PILE DAMAGE ASSESSMENTS USING THE PILE DRIVING ANALYZER

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Abstract

The use of the Pile Driving Analyzer (PDA) for monitoring piles during driving has been advanced significantly over the past several years. While the pile capacity and energy transferred to the pile head are usually considered the most important output quantities, the measured pile stresses are also of significant value. Often the driving stresses control how piles are to be installed as excessive stresses will result in pile damage. Identifying such damage may often be difficult if dynamic measurements are not employed. Even when dynamic measurements are used the observed damage may be difficult to predict and/or identify during the testing procedures.

This paper will present the results from the several dynamic pile testing programs where pile damaged has been observed. Examples of damaged piles will include steel, concrete, and timber pile types. The dynamic stress waves will be shown both before and after pile damage occurs and the suspected pile failure mode will be discussed. This information will be discussed to help other professionals who may use PDA data on an occasional basis, better understand how the PDA data is analyzed.

Introduction

The collection Pile Driving Analyzer (PDA) data has become considerably more convenient with the advent of the computer based PDA. As such more and more civil engineers and designers are becoming involved with the use and interpretation of the dynamic data. The use of the PDA data (ie. the numerical output) is usually the primary concern for the engineer or designer

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considering foundation design. However, the interpretation of the actual data (ie. the stress wave curves) may be just as important when considering the integrity of the driven pile.

Since it is generally considered that pile integrity should not be compromised during pile driving, pile damage assessments should be performed for each pile tested. If no pile damage is observed then the dynamic test data can be used for foundation evaluation, and it may be assumed that a significant number of piles will not likely be damaged during production pile installation. However, if pile damage is encountered during test pile installation, immediate action should be taken to prevent additional test piles being damaged. If such action is not taken, it is likely that pile damage will continue during later pile driving, which may or may not be identified.

Five (5) cases of pile damage will be presented which will include concrete, steel, and timber piles. These cases will be discussed with reference to identifying the damage and determining the most likely cause of the damage. The location and its importance in determining the cause of the pile damage will also be discussed. Finally, any changes made to the driving systems to prevent further damage, or recommendations provided to prevent such damage, will also be discussed.

Stress Wave Evaluations

Figure 1 shows a typical stress wave obtained during dynamic testing with a theoretical soil resistance model shown above the stress wave (Hannigan, 1990). As shown the force and velocity wave traces are proportional at impact, time 0. The force and velocity traces remain proportional until time 2A/c where the first of two soil resistance responses are encountered. At this time the force trace moves slightly above the velocity trace due to the activation of the soil resistance located at depth A. The force curve actually increases slightly and the velocity curve decreases a corresponding amount. Between time 2A/c and 2B/c no additional separation occurs as no additional soil resistance is encountered. At time 2B/c the force and velocity traces diverge rapidly due to the activation of the large soil resistance at depth B. If no soil resistance were encountered the force and velocity traces would remain proportional until time 2L/c. Figure 1 shows the typical response of a pile where little or no toe resistance is encountered. At time 2L/c the velocity curve increases and the force curve decreases.

An example of pile damage is shown by the plotted stress wave curves in Figure 2. Once again the force and velocity curves are proportional at impact time zero. The force and velocity remain proportional until some minor soil resistance is encountered just after impact. At a depth of about 15.2 meters (50 feet), or 7.8 ms, the velocity and force curves begin to converge. As the

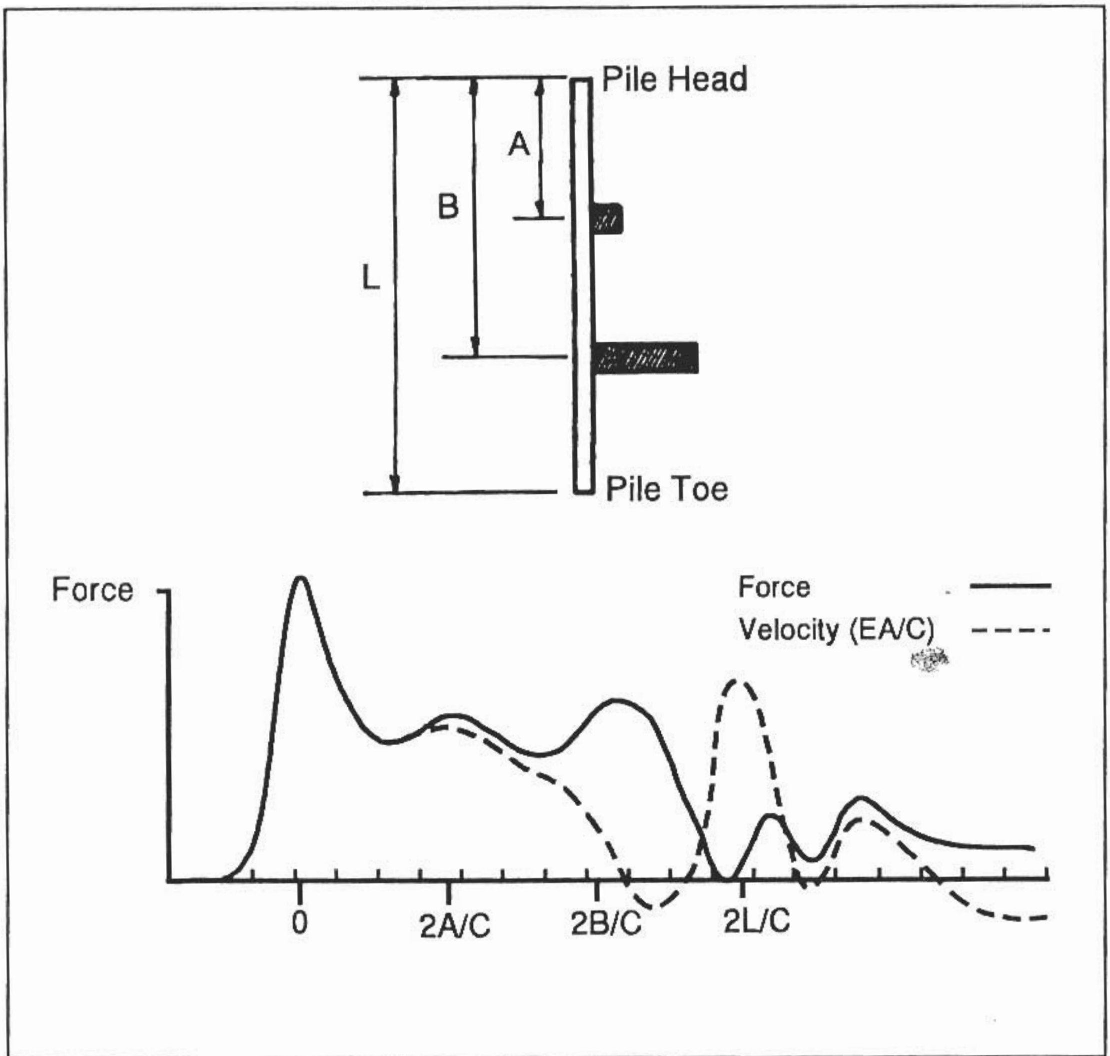
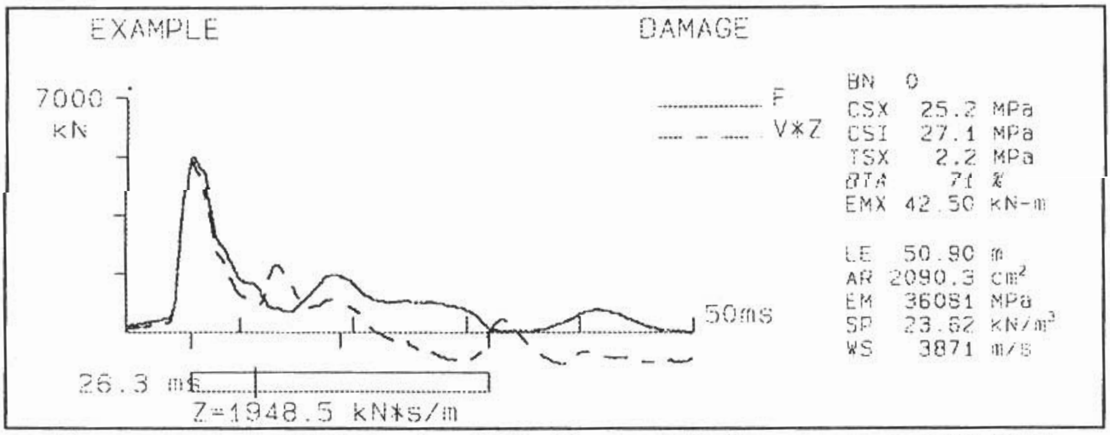


Figure 1: Typical Stress Wave with Localized Soil Resistances (Hannigan, 1990)



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BN   0
CSX   25.2  MPa
CSI   27.1  MPa
TSX    2.2  MPa
BTA     71  %
EMX  42.50  kN-m

LE   50.90  m
AR  2090.3  cm²
EM   36081  MPa
SP   23.62  kN/m³
WS    3871  m/s
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Figure 2: General Example of Pile Damage Indication from PDA Data

convergence continues the velocity curve actually crosses the force curve and continues until it reaches a peak. The force curve decreases at this time and forms a trough. These responses, a velocity peak and force trough, are typical of a reduction in pile impedance or pile damage. The PDA calculates an integrity factor based upon the change in impedance from one pile section to another. This integrity factor is called the BETA value, and provides a measure of the reduction of cross sectional area at the damage location. Rausche and Goble (1979) suggested the following guidelines for determining the degree of pile damage based upon the BETA value:

Pile Damage Guidelines (Rausche and Goble, 1979)

BETA	Severity of Damage
1.0	Undamaged
0.8 - 1.0	Slightly Damaged
0.6 - 0.8	Damaged
Below 0.6	Broken

While use of the BETA value is helpful in determining the integrity of a driven pile, sole reliance on the BETA is not appropriate. False indications of pile damage will be given by the BETA value where an in proper wavespeed or modulus is entered, where significant bending is present in the force records due to poor hammer alignment, and where pile cross sectional area changes occur by design. In addition, for very short piles the time to between the hammer impact and the toe response may be so short that the BETA calculation may not be possible. In this case the BETA value will be computed as 200 indicating that no calculation is possible.

Examples of Pile Damage

Concrete Piles

The most common pile to be damaged during driving in the United States is precast, prestressed concrete piles. The primary reason for this damage is due to over stressing during easy driving, in tension. Most piles produce in the US have an effective prestress ranging from 4.8 to 8.3 MPa (0.7 to 1.2 ksi). This limits considerably the allowable tension driving stress which should be permitted, while at the same time reduces the piles ability to resist compression driving stresses. In addition, bending stresses may also result in damage of concrete piles, when poor hammer and pile alignment is not maintained.

When dynamic testing is performed on concrete piles it is extremely important to assess and calculate the overall pile wave speed for each pile tested. Variations in pile wave speed are common and the use of the wrong or in proper wave speed will likely result in an indication of pile damage. Wave speed measurements should be made during very early driving, or if possible prior to driving. This will help in providing more accurate wave speed determinations. Finally, for piles driven with hammers having long strokes such as a single acting diesel hammer, micro-cracking may occur during driving. Micro-cracking is typically described as extremely small hairline cracks that occur in the pile during driving. The presence of micro-cracking is usually identified by the slowing down of the overall pile wave speed. This may require an adjustment of the 2L/c time but should not necessarily require a change in pile head wave speed and modulus.

Figure 3 shows recorded stress waves for a 30 cm (12 inch) square, precast, prestress concrete pile. Three stress waves are presented to with the top being at very early driving, the middle just prior to pile damage occurring, and the bottom indicating the resulting pile damage. As shown in the top stress wave, the pile experienced tension stresses on the order of 7.3 MPa (1.05 ksi), during very easy driving. This tension stress is equal to the project specified tension driving stress limit. The second, or middle stress wave indicates that the tension stress has been reduced to 4.4 MPa (0.64 ksi) just prior to the resulting pile damage which is shown in the bottom stress wave plot. Since the compression driving stresses were well below the project specified limit, and the damage is indicated at the middle of the pile about 10.7 meters (35 feet), it appears that the pile has broken due to over stressing in tension during easy driving. This example demonstrates that concrete piles may experience damage even when tension driving stresses are maintained below a specified limit, but are still relatively high compared to the effective prestress.

Use of long stroke and light ram hammers generally produce greater tension stresses than hammers with heavier rams and shorter strokes. Therefore, for very long concrete piles, with the potential for high tension driving stresses single acting air or hydraulic hammers are usually better suited for pile installations. However, proper hammer and pile cushioning, and reduced hammer strokes may also be necessary to prevent pile damage.

Figure 4 shows recorded stress waves for a 14" square, precast, prestress concrete pile. Once again the top stress wave plot shows the recorded data prior to any observed pile damaged. The bottom plot indicates that the pile has broken at approximately 5.8 meters (19 feet) below the gage location. A review of the compression driving stresses shows that the average compression stress from both strain gages was 25.7 MPa (3.73 ksi) prior to the pile damage. In addition, the maximum pile head stress calculated from

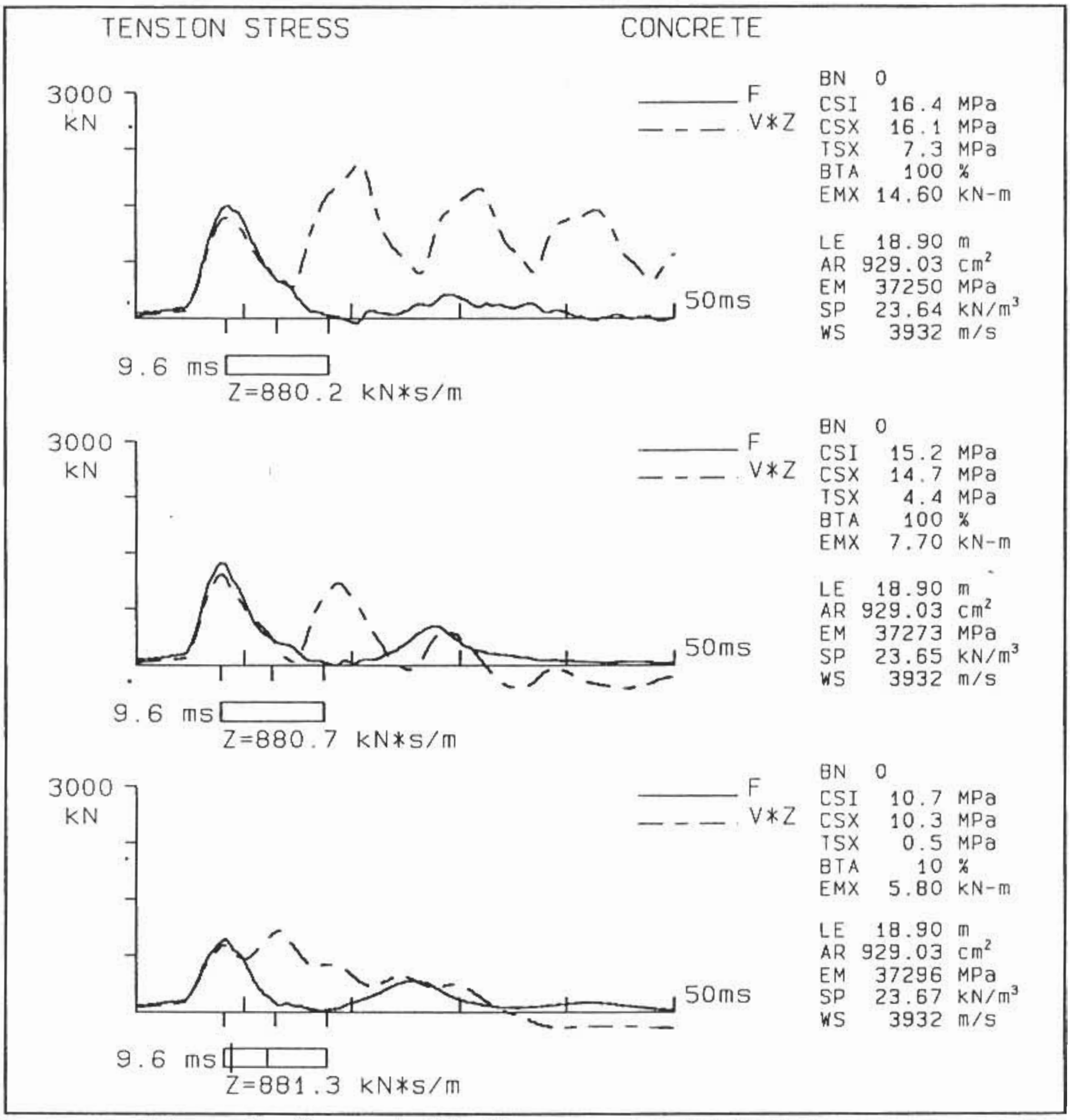

Figure 3: Concrete Pile Damage due to Tension Stress

a single strain gage was 29.9 MPa ((4.34 ksi). Since these piles were being driven to bedrock, compression stresses were likely even greater at or near the pile toe. Based upon this information, and the fact that the generally accepted compression driving stress limit for these piles was 24.5 MPa (3.55 ksi), it is likely that this pile broke due to over stressing in compression.

Although most concrete piles are broken due to excessive tension or compression driving stresses, these piles may also be damaged due to bending. Bending occurs when eccentric driving occurs due to poor hammer-pile alignment, or when the pile toe deflects off of underground obstructions. The PDA does not provide a direct measurement of bending stress, although an idea of localized bending from poor hammer alignment may be obtained

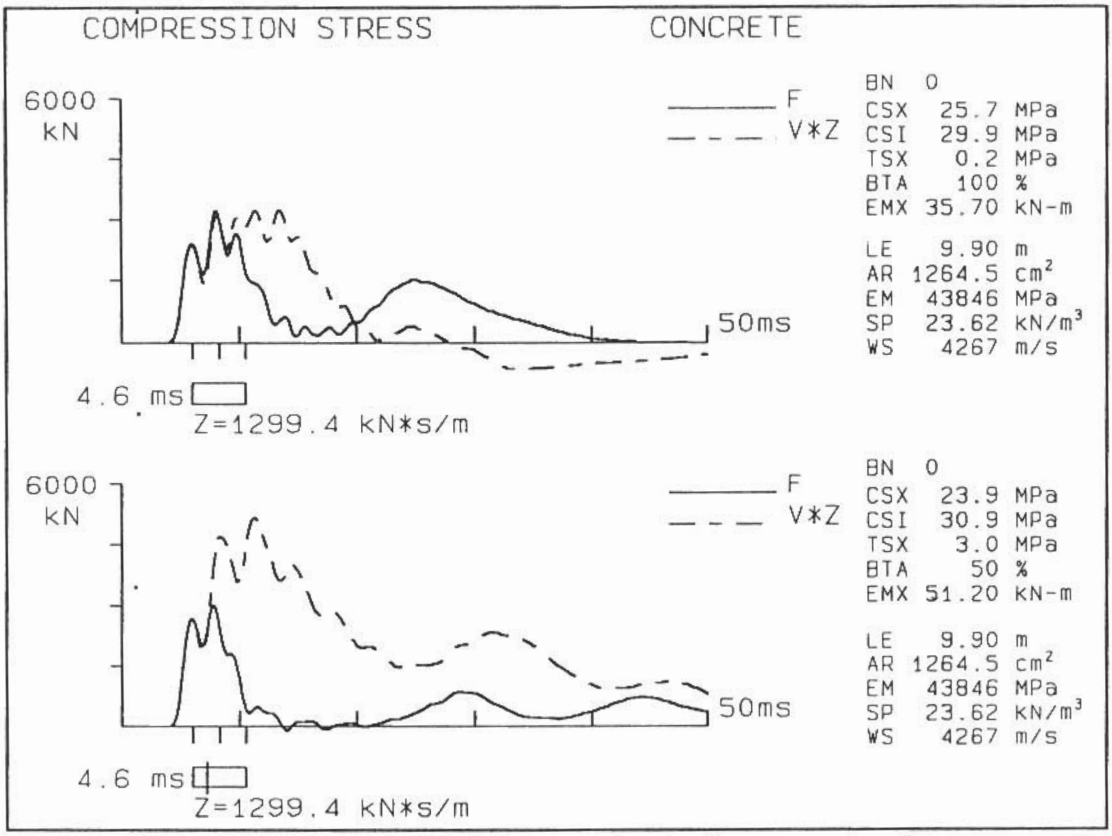

Figure 4: Concrete Pile Damage due to Compression Stress

from the two force signals. The quantities CSX and CSI represent the maximum compression stress at the gage location from the average of the two strain gages, and from a single strain gage, respectively. The local bending stress at the gage location is approximately equal to CSI minus CSX. Of course higher bending stresses may be present at other locations and a complete review of the two strain gage signals should assist in this evaluation. When large differences in the CSI and CSX stresses are observed, the potential for excessive bending stresses is likely to exist.

Steel Piles

Determining pile damage for steel piles is generally easier than for concrete piles due to the fact that the wavespeed of steel piles is known. In addition, steel piles generally have less potential for damage due to the fact that steel has equal strength in tension and compression. However, there are some situations in which damage of steel piles does occur. The most common of these is where steel H-piles or pipe piles are driven to rock. The toe of these piles often are damaged when reaching the rock surface. This damage is usually a result of over stressing the pile in compression. Since the PDA measures stresses at the pile top it may be difficult to determine if the piles are being over stressed at the toe. Usually the best method for determining if the pile toe is being over stressed is to perform CAPWAP analysis.

Fellenius (1995) reported a case history where steel pipe piles were installed to a rock surface and damage at the pile toe occurred. The pile damage was indicated by the recorded stress waves as a slightly early reflection of the tensile wave, or velocity rise just prior to the toe reflection. These piles were pulled after driving and the damage at the pile toe was observed. The "slightly" early velocity rise was very difficult to detect, and in some cased was not detectable although damage was later discovered at the pile toe. This illustrates the need to be very cautious when attempting to determine the presence of pile toe damaged for steel piles driven to bedrock.

Figure 5 shows the recorded PDA stress waves for a steel H-pile driven through an existing land fill to a dense sand layer. The top stress wave indicates the stress wave obtained prior to the damage and the lower stress wave indicates the pile broke at a depth of 15.5 meters (51 feet) below the gage location. As shown in Figure 5, the compression stresses at the pile head were well below the 345 MPa (50 ksi) yield strength of the steel H-pile. The pile length require for the project was 34 meters (110 feet). This length required that the piles be spliced to achieve the final length.

The test pile data shown in Figure 5 indicates that the pile broke at a splice location. Normally, this would indicate that the splicing had been poorly performed. However, the splice was completed by a certified welder and was then inspected using ultrasonic testing to confirm the suitability of the weld. After a more detailed study of this particular case it was determined that the steel strength and chemical makeup required that special procedures be followed in order to provide suitable welds. Based upon this example it appears that special precautions should be taken when high strength steel is being used or when the chemical composition of the steel varies from that usually used in steel H-piles.

Timber Piles

Timber piles are probably the most difficult pile type to perform dynamic testing and analysis. In addition, these piles are non-uniform, and therefore make assessment of pile damage even more difficult than normal. Since the piles are non-uniform the use of the BETA value is limited, since a BETA value below 100 may be calculated for the undamaged pile. In addition, timber piles are the most non-uniform pile material due to the presence of knots, unusual cross sectional area changes, and axial alignment. These conditions often result in velocity reflections prior to the 2L/c time which would normally be associated with pile damage. Finally, the lack of well established guidelines for limiting driving stresses, and the lack of information concerning

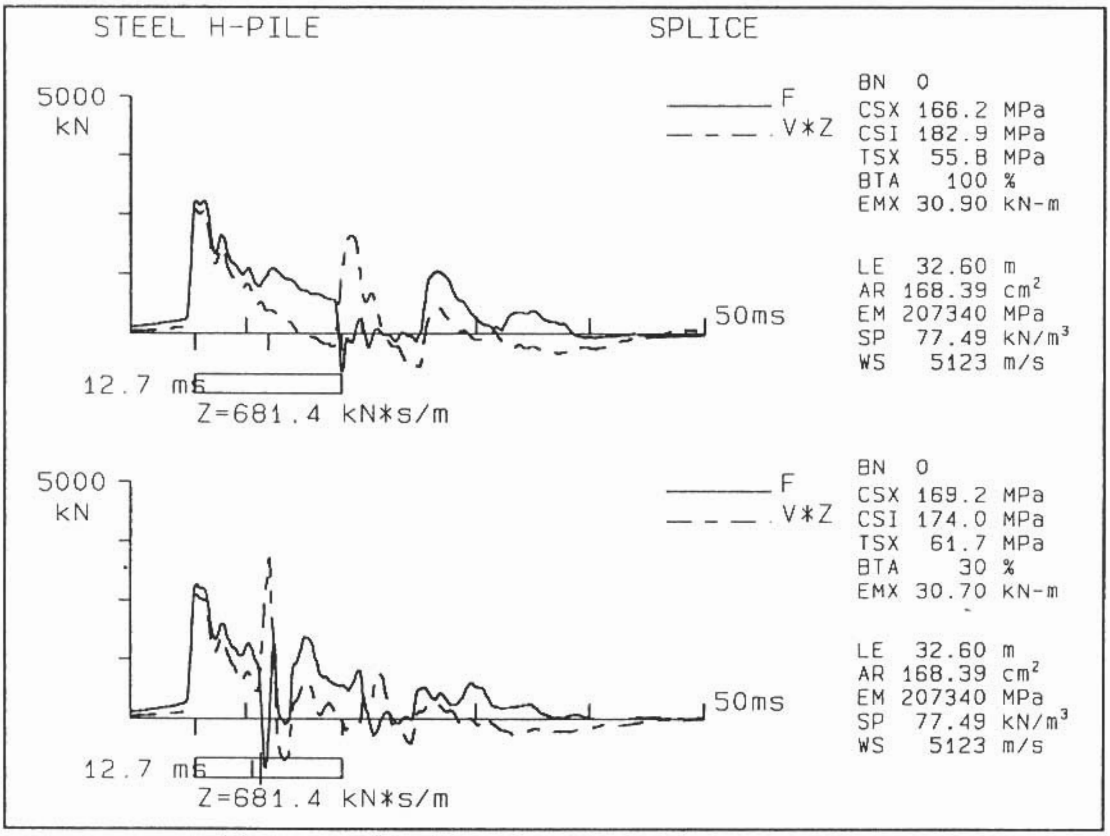

Figure 5: Steel Pile Damage at Splice Location

the strength of the species of timber piles also contribute to the difficulty of determining pile damage.

Figure 6 shows dynamic test data from a timber pile. The top stress wave shows the dynamic test data prior to damage, and the bottom stress shows the stress wave just after damage has occurred. As shown the pile head compression stresses are relatively low (11.4 MPa or 1.65 ksi) and would not generally be considered likely to cause damage. However, the pile damage occurs near the toe of the pile at a depth of about 9.0 meters (29.5 feet). Since the timber pile area is reduced at this location, due to the pile taper, it appears that the pile damage may have been a result of over stressing in compression. A review of the top stress wave further confirms this as it appears that significant end bearing resistance was encountered, based upon the force response at 2L/c. CAPWAP analysis of the data prior to pile damage would assist in further evaluating the compression stresses experienced at the pile toe.

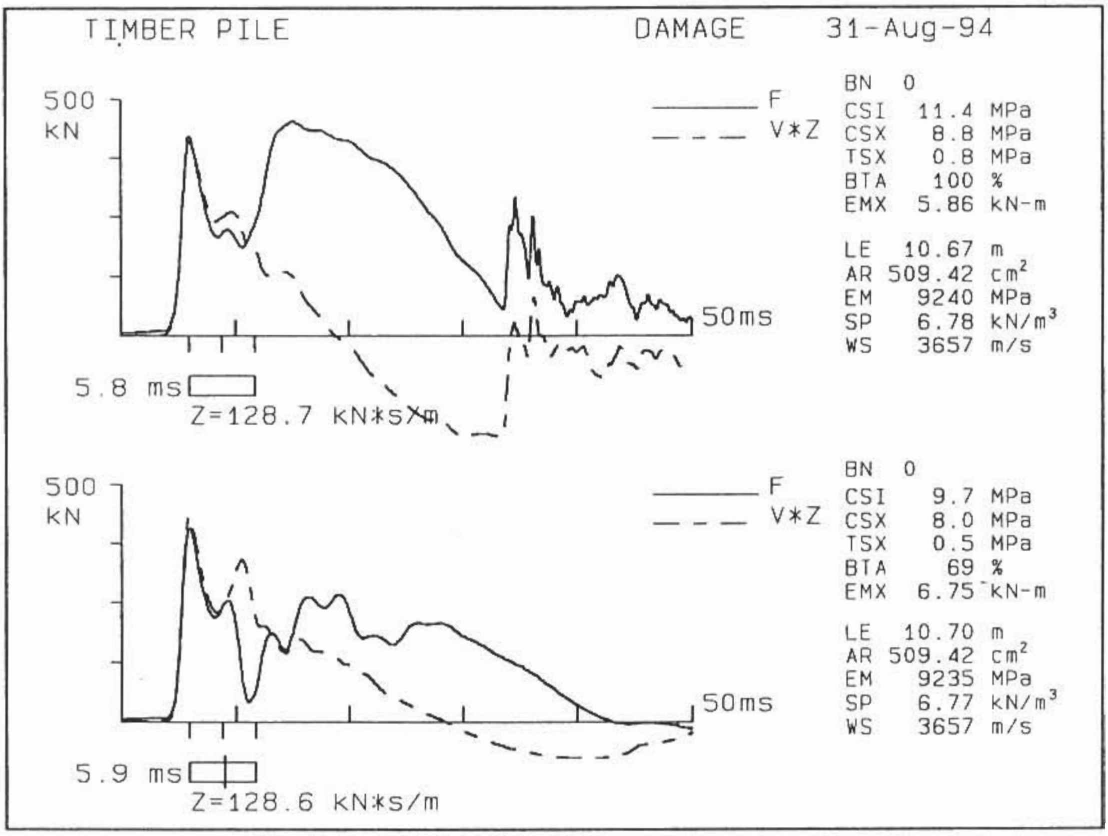

Figure 6: Timber Pile Damage Near Pile Toe

Conclusions

We have attempted to provide typical examples of pile damaged as assessed using PDA test data. Most of these examples are considered to be relatively common occurrences for driven pile foundations. Although not every project will experience pile damage, most pile foundation projects have at least some pile damage. This damage is most often the result of unknown subsurface obstructions which result in damage of piles in a localized area. PDA testing is often useful in such instances to provide a driving criteria which prevents pile damage and provides adequate foundation support.

The PDA user should be aware of the potential for pile damage and confident in his/her ability to detect such damage. However, it is often more useful if such damage can be predicted before it occurs and actions taken to prevent it. Proper sizing of pile driving equipment and adequate cushioning should be determined prior to or at least during the test pile program. When the pile driving hammer or cushion are determined to be insufficient, then alternatives should be evaluated. It is often the case that minor adjustments in the amount or frequency of changing the pile cushion can result in preventing significant amounts of pile damage during a given project.

References

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