Wave Speeds in Large Diameter Open-End Steel Pipe Piles

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ABSTRACT

Open-end pipe piles with diameters of 36 inches (914 mm) or larger and wall thicknesses in excess of 0.5 inches (13 mm) are increasingly being used for deep foundation support of large bridge projects in the United States. In the last several years, initial driving dynamic test data on these large diameter open-end pipe piles on some bridge projects as well as on offshore platforms has indicated overall wave speeds for the measured length in excess of the commonly used value of 16,800 ft/s (5,122 m/s) for steel piles. Measurements were undertaken on a recent Minnesota bridge project to directly quantify the pile wave speed. Two pairs of accelerometers were positioned 64.2 ft (19.6 m) apart during initial driving of a test pile. This dynamic test data indicated a most likely wave speed for the pile of 17,000 ft/s (5,182 m/s). Steel coupon testing also indicated a higher elastic modulus than commonly assumed. This paper presents the field dynamic test data and laboratory test results indicating a faster wave speed and higher elastic modulus, with respect to standard values, observed on this project. Other recent cases supporting use of a faster steel wave speed and higher elastic modulus are included and discussed. Recommendations are provided for dynamic testing on large diameter open-end steel pipe piles.

Keywords: steel pipe pile wave speed, steel pipe pile elastic modulus**,** dynamic pile testing, pile toe damage.

INTRODUCTION

The elastic modulus, material wave speed, and mass density are interrelated in accordance with wave mechanics principles [1]. This relationship is expressed in Equation 1.

$$E = \rho c^2 \qquad \text{(Equation 1)}$$

Where:
E = elastic modulus, ksi or MPa
ρ = mass density, slugs/ft^3 or kg/m^3
c = material wave speed, ft/s or m/s

For steel piles the elastic modulus, unit weight, and wave speed have historically been taken as constants with an elastic modulus value of 30,000 ksi (206,843 MPa), a unit weight of 492 lb/ft^3 (77.3 kN/m^3), and a material wave speed of 16,800 ft/s (5,122 m/s) [2]. A stress wave will travel down the pile at the wave speed of the pile material. For a uniform pile with no changes in cross section, the stress wave will return to the top of the pile at a time 2L/c after impact, where L is the pile length and c is the wave speed of the pile material. For steel piles of a known length, the time of wave return is therefore known and fixed based on the historically assumed constant wave speed. Wave return prior to the expected return time would suggest either an incorrect pile length measurement or a pile with toe damage.

CASE 1 – MINNESOTA

On a recent bridge project in Minnesota, 42 inch outer diameter (O.D.) by 0.75 inch wall (1067 mm O.D. by 19 mm wall), open-end pipe piles were used for foundation support. The pipe piles were made from hot rolled black steel coils converted to spiral-weld steel pipe meeting ASTM A252-10 Grade 3 steel requirements which stipulate a minimum yield strength of 50 ksi (345 MPa). Mill certificates indicate the steel had an actual yield strength of 59.9 ksi (413 MPa), a tensile strength of 69.2 ksi (477 MPa), and a total elongation of 44% at 2 inches (51 mm). The steel chemistry was reported as detailed in Table 1.

Table 1 - Steel Chemistry (% by weight)			
Carbon = 0.06%	Silicon = 0.17%	Chrome = 0.03%	Tin < 0.02%
Manganese = 0.84%	Copper = 0.02%	Columbium = 0.27%	Titanium = 0.15%
Phosphorus = 0.009%	Nickel < 0.02%	Vanadium < 0.008%	Nitrogen = 0.0042%
Sulphur = 0.002%	Molybdenum < 0.02%	Aluminum = 0.04%	Boron = 0.0001%

Wave speed measurements were acquired following splicing of the final pile section onto a partially driven pile. Two accelerometers were bolted to the final add-on pile section at diametrically opposite locations two diameters below the pile head. Two additional accelerometers were bolted to the pile at diametrically opposite locations 64.2 ft (19.6 m) below the upper pair. These two point acceleration measurements were collected from 30 hammer impacts on the pile. The acceleration records were recorded at a digitizing frequency of 40,000 Hz. The calibration of the digitizing board was also checked and verified in the data acquisition unit prior to conducting the test.

Figure 1 presents partial, average acceleration and velocity records from the two accelerometers attached near the pile head as well as partial, average acceleration and velocity records from the two accelerometers attached a distance of 64.2 ft (19.6 m) apart. Partial records are presented so as to not obscure the lower measurement data. Ideally, the beginning of the impact event can be easily identified by a clear change in slope. The change in slope of the velocity records is rounded due to the pre-compression effect from the diesel hammer used to drive the pile. The change in slope apparent in the lower gage data is also slightly more rounded relative to the change in slope observed in the pile head data. Therefore, the average acceleration records with their clearer defined change in slope were also evaluated for pile wave speed determination.

The left most solid vertical line corresponds to the start of the impact event identified by the rise in the pile head acceleration record. The right most solid vertical line identifies the time where the wave arrives at the lower gage location based on a wave speed of 17,150 ft/sec (5,227 m/s). The dotted vertical line marks the wave arrival at the lower gages based on a wave speed of 16,800 ft/sec (5,122 m/s).

In Figure 1, the rise in the lower gage average acceleration record clearly begins prior to the arrival time associated with the standard wave speed of 16,800 ft/sec (5,122 m/s). Hence, a faster wave speed is indicated by the data. For the hammer impact presented in Figure 1, a wave speed of 17,150 ft/sec (5,227 m/s) matches the rise in the lower gage average acceleration record indicating the onset of wave arrival.

As noted earlier, the two point acceleration measurements were collected from 30 hammer impacts on the pile. Each velocity record was then analyzed using a measure of similarity. The velocity data collected 64.2 ft (19.6 m) below the sensor location near the pile head was time shifted until the peak approximately matched the peak of the pile head velocity. The difference between the two velocity records was calculated for each data point over the 0.6 ms duration of the initial impact peak, and the sum of the absolute values of these differences was calculated. The time shift was then adjusted earlier or later by 1/40,000 second, and the sum of the differences calculated again. The time shift associated with the minimum sum of the differences was identified as the best travel time for that velocity record. The result of this more detailed analysis most frequently yielded a wave speed of 17,000 ft/s (5,182 m/s) which corresponds to an elastic modulus of 30,690 ksi (211,599 MPa).

The Minnesota Department of Transportation obtained a steel specimen from the longitudinal axis of a steel pipe pile cutoff in order to perform a laboratory assessment of the modulus of elasticity. Two steel coupon specimens were prepared and tested. The modulus of elasticity from these two test specimens were 33,589 and 31,543 ksi (231,588 and 217,481 MPa). The laboratory test report is presented in Figure 2. The wave speed back calculated from the laboratory determined modulus of elasticity values is 17,785 and 17,235 ft/s (5,421 and 5,253 m/s), respectively. Hence, the laboratory test results also substantiate the use of a faster wave speed and a higher elastic modulus.

Eight piles were dynamically monitored during final section driving at one of the bridge piers supported on the large diameter open-end piles. The dynamic test data was processed based on the observed response at the start of the monitored driving sequences as well as consideration of the measured faster wave speed and laboratory elastic modulus test results. Dynamic test data for four piles was processed using a wave speed of 17,000 ft/s (5,182 m/s) and data for the remaining four was processed using a wave speed of 17,100 ft/s (5,212 m/s). These values correspond to a 1 to 2% increase in wave speed above the standard value. In this data case, only a faster wave speed was used for processing the dynamic test data with no modification to the standard elastic modulus or unit weight values.

A 1 to 2% increase in wave speed would result in a 2 to 4% increase in elastic modulus according to Equation 1. This would result in a 2 to 4% increase in the force, stress, transferred energy, and pile bearing capacity calculated from the dynamic records. Hence, it was elected to process the data conservatively for capacity and non-conservatively with regard to driving stresses and energy.

CASE 2 – ARKANSAS

A 36 inch O.D. (914 mm), open-end pipe pile was instrumented with conventional dynamic testing instrumentation near the pile head and additional strain gages and accelerometers at selected locations below the pile head. The pipe pile had a uniform wall thickness of 1.0 inch (25 mm) over the entire length. The lengths below the pile head gage location to the additional instrumentation locations were carefully documented prior to the start of the testing process. Channels were welded over the additional instrumentation prior to driving in order to protect the additional gages as they were driven below grade. The test pile made from steel coils converted to spiral-weld steel pipe meeting ASTM A252-10 Grade 3 requirements.

In this test, one additional accelerometer was bolted to the pile 67.0 ft (20.4 m) below the upper pair of accelerometers. The acceleration records used to determine the wave travel time over this known distance was then recorded at a digitizing frequency of 10,000 Hz. Figure 3 presents the average force and velocity records obtained from the pile head instrumentation at 67 ft (20.4 m) above the pile toe. Also presented in the figure are the force records from 42 and 22 ft (12.8 and 6.7 m) above the pile toe as well as the force and velocity records from 2 ft (0.6 m) above the pile toe. The dashed diagonal lines in Figure 3 depict the stress wave traveling down the pile at a wave speed of 17,200 ft/s (5,243 m/s) past the strain gage and accelerometer locations and then reflecting from the pile toe to the gage location near the pile head.

Figure 4 presents dynamic test data from blow 6 after the start of impact driving acquired from the gage location near the pile head. The top graph in Figure 4 includes the measured acceleration versus time, the middle graph presents the force and velocity records versus time, and the lower graph presents the computed wave up versus time. The velocity record is presented in force units by multiplying the velocity at a given time by the pile impedance, EA/c, also referred to as Z.

Wave up is half of the difference between the force and velocity (times the pile impedance) records. The onset of the toe response is identified by the downward slope change in wave up, which is a result of the tension reflection from the pile toe in easy driving conditions. Hence, a review of the wave up record is also useful in wave speed assessments.

The pile had been installed with a vibratory hammer to a pile penetration depth of 57.6 ft (17.6 m) prior to using the impact hammer. The dynamic test data was processed based on the observed response at the start of the monitored driving sequences using a wave speed of 17,200 ft/s (5,243 m/s) and a corresponding elastic modulus of 31,416 ksi (216,607 MPa). These values correspond to a 2.4% faster wave speed and a 5.8% higher elastic modulus than normally assumed.

The leftmost solid vertical line in Figure 4 identifies the onset of impact. The response from the pile toe is denoted by the dotted vertical line for the standard wave speed of 16,800 ft/sec (5,122 m/s) and by the second solid vertical line for the faster wave speed of 17,200 ft/s (5,243 m/s). The early, easy driving records clearly support using the faster wave speed and the proportionality of the force and velocity records support using a higher elastic modulus.

CASE 3 - OFFSHORE

Case 3 presents dynamic test data from an offshore platform supported by three 30 inch O.D. (762 mm) open-end pipe piles. The pipe piles had a wall thickness of 1 inch (25 mm) throughout with the exception of a 6.6 ft (2 m) long driving shoe at the pile toe that had a wall thickness of 1.5 inches (38 mm). The initial pile sections were 181.1 feet (55.2 m) long and were reported to meet API-2W-50 specification requirements. This material specification stipulates the piles have a minimum yield strength of 50 ksi (345 MPa). The pile lengths below the gage location were carefully documented prior to the start of the testing process.

All three piles were dynamically monitored at the beginning of driving immediately after the pile had settled to the point of equilibrium under the weight of the hammer and pile. Figure 5 presents a representative early dynamic test record on one of the piles tested. The presented data is for the second hammer blow applied during the pile driving process. The top graph in Figure 5 presents the measured acceleration versus time, the middle graph presents the force and velocity records versus time, and the lower graph presents the computed wave up versus time.

Based on the known and carefully documented length, the records indicate a pile wave speed of 17,246 ft/s (5,257 m/s). Records for the other two piles are similar. Using Equation 1, a 2.6% increase in wave speed would result in a 5.4 % increase in elastic modulus which would cause a 5.4% increase in force, stress, transferred energy, and pile bearing capacity. However, this data was processed using only the faster overall wave speed.

The left most solid vertical line in Figure 5 identifies the onset of impact. The response from the pile toe is denoted by the dotted vertical line for the standard wave speed of 16,800 ft/sec (5,122 m/s) and by the second solid vertical line for the faster wave speed of 17,246 ft/s (5,257 m/s). The early, easy driving records support using the faster overall wave speed.

CASE 4 - OFFSHORE

In Case 4, dynamic test data from another offshore platform is presented. This platform was supported by four 48 inch O.D. (1219 mm) open-end pipe piles. The pipe piles had a wall thickness of 1.5 inches (38 mm) throughout with the exception of a 9.8 ft (3 m) long driving shoe at the pile toe that had a wall thickness of 2.0 inches (51 mm). The initial pile sections were 187.8 ft (57.2 m) long and were reported to meet API-2H-50 specification requirements. This material specification stipulates the piles have a minimum yield strength of 50 ksi (345 MPa). The pile lengths below the gage location were once again carefully documented prior to the start of the testing process.

All four piles were dynamically monitored at the beginning of driving immediately after the pile had settled to the point of equilibrium under the weight of the hammer and pile. Figure 6 presents a representative early dynamic test record on one of the piles tested. The presented data is for the third hammer blow of the driving process. Records for the other three piles are similar.

Figure 6 presents the measured acceleration versus time, the middle graph presents the force and velocity records versus time, and the lower graph presents the computed wave up versus time. The left most solid vertical line in Figure 6 identifies the onset of impact. The response from the pile toe is denoted by the dotted vertical line for the standard wave speed of 16,800 ft/sec (5,122 m/s) and by the second solid vertical line for the faster wave speed of 17,232 ft/s (5,252 m/s).

Based on the known and carefully documented length, the early, easy driving records clearly indicate a pile wave speed of 17,232 ft/s (5,252 m/s). Using Equation 1, a 2.6% increase in wave speed would result in a 5.2% increase in elastic modulus which would in turn result in a 5.2% increase in force, stress, transferred energy, and pile bearing capacity. However, in this data case, only the faster wave speed was used for processing with no modification to the standard elastic modulus or unit weight values.

CONCLUSIONS

Dynamic test records from several projects have been presented that support the need and use of a faster overall wave speed for some large diameter open-end steel pipe piles. Wave speed values 1 to 3% greater than the historically used value for steel pipe piles of 16,800 ft/s (5,122 m/s) were apparent and justified. In the four cases presented, the pipe piles were manufactured in accordance with three different steel specification standards, ASTM A252-10 Grade 3, API-2W-50, and API-2H-50. The dynamic test data was also collected with different dynamic testing units, models, and software.

In cases 1 and 2, it is postulated that the manufacturing process of converting high yield strength steel coils into large diameter spiral-weld pipe piles may be a contributing factor in the faster overall wave speed and associated higher elastic modulus values. In cases 3 and 4, high strength steel plate was used to form the vertical seamed steel pipe piles. The manufacturing and reworking process associated with converting the high strength plate into steel pipe piles is again believed to be a contributing factor.

Limited laboratory test results indicate elastic modulus values 2 to 5% greater than the historically used values for large diameter steel pipe piles of 30,000 ksi (206,850 MPa) may be justifiable. These values are in line with the observed faster wave speeds. When dynamic test results indicate faster overall wave speeds, confirming laboratory elastic modulus tests are encouraged when possible.

It is important to note that the authors have not yet observed similar increases in steel pile wave speeds and elastic modulus values for small diameter, spiral-weld or vertical seamed steel pipe piles, or for hot rolled steel H-pile sections.

RECOMMENDATIONS

The cases presented herein highlight the need for accurate steel pile length measurements on large diameter open-end pipe piles and the need for full length dynamic pile monitoring when monitoring is specified. Early easy driving dynamic test records on piles of known length can be used to identify cases with faster overall wave speeds. A faster wave speed should not be arbitrarily assumed as this may result in failing to identify cases of pile toe damage.

Early easy driving dynamic test records on piles of known length can be used to differentiate cases with faster overall wave speeds from cases with pile toe damage. Testing multiple piles can also assist with this determination as it is unlikely that a large percentage of piles would be damaged in early, easy driving conditions. When dynamic testing is performed by splicing and driving on previously unmonitored lower open-end pipe pile sections, the use of the traditional wave speed value may lead to false identifications of pile toe damage if the steel pipe piles have a faster overall wave speed. Careful documentation of pile cutoff lengths during splicing is also important.

At present, it is recommended that the standard values for elastic modulus of 30,000 ksi (206,850 MPa) and wave speed 16,800 ft/s (5,122 m/s) be used at the gage location and a faster overall wave speed be used if supported by a carefully measured pile length and early, easy driving dynamic test records. In high quality dynamic test records, data proportionality (force = velocity x EA/c) at impact, or the lack thereof, in conjunction with an overall faster wave speed may indicate the need for using a higher elastic modulus. This should be evaluated by the engineer on a project by project basis until a larger number of elastic modulus test results supporting a higher elastic modulus are available.

ACKNOWLEDGEMENTS

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REFERENCES

[1]. Rausche, F., “Wave Mechanics and the Wave Equation”, Pile Driving Contractors Association, *Proceedings of The Design and Construction of High Capacity Driven Piles Conference*, Annapolis, MD, 2000.

2]. Pile Dynamics, Inc., “Pile Driving Analyzer, Model 8G Manual” Cleveland, OH, 2017.

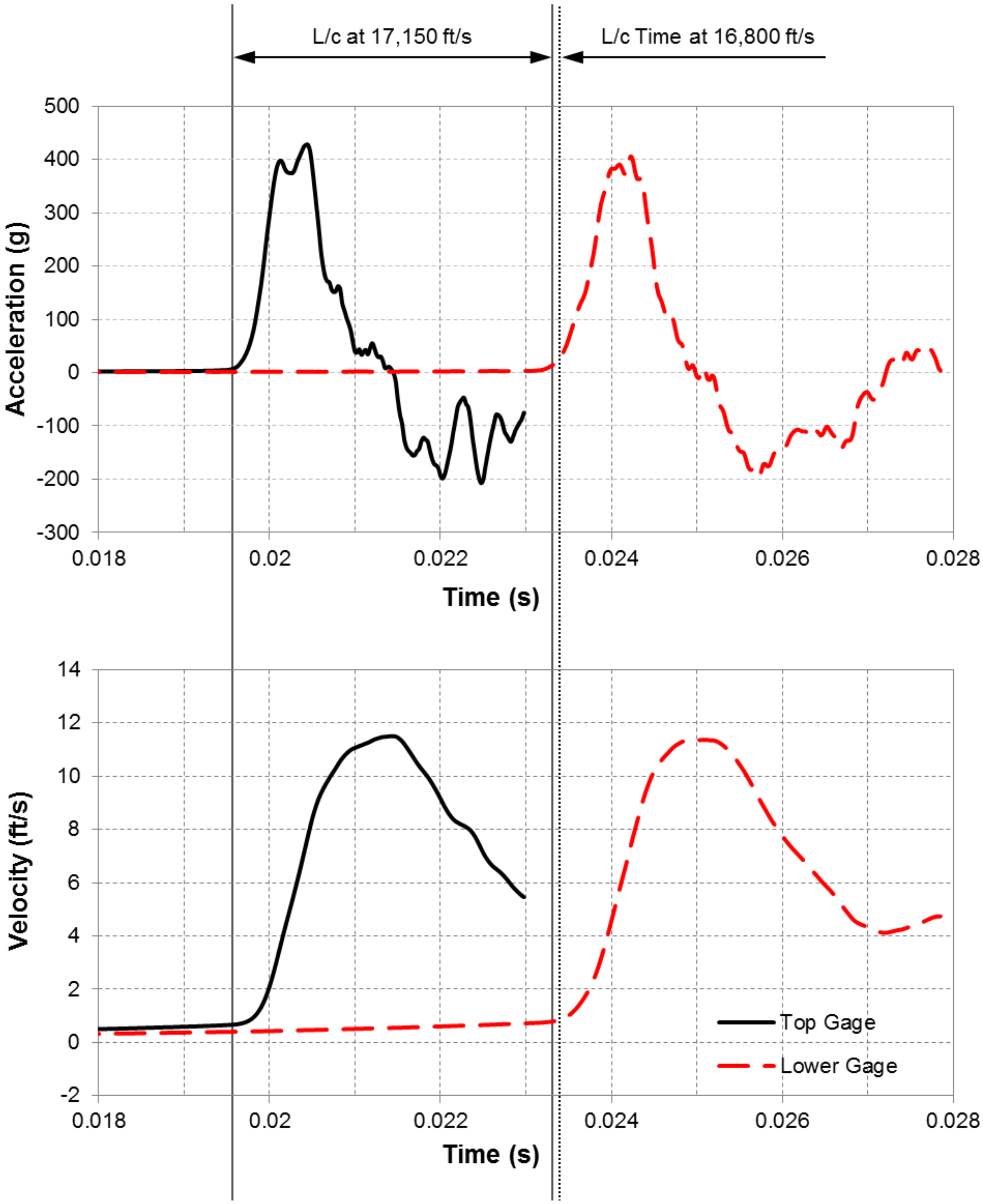

Figure 1. Case 1 – Partial Acceleration Records (top) and Velocity Records (bottom) from Two Gage Attachment Positions Located 64.2 ft (19.6 m) Apart.

MI14-0077 & 78

STATE OF MINNESOTA
DEPARTMENT OF TRANSPORTATION
Office of Materials & Road Research
Test Report on Sample of Steel Pipe Piles

Date 10/27/2014

Project No. 6244-30 **Bridge No.** 62017

Submitted By **Date Sampled** 10/6/2014 **Date Received** 10/13/2014

Source of Material

Furnished By Jobsite **Project Engineer**

Identification Steel Pipe Piles - Wall Thickness 0.750".

Field I.D. 2

Specification No. **MN/DOT 3371, ASTM A252 Grade 3**

Tested By:

TEST RESULTS

		MI14-0077	MI14-0078	SPECIFICATION REQUIREMENTS
Thickness	**in.**	0.732	0.724	
Tensile Strength:	**psi**	71,310	72,580	**66,000 +**
Yield Strength 0.5% EUL:	**psi**	55,420	55,390	**45,000 +**
Yield Strength 0.2% Offset:	**psi**	54,550	54,690	**45,000 +**
Modulas of Elasticity	**psi**	33,589,490	31,543,180	------
Percent Elongation in:	**2 in.**	40	38	**20 +**
Rockwell Hardness "B" Scale:		84	82	------
Brinell Hardness Number (3000 kgf):		179	179	------

Figure 2. MnDOT Laboratory Test Report.

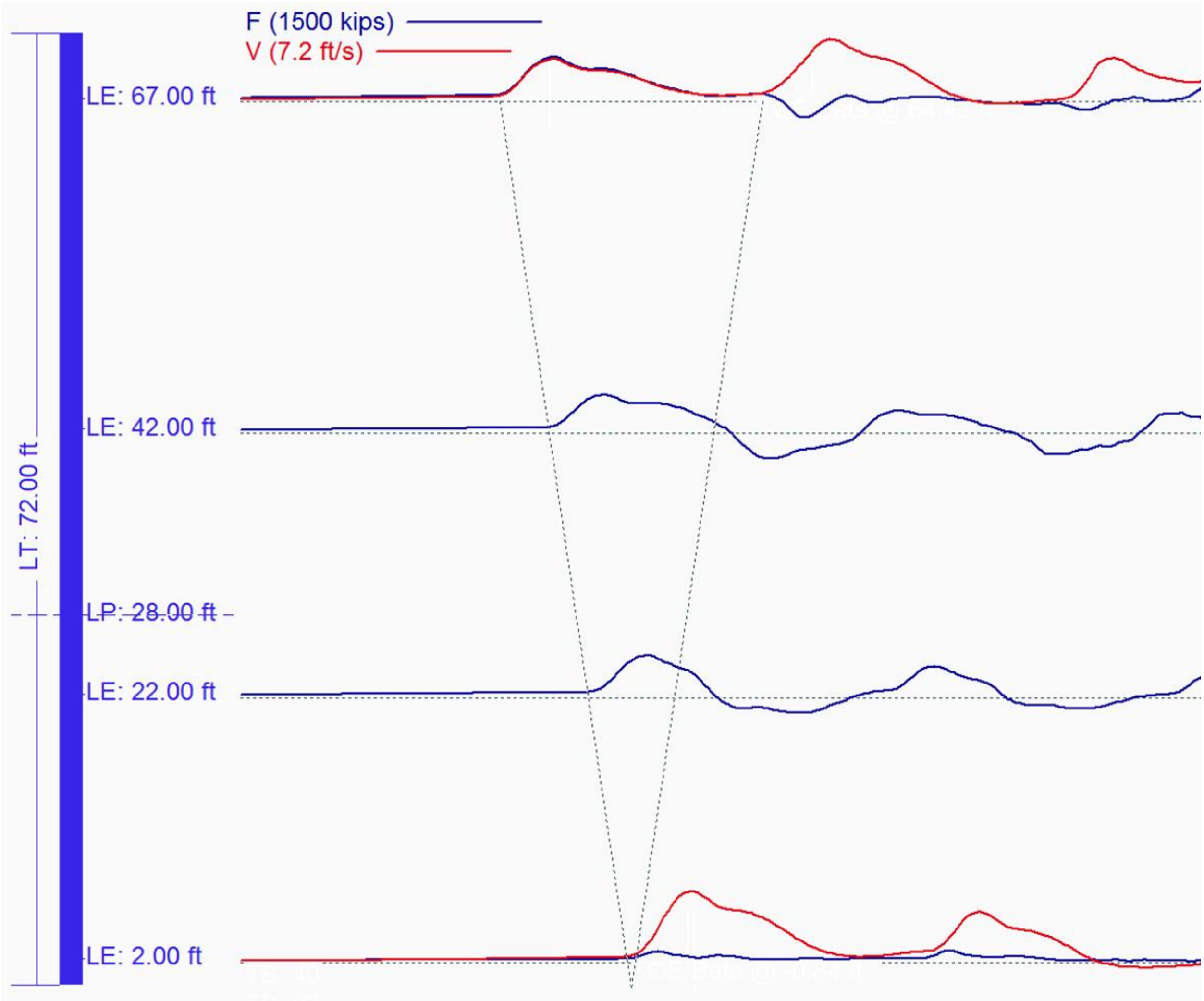

Figure 3. Case 2 - Wave Travel Past Multiple Gage Locations at Wave Speed of 17,200 ft/s (5,243 m/s).

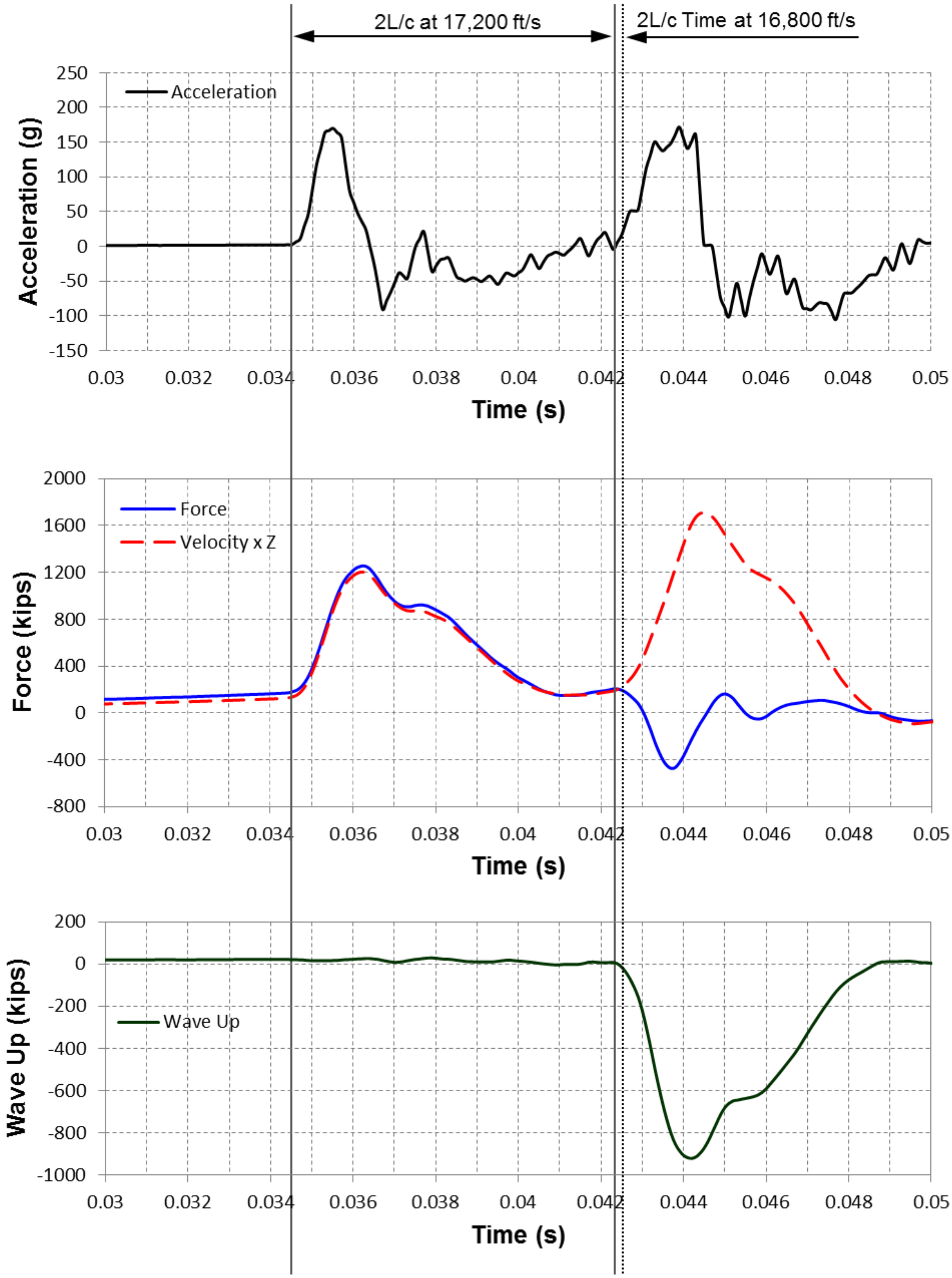

Figure 4. Case 2 – Acceleration (top), Force and Velocity Records (middle) and Wave Up (bottom) for Blow 6 in Early Easy Driving Conditions. Wave Speed of 17,200 ft/s (5,243 m/s).

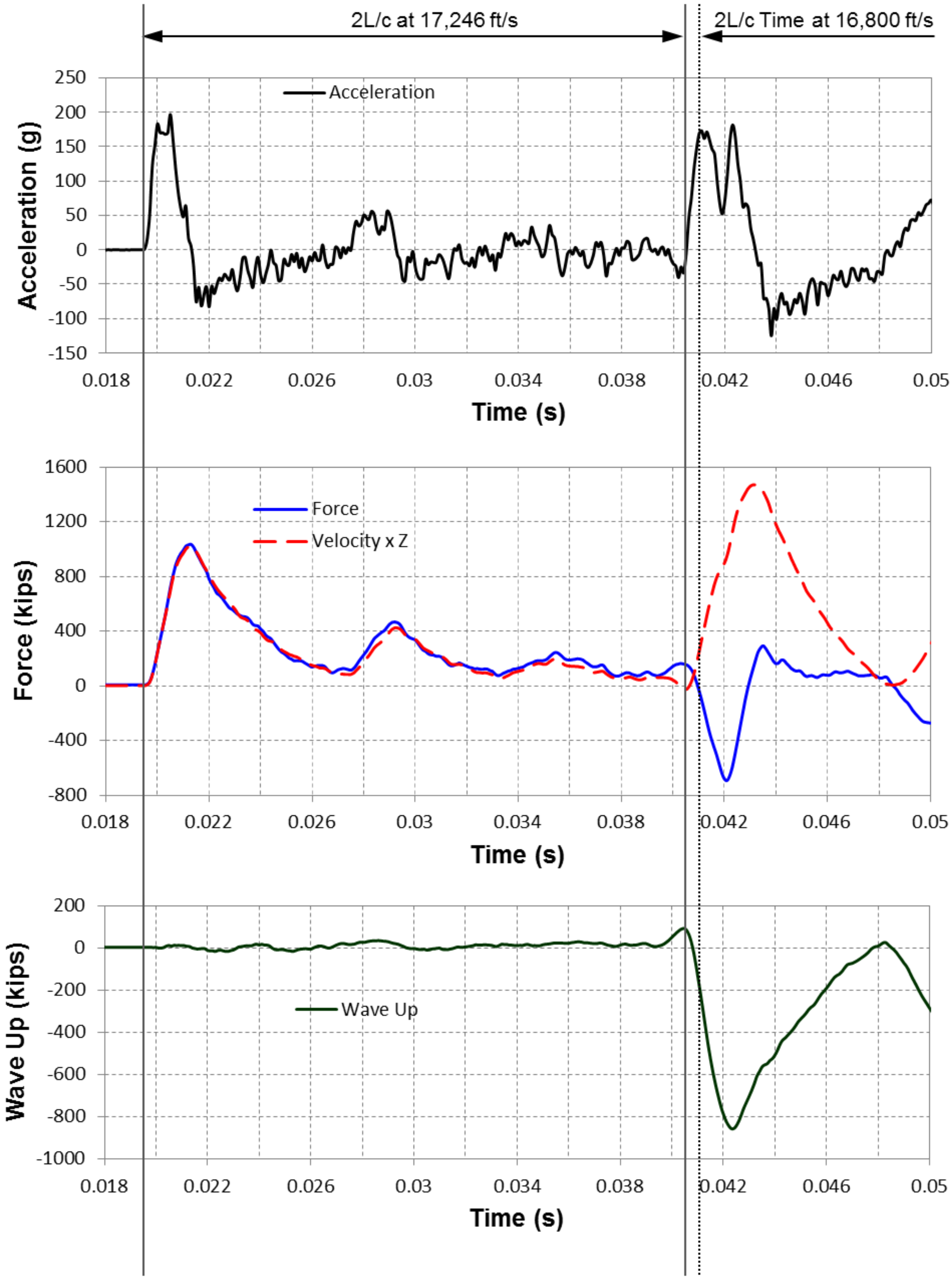

Figure 5. Case 3 – Acceleration (top), Force and Velocity Records (middle) and Wave Up (bottom) for Blow 2 in Early Easy Driving Conditions. Wave Speed of 17,246 ft/s (5,257 m/s).

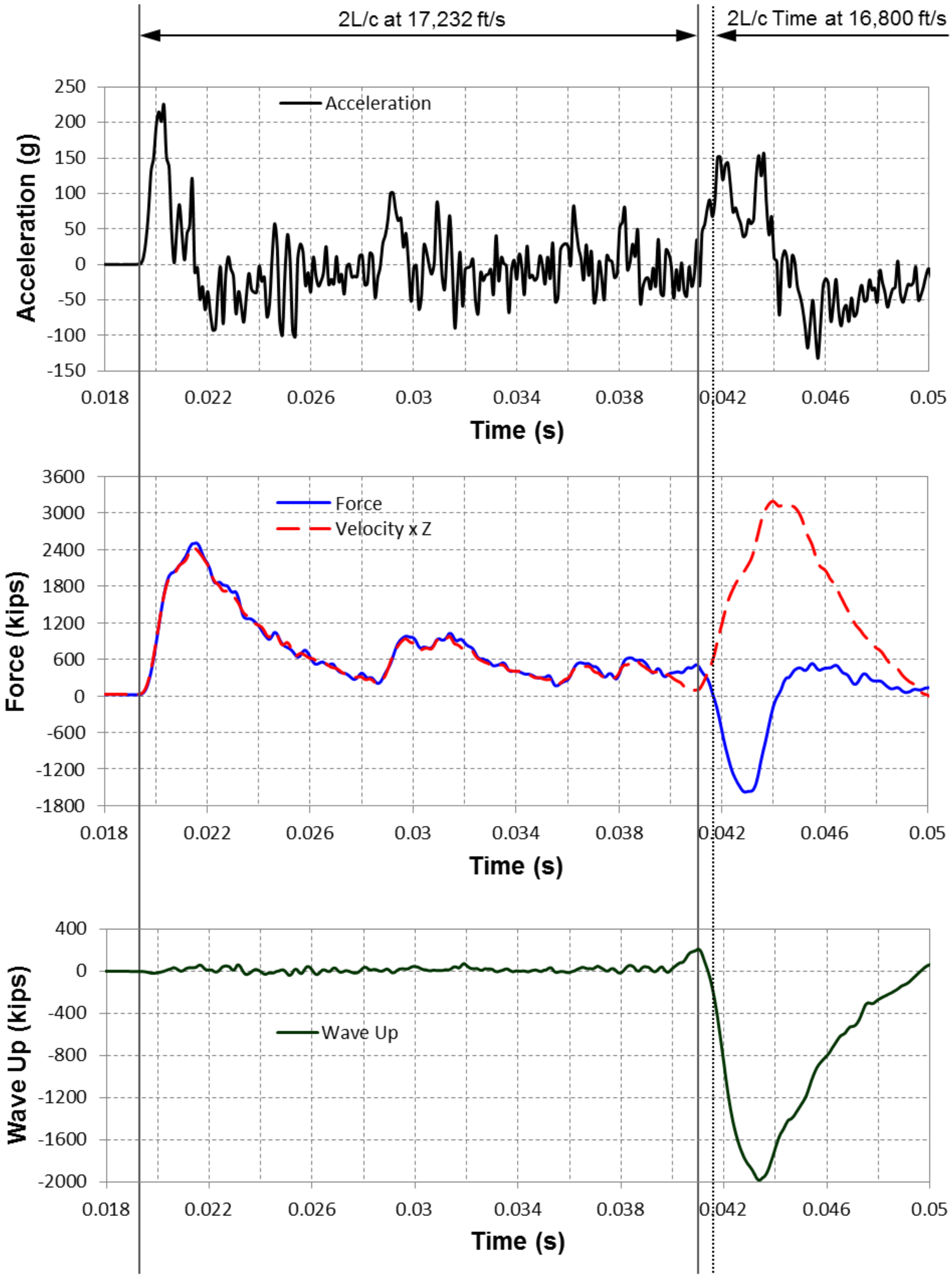

Figure 6. Case 4 – Acceleration (top), Force and Velocity Records (middle) and Wave Up (bottom) for Blow 3 in Early Easy Driving Conditions. Wave Speed of 17,232 ft/s (5,252 m/s).