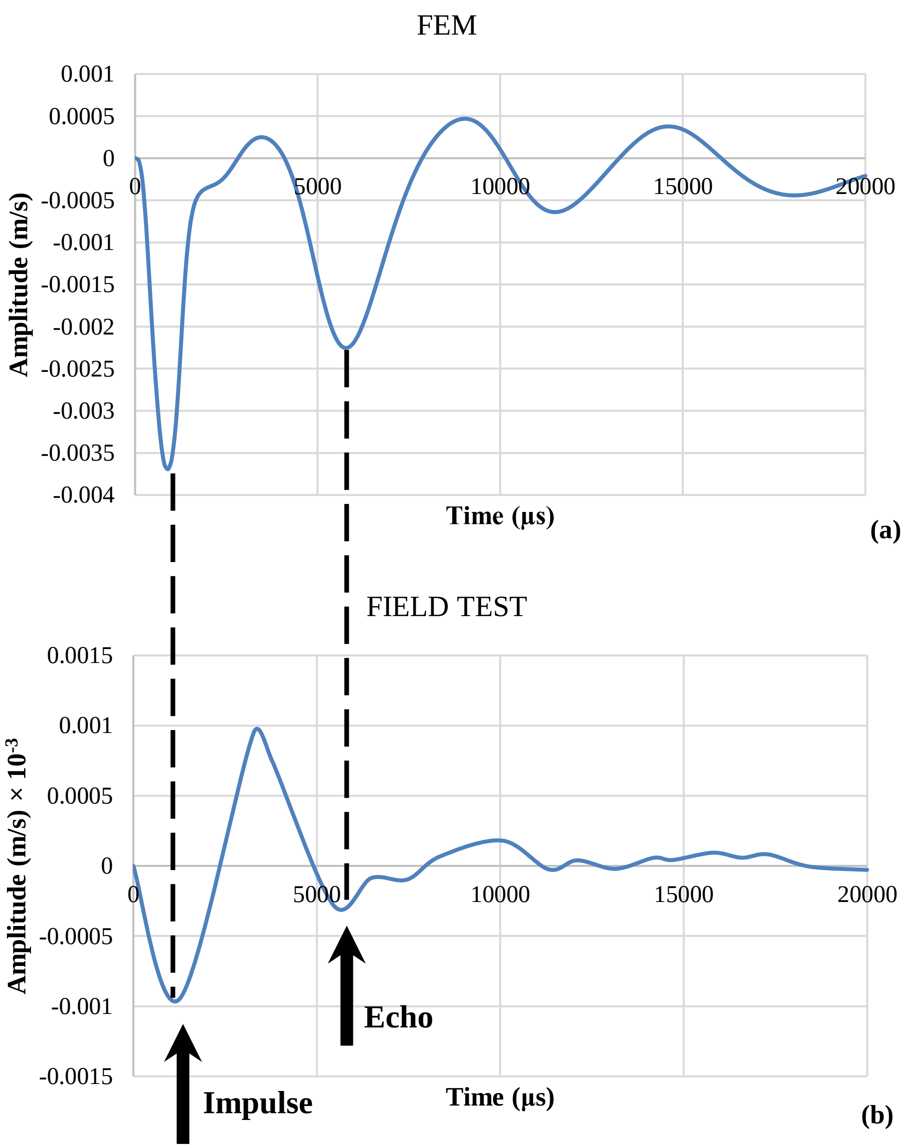


Fig. 11. Velocity signal obtained at Node 1 and produced by striking on point C from: a) numerical simulation; b) field

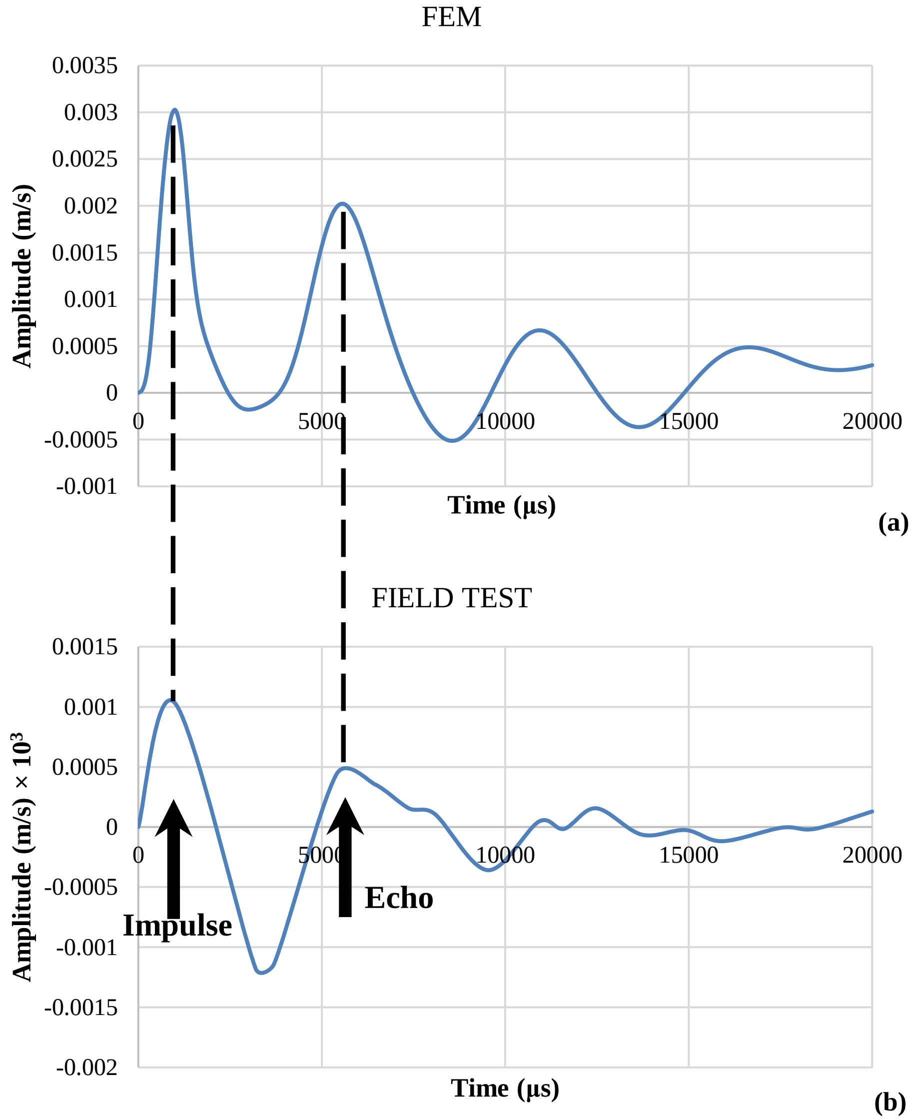


Fig. 12. Velocity signal obtained at node 1 and produced by upward striking on point A from: a) numerical simulation; b) field

The success rate of SE tests for different block material and shape is indicated in (Table 6). The results show that the success rate of using aluminum striking block is unsatisfactory. However, the success rate is improved by using wooden blocks. Figure 15 shows examples of undesirable velocity amplitude-time graphs with no clear pile toe echo, obtained from striking the aluminum block. The reason for poor outcome was the poor quality of input signal which is discussed in the sequel.

Table 6. Success rate of SE tests for different striking blocks

Block type	Aluminum	Wood (cubic)	Wood (wedge)
Success rate (%)	23.3	56.8	35.7

Figure 16 shows the amplitude-time sample graphs of the hammer impulse obtained from striking on the aluminum and wood blocks compared to a regular amplitude-time graph which is usually obtained from striking on a rigid surface. The shape of the source for the aluminum block contains multiple peaks which is different from the typical hammer impulse on a rigid surface. The peaks on aluminum block's graph may be due to either a momentary contact loss or multiple contacts between the block and the pile surface, which cannot be observed visually. Such poor-quality input sources resulted in unsatisfactory SE tests.

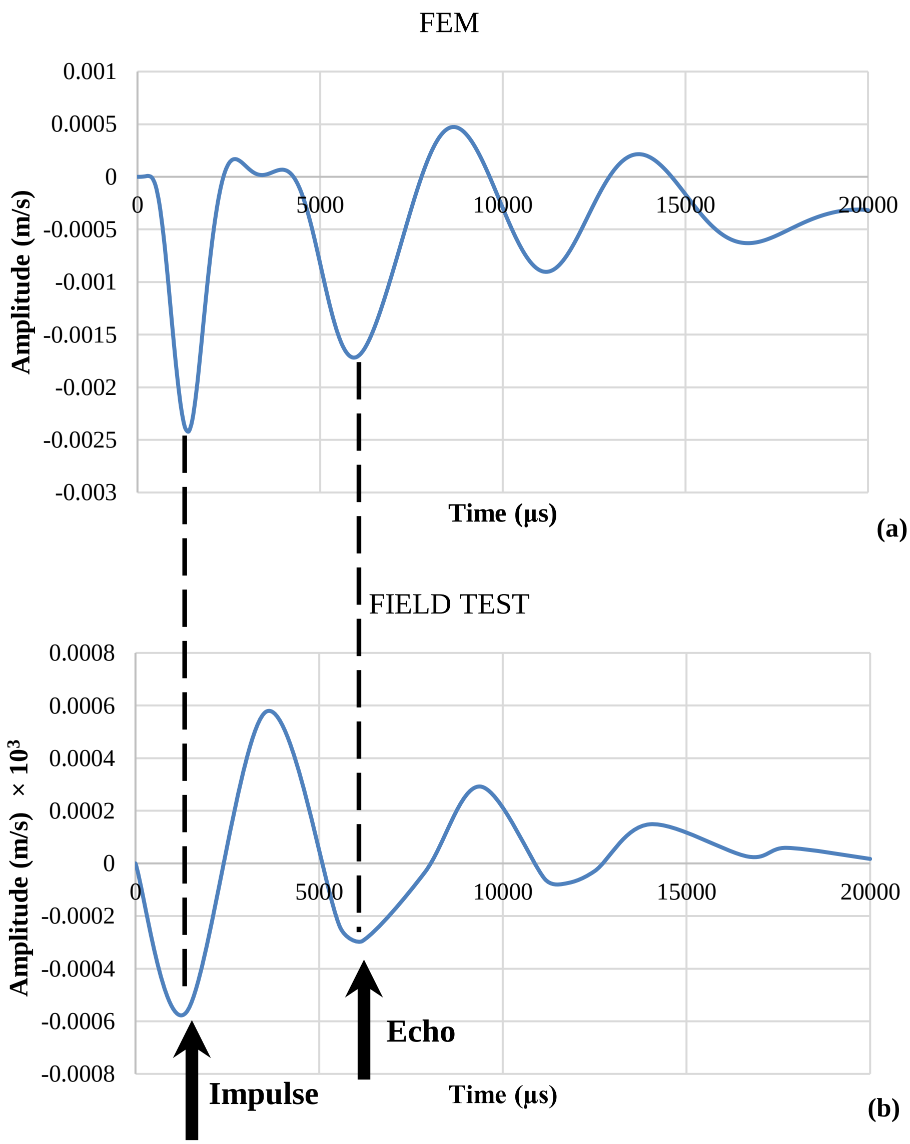


Fig. 13. Velocity signal obtained at node 1 and produced by striking on point B from: a) numerical simulation; b) field

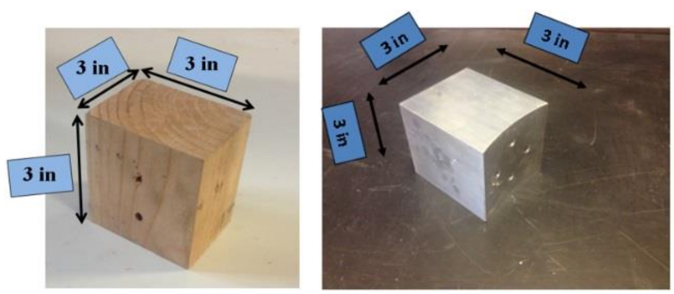


Fig. 14. Utilized aluminum and wood cubic blocks for striking

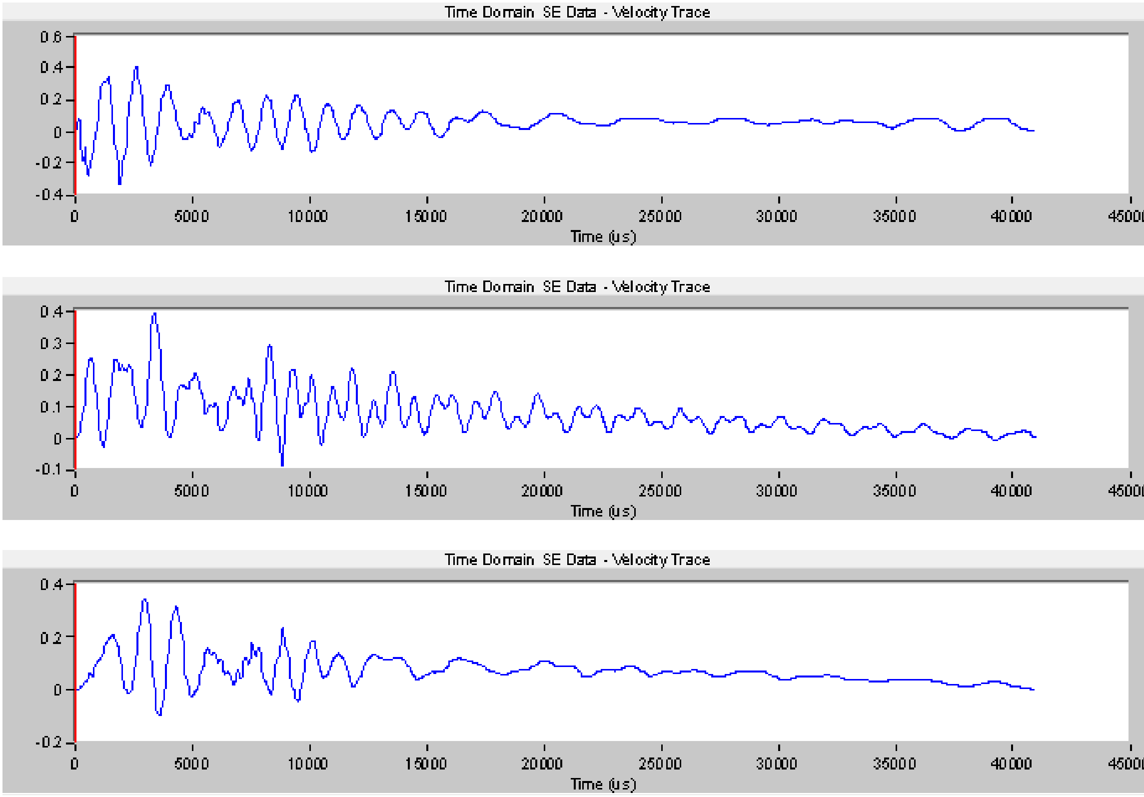


Fig. 15. Examples of velocity signals obtained from striking on aluminum block

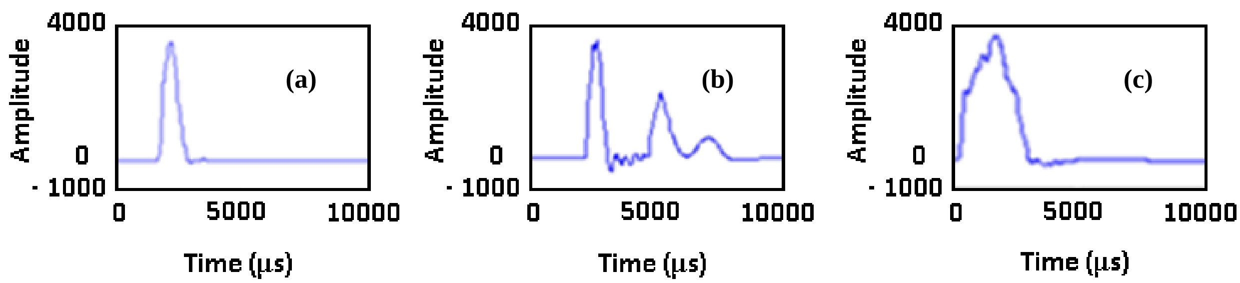


Fig. 16. Initial impulse from hammer's force sensor: a) rigid surface; b) aluminum block; c) wood block

Wedge blocks were also exploited although striking on wedge blocks produced a horizontal wave as well as a vertical compression wave. The results of the study show that inclined hammer strikes can produce similar results to those of vertical strikes on cubic blocks. However, more bad results were obtained compared to cubic blocks.

Hammer Tips

The results of our study showed that, the hard tip with contact time of 1200 μs produced more successful SE tests than the other three softer tips indicated in Figure 8. The success rate of the SE tests performed by different hammer tip types are indicated in (Table 7). This hammer tip type has provided the best combination of wave energy with minimal wave energy attenuation.

Table 7. Success rate of SE tests performed by different hammer tip types

Hammer tip type	Hard	Medium -hard	Medium-soft	Soft
Success rate (%)	81.6	80	77.8	75

Besides determining the success rate of the SE tests for different hammer tips, additional investigation on the effect of the strength of source signal was conducted for the investigated wood piles. The success rate of SE tests performed by different hammer tips are indicated in (Tables 8-11) based on the amplitudes of the source signals. The tables' data has following specifications:

- In each table, depending on the amount of available data, the amplitudes of the source were broken down into multiple ranges to provide a better understanding of the SE tests success rate at specific amplitudes.
- The data of striking on the wood and aluminum blocks have not been considered since the success rate in such cases remarkedly depends on the quality of the attachment of the block to the pile surface.
- All the tests conducted by hard and medium hard tips with amplitudes greater than 1 lbf produced good results. They have not been brought in the tables.

Table 8. Success rate of SE tests for tests performed by hard hammer tips

Source amplitude signal range (lbf)	Success rate (%)
0.85-1	100.0
0.65-0.85	85.7
0.4-0.65	85.7
0.2-0.4	28.6

Table 9. Success rate of SE tests for tests performed by medium-hard hammer tips

Source amplitude signal range (lbf)	Success rate (%)
0.7-1	85.7
0.6-0.7	100
0.5-0.6	71.4
0.35-0.5	71.4
0.1-0.35	42.9

Table 10. Success rate of SE tests for tests performed by medium-soft hammer tips

Source amplitude signal range (lbf)	Success rate (%)
0.8-1	85.7
0.64-0.8	85.7
0.45-0.64	100
0.35-0.45	85.7
0.1-0.35	42.9

Table 11. Success rate of SE tests for tests performed by soft hammer tips

Source amplitude signal range (lbf)	Success rate (%)
0.7-1	100
0.5-0.7	100
0.4-0.5	75
0.2-0.4	25

The results indicated in (Tables 8-11) show that the success rate of the SE tests is greater for sources with large amplitudes. It implies that stronger strikes can generate more interpretable results. As a result, for our existing equipment, the SE test performer should strike strong enough such that the amplitude of the produced signal exceeds 0.4 lbf to achieve satisfactory results for all types of the hammer tips.

CONCLUSIONS

SE tests were conducted on 16 piles of three highway bridges with known and unknown foundations. The lengths of the piles were determined using the velocity graphs obtained from accelerometers. The depths of 15 piles were determined using SE tests. The success rate in the performed SE tests were affected by a range of factors. In the current study, the effects of striking method and hammer tip type were investigated.

Depending on the accessibility of the pile top and the geometry of the superstructure, various source locations able to produce a longitudinal wave along the test object were examined. Vertical downward striking on either the pile top or a point inside the projected pile cross section on pile cap top surface transmitted the most impulse energy directly to the pile, whereby the most consistent results were obtained. Consequently, these two methods were the best to conduct SE tests. If direct striking at the top of the pile is not feasible, eccentric striking on the top of the pile cap or upward striking on the bottom of the pile cap next to the pile are alternative options. If none of these striking methods can be used, impulse source can be generated by striking on a wooden block that is tightly attached onto the pile. Although eccentric downward and upward striking on pile cap and striking on wood blocks can be considered as proper options for striking, they suffer from less success rate compared to vertical downward striking on either the pile top or a point inside the projected pile cross section on pile cap top surface.

In addition to the study of the field tests results, numerical models were also investigated to reveal the effect of striking methods on the obtained velocity signals. The selected FEM model had the same dimension as one of the investigated wood bridge foundations. Using this FEM model, signals obtained from different striking methods were compared and the best method was identified. The finding was in accordance with the field tests. The results showed that downward striking at the pile's center, downward eccentric and upward striking on the pile cap are all capable of producing interpretable results. The impulse and echoes were completely detectable on the graphs. The resulted lengths corresponding to the time differences between the impulse and echo were very close to the actual length. The results also showed that, among these three striking methods, the signals' amplitudes for striking at center point of the pile was maximum whereas the amplitudes were minimum for eccentric strike. This observation can be one of the main reasons for superiority of striking at center over eccentric and upward striking on the pile cap.

It should be noted that, in the investigated numerical models it was only decided to provide a comparison of different striking methods in terms of their location respect to the pile center. In reality, the obtained velocity signals are affected by the reflections from superstructure boundaries such as girders and bridge deck which is neglected in the study.

The field tests result also showed that, the hard tip hammer with contact time of 1200 μs produced more successful SE tests than the other three softer tips. This hammer tip type has provided the best combination of wave energy with minimal wave energy attenuation. In addition to determining the success rate of the SE tests for different hammer tips, more investigation on the effect of the source signal amplitude was conducted for wood bridge foundations. The results showed that the success rate of the SE tests is greater for sources with larger amplitudes. It implies that stronger strikes can generate more interpretable results. As a result, for our existing equipment, the tests should be performed with a moderately strong strike such that the amplitude of the produced signal exceeds 0.4 lbf to achieve satisfactory results for all types of the hammer tips. This finding is important in practice when the test performer would like to obtain the most success rates.

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