STRESS WAVE TIMING, A SIMPLISTIC AND COST EFFECTIVE METHOD TO EVALUATE DETERIORATED AND REPAIRED TIMBER BRIDGE PILES

By

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MOE	dynamic modulus of elasticity
NDE	nondestructive evaluation
R^2	correlation coefficient
SWT	stress wave time
SWV	stress wave velocity
SWTT	stress wave transmission time

CHAPTER 1

INTRODUCTION

Bridge foundations in the state of Oklahoma can consist either of concrete, steel, or timber piles. Piles are subjected to axial, horizontal and uplift loads. The piles must be able to transmit the loads to the underlying soils beneath without exceeding the allowable bearing capacity and minimum settlement requirements of the soil. Problems related with bridge foundations are timber deterioration, steel corrosion and concrete durability. It has been estimated that problems with bridge foundations have resulted in repairs or replacements in over 1 billion dollars in cost (Lampo, 1996). High costs spent each year on bridge foundations have resulted in new techniques for bridge analyses and repairs.

TIMBER PILE PROBLEMS

Oklahoma has more than 450 bridges supported by over 6,000 timber piles (Travis, 2005). Not only do timber piles support superstructures, but they must also resist the effects of harsh environmental conditions. The exposure to the environment leads to wood deterioration. The worst condition a pile is subjected to is repeated cycles of wetting and drying. Bridges with standing water under them are ideal living situations for decay fungi, and when the weather is mild it is also excellent living conditions for termites. Many of the piles have to be treated with preservatives to protect it from decay fungi and termites, but when treated the wood can become weakened. Preservatives used to treat wood are an environmental concern. A number of states do not allow the use of preservatives on timber piles. If piles are not treated correctly, the life span of a pile can be reduced.

Since piles in the state of Oklahoma are subjected to repeated cycles of wetting and drying, moisture content in wood is constantly fluctuating. Changes in moisture content cause wood to shrink or expand. These deformations can cause the wood to split and crack. These splits and cracks leave piles vulnerable to penetration of decay fungi and insects which can diminish the structural integrity of the wood.

Wood is different from other types of building materials like steel and concrete which are homogeneous and isotropic materials, where the properties are known. Wood is an organic material that has different characteristic throughout and the properties are difficult to predict and analyze. Nearly 300 reports over the past 40 years have presented research on measuring and predicting the properties of wood (Ross, 1998).

Piles obtained for this research, according to the engineer manager Troy Travis have been in service since the 1930s. Many of the timbers piles in Oklahoma have been in service for over sixty years and either need to be replaced or repaired. Conventional repair methods involve extracting and replacing the deteriorated timber piles, but this method is time consuming and expensive.

OBJECTIVES

The purpose of this thesis is to develop a simplistic and cost effective technique to evaluate deteriorated and repaired timber piles. Stress wave timing is an adequate choice for use in a simplistic nondestructive evaluation. Once the timber piles are evaluated, correlations between stress wave velocity and repair material quantities are established.

Stress wave timing is used to determine if decay is present in timber piles. Stress wave timing is used to detect early, moderate, to severe decay in wood. Stress wave timing in repaired piles is expected to be much lower than in deteriorated piles. If an unrepaired pile is made up of sound wood, the stress wave times for the repaired piles are still expected to be lower. The repair techniques are expected to restore and/or increase the strength of deteriorated piles.

Stress wave timing was conducted on two bridges. Nine piles were taken from a bridge on SH-76 in Oklahoma and acquired by Oklahoma State University. Each pile was thoroughly inspected visually and by stress wave timing. The inspection was used to create visual representations of the internal condition of each timber pile. Visual representations were created for the deteriorated and repaired timber piles. The amount of repair material quantities were correlated with stress wave velocity and pile dimensions. These correlations may be used to help predict the quantities of materials that will be required for future timber pile repairs. A second bridge was evaluated in a field inspection located in Cotton County, Oklahoma. Eleven of the twelve timber piles were repaired in-service and all were evaluated via stress wave timing. The objective was to observe if the repair technique was adequate and to see if the decay and voids were removed during repair.

CHAPTER 2

LITERATURE REVIEW

STRESS WAVE TIMING (SWT)

Stated earlier, nearly 300 published technical reports representing more than 40 years of research have presented research on Nondestructive Evaluation (NDE) to measure and predict the properties of wood (Ross, 1998). NDE is the science of identifying the physical and mechanical properties of a piece of material without altering its end-use capabilities. There are many NDE methods used to predict the characteristic of wood, including stress wave timing. Nondestructive evaluation using stress waves is an ongoing research topic. Stress waves have been used to examine structural materials including concrete and timber materials. Studies have shown the velocity of a stress wave is correlated with dynamic modulus of elasticity (MOE = $\rho V^2/g$) of wood. The parameters needed to calculate dynamic MOE are velocity of stress wave (V), density of material (ρ) and acceleration of gravity (g). Dynamic MOE has been related with static bending MOE, tensile and compressive strength, and modulus of rupture (Bertholf, 1965 and Emerson, 1999).

Nondestructive inspection by stress wave timing was adequately defined by Ross (1999), “A stress wave can be created by striking the specimen with an impact device that is instrumented with an accelerometer that emits a start signal to a timer. A second accelerometer, which is held in contact with the other side of the specimen, serves to identify the leading edge of the propagating stress wave and sends a stop signal to the timer. The elapsed time for the stress wave to propagate between the accelerometers is displayed on the timer." Stress wave timing (SWT) is imposing an elastic wave into a material and recording the time it takes that wave to travel over a specified distance. Figure 2.1 displays a photo of the leading edges of a stress wave as captured by start and stop accelerometers and displayed on an oscilloscope.

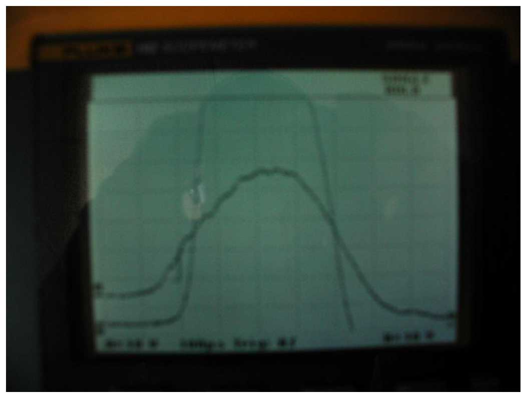

Figure 2.1. Typical Stress Wave

There are several types of stress wave inspection techniques including impact-echo and through-transmission. Through-transmission is the type used throughout this research. The wave is generated on one surface of the member, propagates through the member, and is recorded on the opposite surface (Emerson, 1999). The time it takes the wave to travel through the member is the time-of-flight.

Once the time-of-flight of the stress wave and dimensions of the wood are known, the velocity of the stress wave can be calculated. Many studies have presented stress wave velocities for various types of wood. One of the leaders of NDE of wood is Ross (1999). He and others have done extensive research and have developed Table 2.1 and Table 2.2 to help as a guide for typical stress wave velocities in nondegraded wood for various species. The table shows results of what should be expected of nondegraded wood. According to the engineer manager Troy Travis the species of wood obtained for this project is not known but can possibly be Pine.

Table 2.1. Stress Wave Transmission Times for Nondegraded Wood

Reference	Species	Moisture Content (% ovendry)	Stress Wave Transmission Time (us/ft) Parallel to Grain	Stress Wave Transmission Time (us/ft) Perpendicular to Grain
Smulski 1991	Sugar Maple	12	78-59	-
	Yellow Birch	11	70-55	-
	White Ash	12	77-60	-
	Red Oak	11	80-61	-
Armstrong and others 1991	Birch	4-6	65-53	218-206
	Yellow-Poplar	4-6	59-53	218-206
	Black Cherry	4-6	63-56	210-189
	Red Oak	4-6	69-54	197-174
Elvery and Nwokoye 1970	Several	11	62-51	-
Jung1979	Red Oak	12	92-69	-
Ihlseng 1978,1979	Several	-	83-58	-
Gerhards 1978	Sitka Spruce	10	52	-
	Southern Pine	9	60	-
Gerhards 1980	Douglas-Fir	10	62	-
Gerhards 1982	Southern Pine	10	60-59	-
Rutherford 1987	Douglas-Fir	12	-	333-190
Ross 1982	Douglas-Fir	11	-	259-182
Hoyle and Pellerin 1978	Douglas-Fir	-	-	327
Pellerin and others 1985	Southern Pine	9	61-52	-
Soltis and others 1992	Live Oak	12	-	187-486
Ross and others 1994	Northern red and white oak	green	-	242

Table 2.2. Stress Wave Transmission Times for Detecting Decay in Timber

Reference	Wood Product	Structure	Stress Wave Transmission Time (us/ft), Parallel to Grain			
			Sound Wood	Incipient Decay	Moderate Decay	Severe Decay
Volny 1992	Douglas-fir glulam, creosote pressure treated	Bridge	390	-	557	741
Ross 1982	Solid-sawn Douglas-fir, creosote pressure treated	Football Stadium	260	389	-	>1000
Hoyle & Pellerin 1978	Douglas-fir glulam, arches	School Gym	327	Decayed wood: (480 us/ft)		

Stress wave timing has been used to measure early, moderate, to severe decay in wood members. Early studies have publicized that SWT can measure incipient decay, like Rutherford (1982). Rutherford's thesis concluded that SWT was an adequate tool for measuring incipient decay. The most recent studies although, have shown that SWT is not a good measure to detect incipient decay (Wang, 2005). For this research incipient decay was disregarded. This research focuses on early, moderate, to severe decay. Stress waves travel faster through sound wood than through decayed wood. The increase in propagation time, in extensively decayed wood, may be as great as 10 times the propagation for solid wood (Pellerin, 1994). Stress waves travel around the decay. The following figure represents the path of the stress wave through nondegraded and decayed wood (courtesy of FPL, 2004). Ring orientation can also affect the SWT.

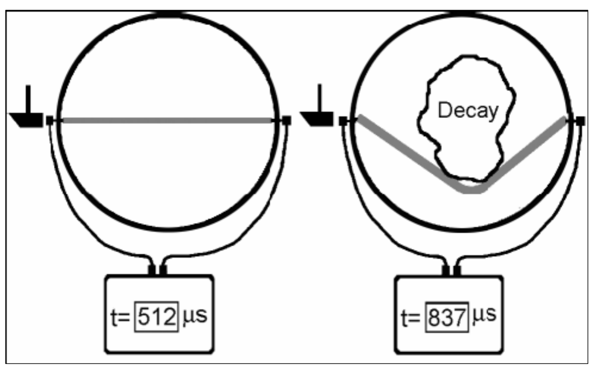

Figure 2.2. Concept of Stress Wave Timing for Detecting Decay in a Tree

However, knots in wood do not affect stress wave timing much, depending on the size. According to Gerhards (1982) stress waves are not sensitive to knot size. However, stress wave detection may be affected somewhat if the accelerometer rests on a knot.

FIBERGLASS WRAP (Fiber-Reinforced Polymer, FRP)

"Although the concept of fiber reinforced materials can be traced back to the use of straw as reinforcement in bricks manufactured by the Israelites in 800 B.C., and in more recent times to the use of short glass fiber reinforcement in cement in the United States in the early 1930's, fiber reinforced resin matrix materials (or fiber reinforced polymers as we know them today) were not developed until the early 1940's" (Tang, 1997).

There are many types of fibers including glass, carbon and aramid fibers. The type of fiber that is commonly used for strengthening structural members is the glass fiber. The glass fiber fabric is also known as E-glass fiber fabric. Glass fibers are used on beams or columns made up of concrete or timber to increase the allowable shear, compressive and/or bending stresses. In seismic regions fiberglass wraps are used on concrete columns to increase the ductility of the member.

According to the US Army Corps of Engineering, “E-glass fiber has a tensile strength nearly double that of steel and has modified versions that resist strong acids. An interesting characteristic of glass fibers is that they are elastic - elongating until failure without yielding. After the load is released the fiber returns to its original length.”

In a structural column a transverse fiberglass wrap significantly increases the compressive strength. Studies have shown that longitudinal wraps do not improve compressive strength in piles. Longitudinal fiberglass reinforcement does little to enhance pile performance (Wong, 2004). Wong repaired piles with transverse and/or longitudinal fiberglass reinforcement, and subjected the piles to destructive evaluation.

Wong concluded that longitudinal fiberglass reinforcement did little to increase the strength of the piles.

Fiberglass wraps are a cost effective technique for repair of structures. FRP is a lightweight material that is easy to install and work with. FRP can be wrapped around complex structures and is easy to transport. A disadvantage to using a fiberglass wrap is the ease the wrap can be torn apart if not handled properly. Since concrete beams or columns are smooth on the exterior the FRP can be installed easily. But for timber piles the wood can easily tear the fiberglass wrap so extra caution has to be used when using on timber piles. To prevent tears in the fiberglass wrap, timber piles can be coated with a structural epoxy paste to smooth the exterior surface. The epoxy paste serves as a bonding agent between the timber pile and fiberglass wrap. An important characteristic about FRP is too make sure it has bonded to the structural member to provide confinement and to make sure the full use of the FRP is achieved.

A recent study involved the repair of marine piles by Lopez-Anido (2005). Lopez-Anido and others repaired marine piles with pre-fabricated FRP shells. The research concluded the repair technique was cost effective. Also concluded in the study was the repair technique was environmental friendly, and provided marine borer protection and structural restoration. Figure 2.3 shows the cross-section of a timber pile repaired by Lopez-Anido which is similar to the repaired piles presented later in this thesis.

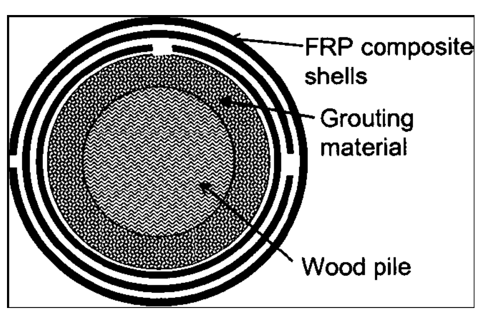

Figure 2.3. Cross Section of Repaired Pile (Courtesy of Lopez-Anido, 2005)

EPOXY IN STRUCTURAL MEMBERS

Epoxy resin is used to impregnate cracks and voids in wood and concrete to restore the structural integrity of the members. Epoxy has been used throughout the years to help increase the strength of wood and concrete members. According to the *AZo Journal of Materials Online* one of the main changes that has occurred in wood construction in the last 50 years has been the adoption of resin technology. One of the earliest reported studies on the use of epoxy repair was by Avent (1976, 1985). The epoxy was used for repair to increase shear strength in wooden trusses. The epoxy was applied at the joints of the trusses. Epoxy was applied to sound timber joints and joints that have been deteriorated. In both cases the epoxy responded well, and it was concluded that seriously deteriorated timber can be epoxy repaired. Epoxy glues today, are well built and extremely waterproof, as well as being resistant to wood treatments and changes in weather. Epoxy resin has a low viscosity allowing it to penetrate the smallest cracks in wood.

Even though epoxy has been used on timber for a number of years, there is no experimental data on the successful use of epoxy. A review of the literature shows practically nothing concerning repair of timber structures (Avent, 1979). This same statement still exists today.

AGGREGATE/EPOXY CORE IN TIMBER PILES

Repairing a severely decayed core with aggregate and epoxy is fairly new and research has been done by a previous Oklahoma State University graduate student, Wong (2004). Included in Wong's research was the increase in compressive and bending strength the piles had with an epoxy/aggregate core and a fiberglass wrap. The piles were subjected to destructive bending and compression evaluations. The results from the evaluation tests were used to create Load versus Displacement Graphs. The piles that were repaired had a much greater compressive and bending strength than the unrepaired piles. A nondestructive evaluation was not included in Wong's thesis.

In a past experiment at Oklahoma State University for the Oklahoma Transportation Center there were eighteen one-foot piles that were completely repaired with fiberglass wrap and epoxy/aggregate cores. A nondestructive evaluation via stress wave timing was conducted on the eighteen pile sections. Three stress wave timing tests were conducted on each pile. The first SWT test was on the pile that was repaired completely with FRP and epoxy/aggregate core. For the second SWT test the fiberglass wrap was removed. For the final SWT test, the wood was removed from the epoxy/aggregate core. The results are translated into stress wave transmission time. The table below shows the results of the stress wave transmission time of the three tests conducted on each pile. The stress wave transmission times are the lowest with the fiberglass wrap. No correlations were developed between the stress wave and the properties of the wood.

Table 2.3. Average Stress Wave Transmission Time from Past Experiment

	Complete Repair	Pile w/o FRP	Epoxy/Aggregate Core
Transverse SW Transmission Time (μs/ft)	368	545	566

CHAPTER 3

TEST PROCEDURES

Nine timber piles were evaluated nondestructively via stress wave timing, both for unrepaired and repaired piles. Nondestructive evaluation of the piles was used to determine if decay was present in the specimen. The NDE consisted of two stages: (1) NDE of the piles at their current stage, and (2) NDE of the piles after repair.

TEST SETUP: BEFORE REPAIR

All nine piles were of different lengths, weights and diameters. Each pile was designated a label from Pile A to Pile I. Each pile was marked to distinguish left from right and top from bottom. Most of the piles were squared off at the ends to obtain uniform lengths. The shortest pile measured was 91 inches and the longest pile was measured to be 189.5 inches. After the ends were sawed off a spatial grid was drawn on each pile. Lines were drawn in the transverse and longitudinal directions. The transverse lines were spaced at two inches apart over the pile surface. The longitudinal lines were spaced equally around the perimeter of the pile. Sixteen longitudinal lines were marked on each pile. With this line arrangement eight test points in the transverse direction can be taken at every two inches as illustrated in Figure 3.1. A total of 4400 test points were marked on the piles. Figure 3.2 shows a section of Pile A labeled with a spatial grid. Five test points were evaluated in the longitudinal direction as seen in Figure 3.3.

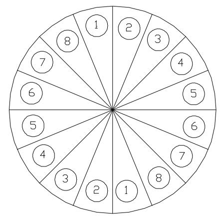

Figure 3.1. Transverse Test Points for Piles

Figure 3.2. Partial View of Pile A with Spatial Grid

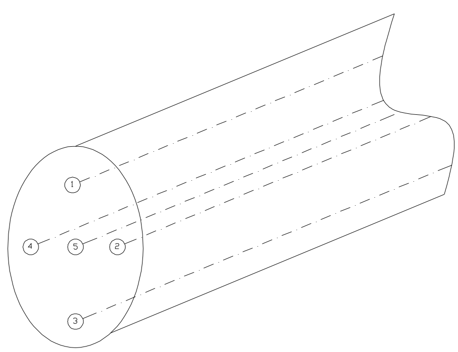

Figure 3.3. Longitudinal Test Points for Piles

Once the timber piles were labeled with a spatial grid, stress waves were sent through the piles transversely and longitudinally. An accelerometer instrumental hammer was used to impose the stress wave. An accelerometer attached to a handle was used to receive the sent stress wave. Both accelerometers were connected to a Fluke Scopemeter 192 handheld digital oscilloscope. A picture of the equipment is shown in Figure 3.4.

Figure 3.4. Photo of Fluke Scopemeter 192

The results of the stress wave inspections were then used to create a spreadsheet which could establish a relationship between the stress wave times and the internal condition of the piles. The stress wave time values were used to obtain the stress wave transmission time throughout the wood. Stress wave transmission times were used since many publications published results for stress wave transmission times instead of stress wave velocity. Nine different spreadsheets were created, one for each pile. Each spreadsheet contained the data from the test points, geometry from the piles and graphs created from the geometry and test points. The results of the data are in the next chapter.

TEST SETUP: REPAIRED

The first stages of repairing the piles were to cut an assortment of two-foot sections from each pile. Three-two foot sections were cut from the shorter piles and six-two foot sections were cut from the longer piles. The way each section was labeled depended from which pile it came from. For example, three sections were taken from Pile A so the sections were labeled A1, A2 and A3. The same procedure was repeated for all the other sections. There were a total of thirty-six sections taken from all nine piles. Fourteen sections were chosen randomly to be repaired; at least one section repaired from each pile. From each pile there is at least one control specimen which is not repaired. There are two types of repair techniques. One type of repair has epoxy paste applied around the pile, wrapped with fiberglass, and epoxy injected into the voids. The other type of repair consists of epoxy paste applied around the pile, wrapped with fiberglass, an aggregate/epoxy core, and epoxy injection into the pile. The sections repaired with an aggregate/epoxy core were sections: A1, B2, E1, H5 and I2. The sections repaired with fiberglass and epoxy were sections: A3, B1, C2, D2, E3, F3, G1, H1 and I6.

A 4.5 inch drill bit was used to drill a hollow core into the specimens. Five test specimens were chosen to be repaired with an aggregate/epoxy core. Figure 3.5 shows the drilling of one of the two-foot sections. The core was drilled to simulate severe decay where a pile becomes hollow.

Figure 3.5. Photo of a Pile Being Drilled

The five two-foot sections that have drilled cores were reevaluated for stress wave timing. A graph was created too see how much the stress wave changed through the piles with drilled cores. One is to expect that the pile with the drilled core will have slower velocities than the pile that is fully intact since the stress wave has to travel around the drilled core. If the pile was severely decayed at the core then the stress wave times should be relatively close to one another.

Once the sections were repaired they were labeled with a spatial grid to evaluate nondestructively. Figure 3.6 illustrates a spatial grid on a repaired pile.

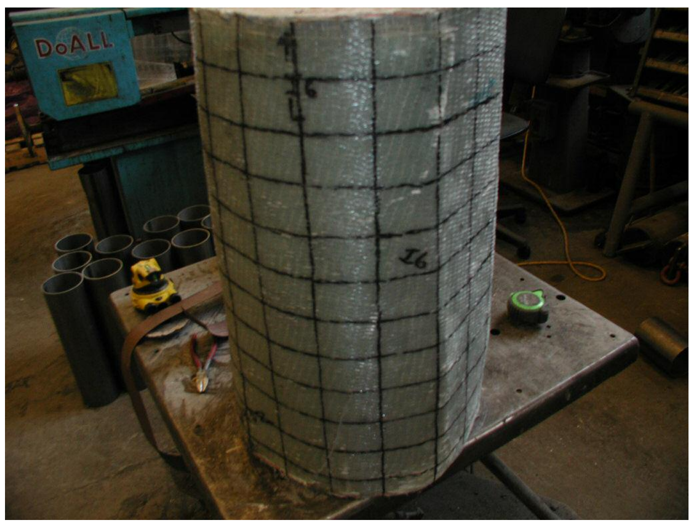

Figure 3.6. Spatial Grid on a Repaired Pile

MATERIALS USED FOR REPAIR

Materials used for repair of the timber piles were Sikadur 30, SikaWrap Hex 100G, Sikadur 300, Pro-Poxy 100 LV, and Pea Gravel. All the specifications for the data sheets are in APPENDIX A. Each repair material will be discussed briefly below. The amount of each material used for each pile was recorded to have an estimate on how much it would take to repair a pile. A correlation was established in the next chapter to relate stress wave inspection with the amount of materials used for repair.

Sikadur 30 is a structural epoxy paste that was applied around the perimeter of the piles. It was used to seal cracks and voids on the outside of the pile. Sikadur 30 helped to smooth out the surface of the piles so that the fiberglass wrap bonded well to the pile. The figure below shows Sikadur 30 being applied to a pile.

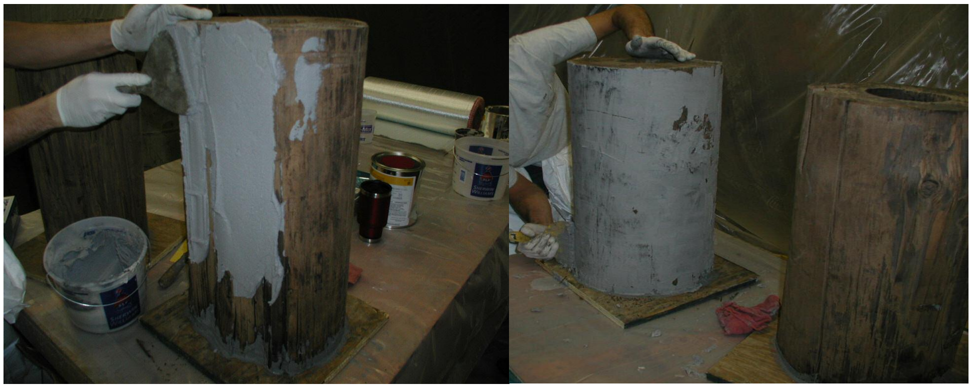

Figure 3.7. Sikadur 30 Being Applied to Piles

Once Sikadur 30 was applied, SikaWrap Hex 100G was wrapped around the pile. The SikaWrap was saturated with Sikadur 300 which allowed the wrap to bond to the Sikadur 30. Sikadur 300 was used as an impregnating resin. Sikawrap Hex 100G, a glass fiber fabric was used for structural strengthening. Figure 3.8 illustrate the fiberglass wrap saturated with Sikadur 300, and the wrap applied to the pile.

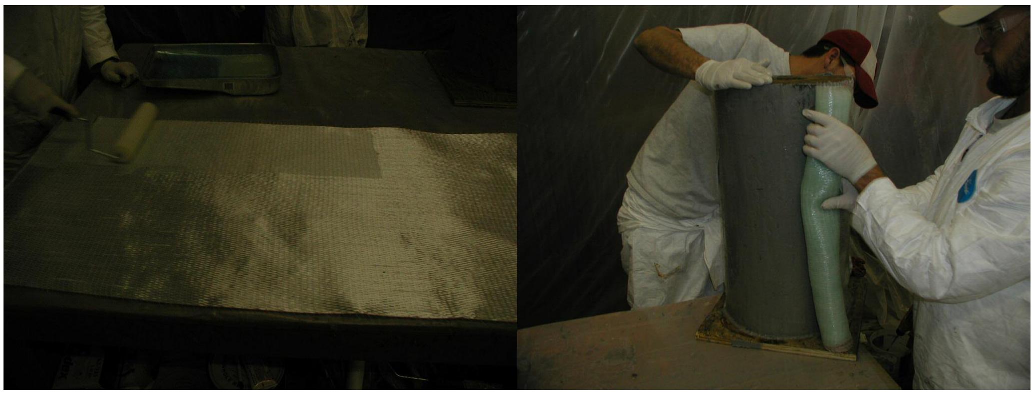

Figure 3.8. Application of Sikadur 300 and SikaWrap Hex 100G

The materials were allowed to cure before the injection process was begun. Once the SikaWrap Hex 100G was dried Pro-Poxy 100 LV was injected into the piles to seal the inner cracks and voids. Pro-Poxy 100 LV is an injection resin and mortar binder. The piles with the drilled cores were filled with pea gravel and Pro-Poxy 100 LV. Seen in the following figures was the location of the injection ports and the equipment used to inject the epoxy resin. Figure 3.11 is a top view of a repaired pile with an aggregate/epoxy core.

Figure 3.9. Location of Injections Ports

Figure 3.10. Equipment Used to Inject Epoxy Resin


Figure 3.11. Top View of a Repaired Pile

POST REPAIR INSPECTION

Once the piles were completely repaired, the piles were evaluated via stress wave timing. They were evaluated the same way as the unrepaired piles. All of the stress wave timing results were inputted into a spreadsheet. The stress wave results were taken from the deteriorated and repaired piles. The results were compared to the amount of materials used during the repair. Correlations were then established between stress wave velocity and repair material. Correlations are established to see if an approximation can be made to predict the amount of material needed for repair if stress waves velocities and pile dimensions are known.

CHAPTER 4

RESULTS

Fourteen two-foot sections piles were taken to Concrete Services, Inc. in Tulsa, Oklahoma to repair. Nine sections were wrapped with fiberglass wrap and injected with epoxy resin. The remaining sections were the piles with the drilled cores. These sections were repaired with fiberglass wrap, injected with epoxy resin, and filled with an aggregate/epoxy core. The amount of material used in the repair was recorded to have an estimate on how much material is needed for repair. The piles were evaluated via stress wave timing in the transverse direction in their unrepaired stage. The piles were then repaired and evaluated again. Correlations were then made between the amount of repair materials, stress wave velocities and physical dimensions of the piles.

PILE A

Pile A was a length of 111 inches and the largest diameter recorded was 13.9 inches before repair. Figure 4.1 displays a photo of Pile A. From visual inspection Pile A is well intact but has many cracks and splits on the outer surface. Figure 4.2 shows a color gradient map of the stress wave transmission time throughout Pile A. Even though the species of the wood is not known a comparison can be made to Table 2.1 and Table 2.2. From the table the highest value for sound wood is approximately 486µs/ft in the transverse direction for live Oak. Most of the readings from Pile A are in the 400-500µs/ft region, and the wood species for this research is more likely to be Pine. Most of the results from Table 2.1 for sound wood are in the 200-400μs/ft region. The values of 200-400μs/ft was considered the upper boundary for sound wood for this project. The boundaries for early decay were considered to be 400-500 μs/ft. The boundaries for moderate decay were considered to be 400-800μs/ft. Any values above 800μs/ft were considered severe decay.

Figure 4.1. Photo of Pile A

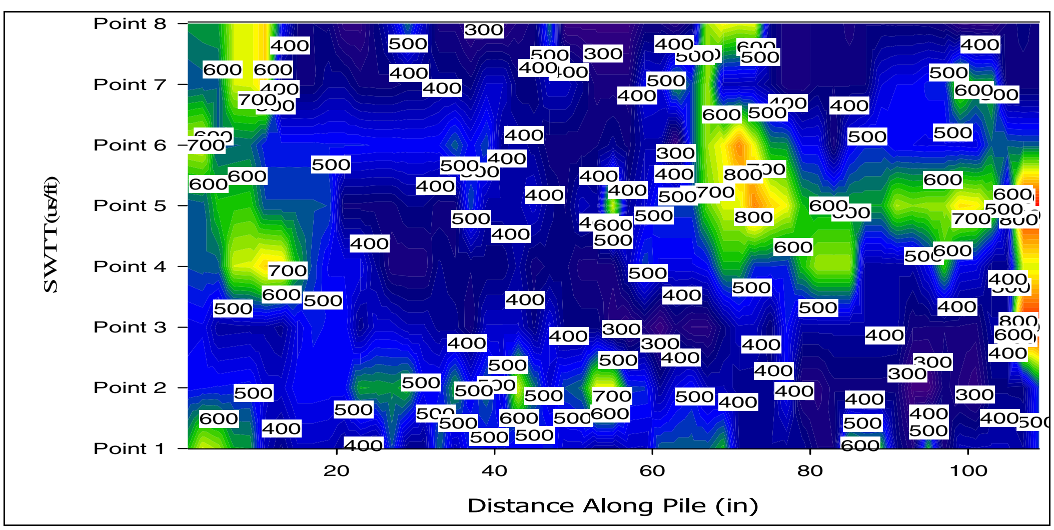

Figure 4.2. Stress wave Transmission Time throughout Pile A

Another representation of the pile can be developed by determining the average stress wave transmission time for each longitudinal pile segment as seen in Figure 4.3.

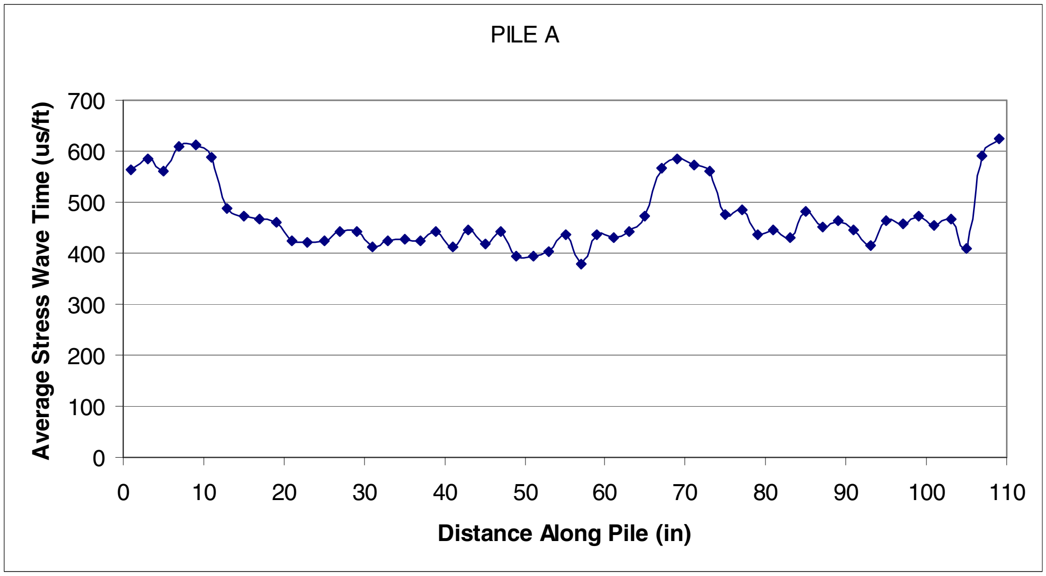

Figure 4.3. Average Stress Wave Transmission Time for Pile A

The ends and the area around 70 inches from the left have the slowest stress wave transmission time (SWTT). Most of the average values are well above the 200-400μs/ft values. Pile A seems to be at the early to moderate stage of decay.

Three two-foot sections were taken from Pile A. Two of the sections were repaired which were sections A1 and A3. Section A1 was repaired with fiberglass and an aggregate/epoxy core and section A3 was repaired with a fiberglass wrap. Section A2 was the control specimen. The results for section A2 are seen in Figure 4.3 between 59 inches and 83 inches. The results of the stress wave inspections of section A1 and A3 are presented in Figure 4.4 and Figure 4.5. The drilled piles were re-evaluated for stress wave timing. One is to expect that the SWTT will increase since the stress waves have to travel around the hollow core. Most of the results for the drilled piles have the SWTT lower than the piles that are fully intact. Reasons why the SWTT are lower are that materials were lost during the experiment or the pile was severely decayed at the core.

When the piles were subjected to drilling, much of the damaged outer surface was lost. By losing the outer surface the dimension of the piles were reduced resulting in a lower SWTT.

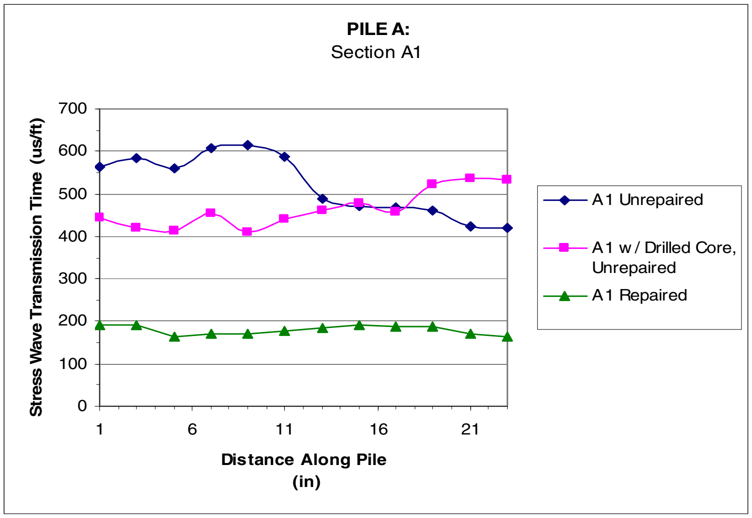

Figure 4.4. Average SWTT for Section A1

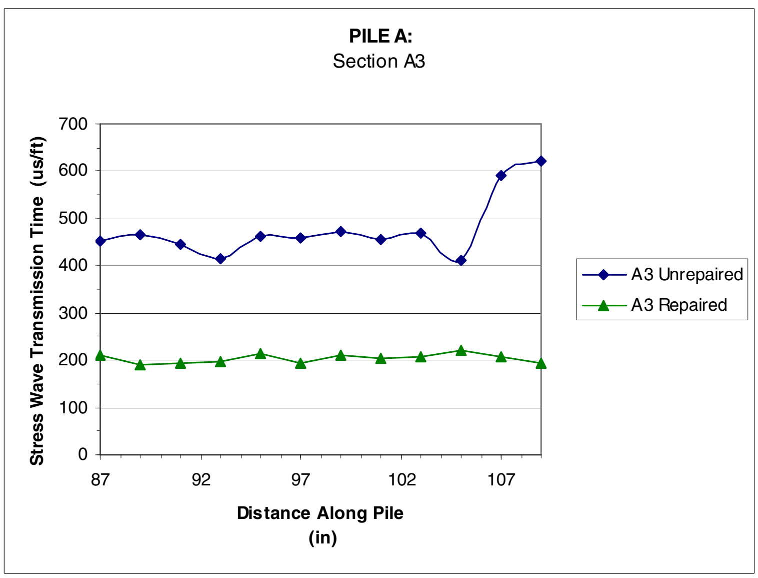

Figure 4.5. Average Stress Wave Time for Section A3

Both sections when repaired have a SWTT of approximately 200µs/ft. The SWTT have decreased by over 200 microseconds. The SWTT are about the same for both sections even though they were repaired differently. It is not likely that the stress waves traveled through the fiberglass alone. The properties of the fiberglass would have resulted in a SWTT well below 200µs/ft.

Since the SWTT has decreased, the velocity of the stress wave has increased. The velocity of a stress wave is directly proportional to the dynamic modulus of elasticity. An increase in modulus of elasticity is correlated to an increase in strength.

PILE B

Pile B was a length of 98 inches and the largest diameter recorded was 12.2 inches before repair. Figure 4.6 displays a photo of Pile B. From visual inspection Pile B is well intact but has certain sections where the outer surface was damaged, most likely during extraction. Figure 4.7 shows a map of the stress wave transmission time throughout Pile B. The highest recorded SWTT was over 1000µs/ft and the readings were taken at the ends. Visually the ends have a lot of cracks. Figure 4.8 illustrates an end view of Pile B. Most of SWTT for Pile B are between 400-600µs/ft. The region between 60-80 inches has high SWTT.

Figure 4.6. Photo of Pile B

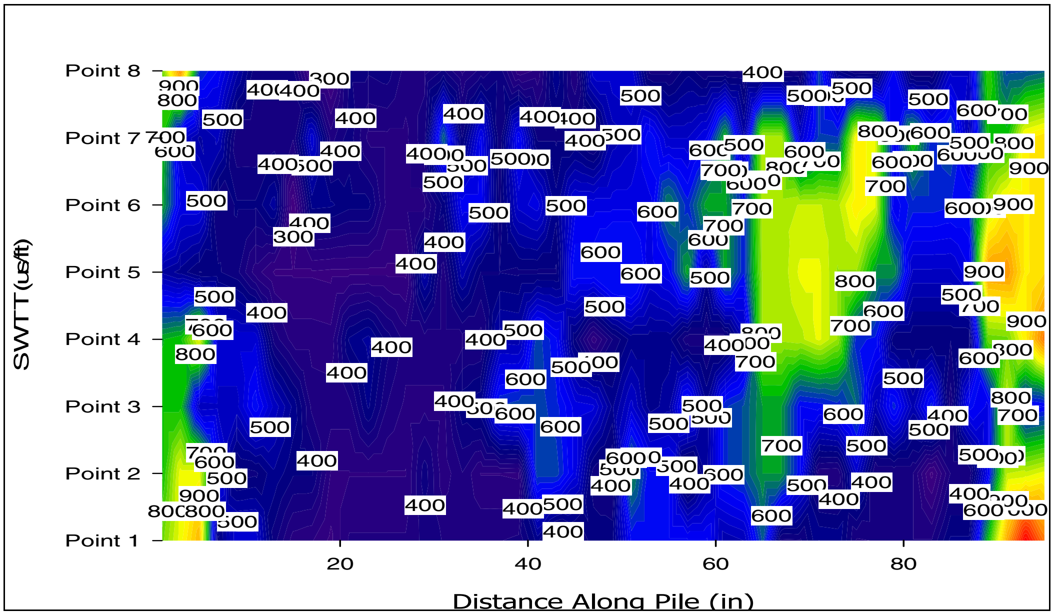

Figure 4.7. Stress Wave Transmission Time for Pile B

Figure 4.8. End View of Pile B

Figure 4.9 displays the average SWTT. Pile B is also at the stage of early to moderate decay because most of the values are above 200-400µs/ft. The region around twenty inches can be considered to be sound wood.

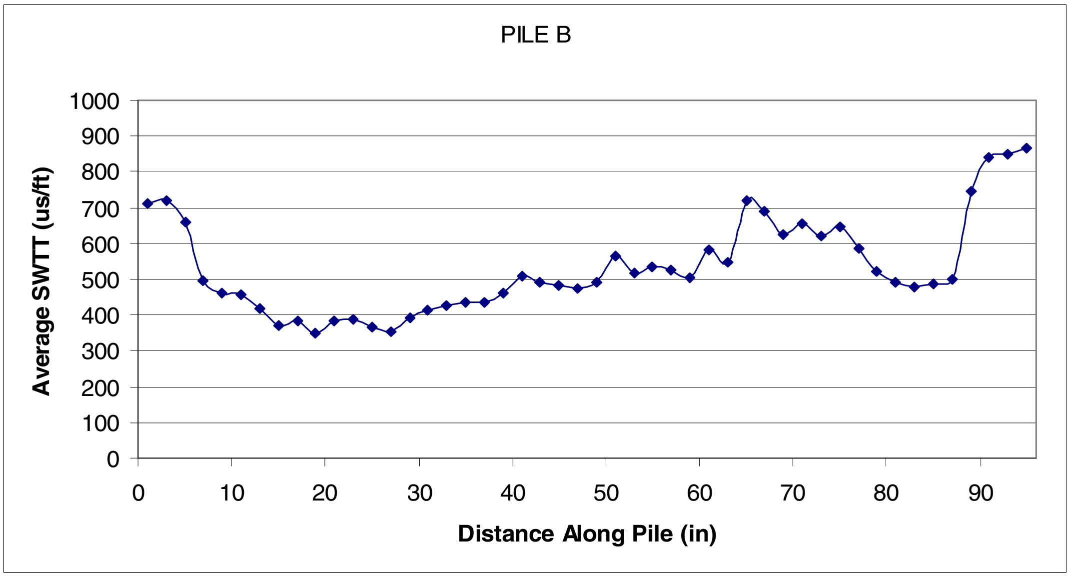

Figure 4.9. Average Stress Wave Time for Pile B

Three two-foot sections were taken from Pile B. Two of the sections were repaired which were sections B1 and B2. Section B3 was the control specimen. The results for section B3 are seen in Figure 4.9 between 25 inches and 49 inches. Section B2 was repaired with fiberglass and an aggregate/epoxy core and section B1 was repaired with a fiberglass wrap. The results are in Figure 4.10 and in Figure 4.11. Most of Section B2 is sound wood. Section B2 with the hollow core has SWTTs higher than the unrepaired section B2. This result is expected since the stress waves have to travel around the hollow core.

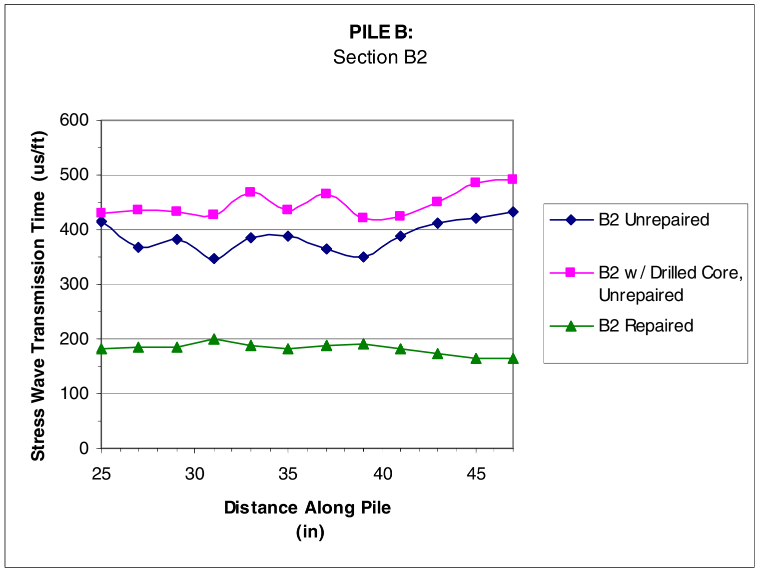

Figure 4.10. Average SWTT for Section B2

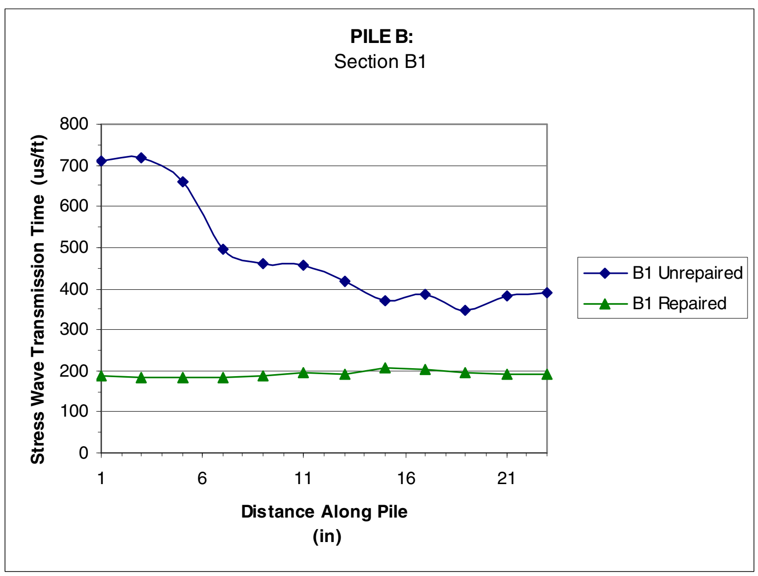

Figure 4.11. Average SWTT for Section B1

The SWTT have decreased to approximately 200us/ft for both repaired sections. It can be seen that the fiberglass wrap has more of an impact on the stress waves than the aggregate/epoxy core. Again, the SWTT has decreased so the dynamic modulus of elasticity has increased resulting in an expected increase in strength in the repaired pile segments.

PILE C

Seen from Figure 4.12, Pile C was badly damaged during extraction from the timber bridge. Pile C was a length of 100.5 inches and the largest diameter recorded was 13.3 inches. The smallest diameter of the pile was measured to be 11.3 inches. From visual inspection the outer shell of Pile C is falling apart. The ends are similar to Pile B where cracks can be seen.

Figure 4.13 shows a map of the stress wave transmission time throughout Pile C. The highest recorded SWTT was over 1600μs/ft and the readings were taken at the right end. Also, at 50 inches along the pile there were SWTT measured to be over 1300μs/ft. Most of the SWTT for Pile C are between 400-700μs/ft. All the values are above the 200-400μs/ft so this pile has early to moderate decay with some areas with advance decay.

Figure 4.12. Photo of Pile C

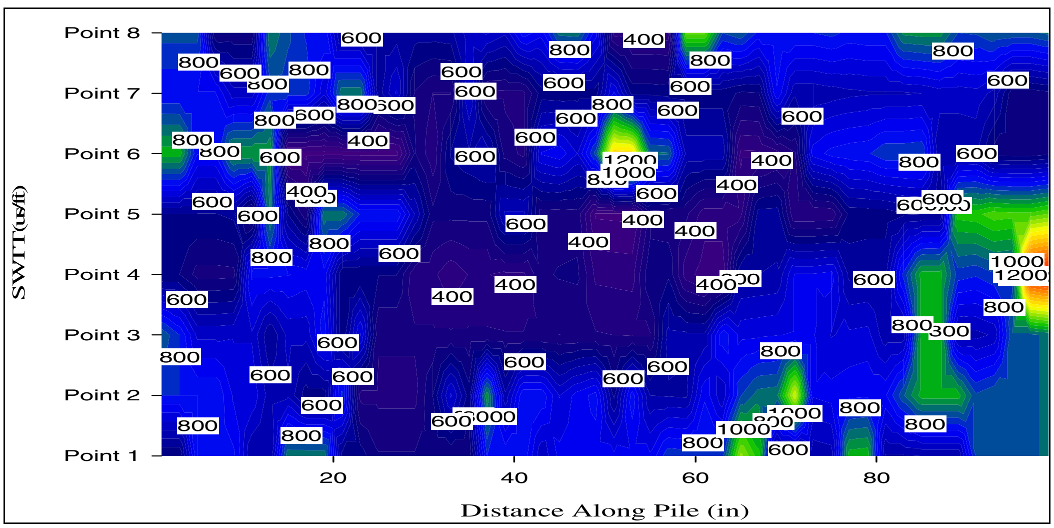

Figure 4.13. Stress Wave Transmisson Time for Pile C

Figure 4.14 displays the average SWTT. All the average values are well above the sound wood criteria of 200-400μs/ft.

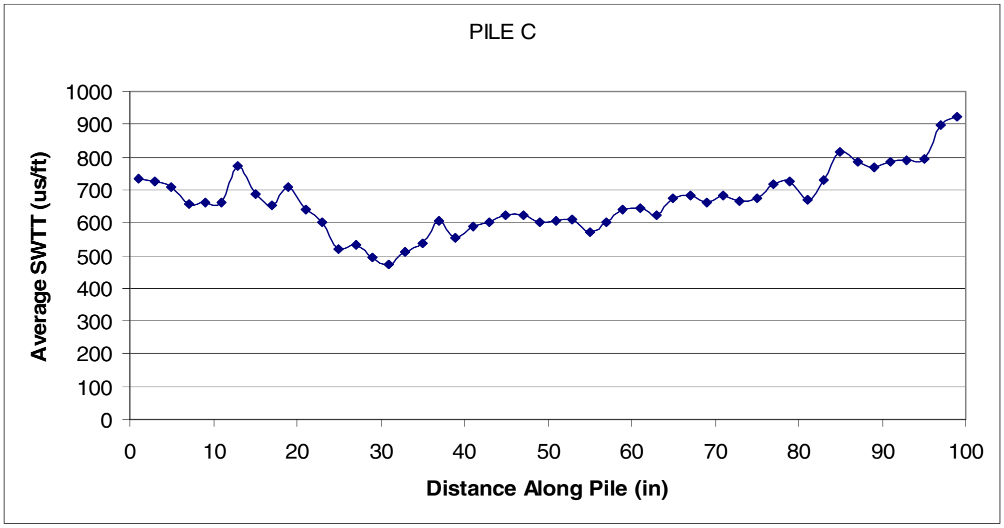

Figure 4.14. Average Stress Wave Transmission Time for Pile C

Three two-foot sections were taken from Pile C. Section C1 and C3 from taken at 0 to 23 inches and 49inches to 73 inches. The results for these two sections can be seen in the figure above. Only one of the sections was repaired which was section C2. Section C2 was repaired with a fiberglass wrap and no aggregate core. The results of the SWTT are displayed in Figure 4.15. The SWTT has decreased to approximately 200μs/ft. The epoxy paste, fiberglass wrap and epoxy resin used to repair the pile have sealed the cracks in the pile allowing the SWTT to be almost the same throughout the section.

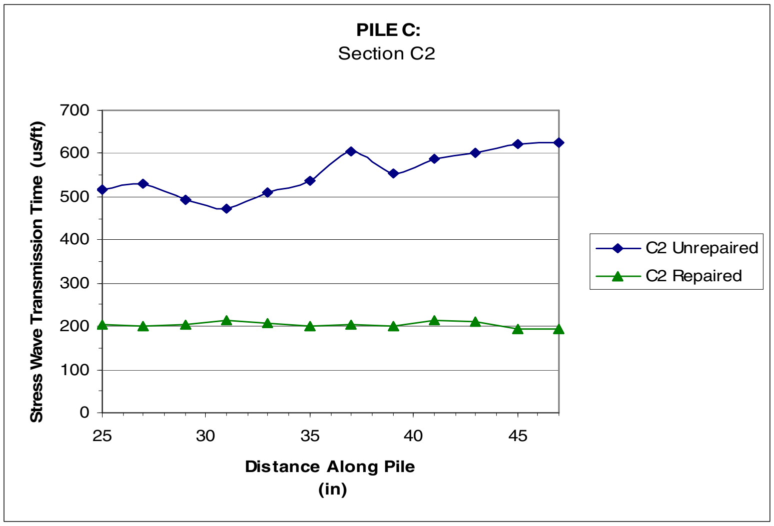

Figure 4.15. Average Stress Wave Time for Section C2

PILE D

Pile D was the shortest and lightest pile of the nine piles. Figure 4.16 displays a photo of Pile D. From visual inspection it can be seen that there is decay present on the outside of Pile D. The figure shows the decay on the pile which is the white area. The outer surface was severely damaged with much of the outer shell missing. Figure 4.17 shows a map of the stress wave transmission time throughout Pile D. The highest recorded SWTT was over 1700μs/ft. Most of the SWTT for Pile D is above 1000μs/ft. The regions from 40 inches to 90 inches have the highest SWTT values, and this is the area where the decay can be seen on the surface. Pile D at 30 inches to 91 inches is at the stage of severe decay. The rest of the pile is at moderate decay.

Figure 4.16. Photo of Pile D

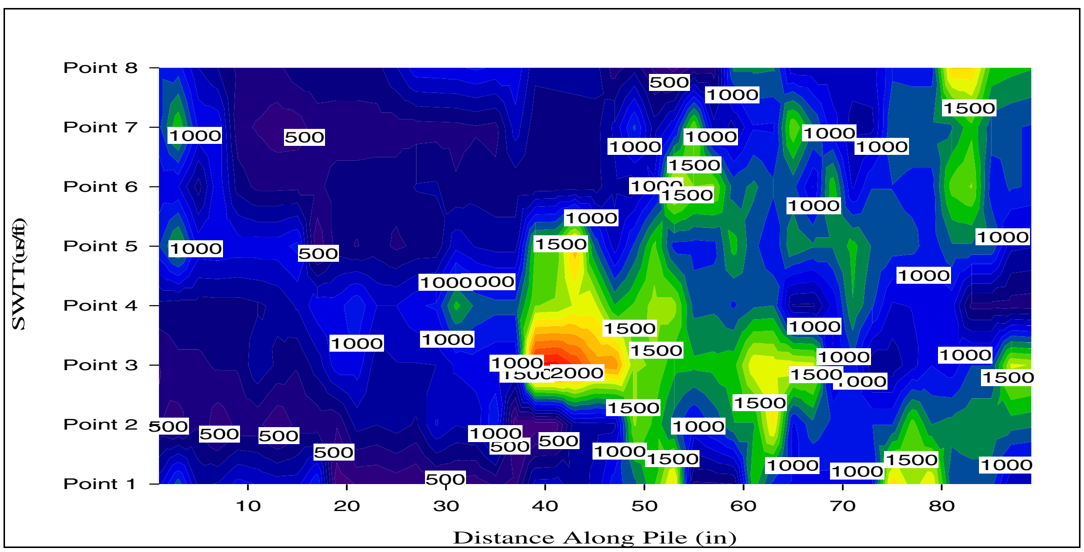

Figure 4.17. Stress Wave Transmission Time for Pile D

Figure 4.18 displays the average SWTT values. Some regions of the pile have SWTT values tripled of what sound wood is expected to be.

Only one of the sections was repaired from Pile D which was section D2. Sections D1 and D3 were not repaired. Sections D1 and D3 were taken between 6 inches to 30 inches and 63 inches to 87 inches. Section D2 was repaired with a fiberglass wrap and injected with epoxy resin. The results of the SWTT are displayed in Figure 4.19. Again, the SWTT has decreased to approximately 200µs/ft.

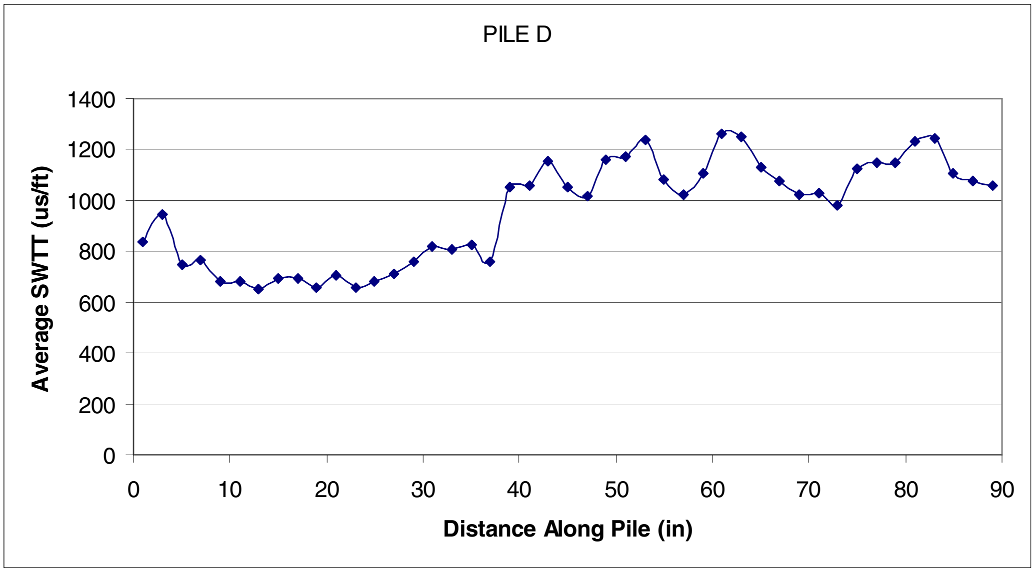

Figure 4.18. Average Stress Wave Transmission Time for Pile D

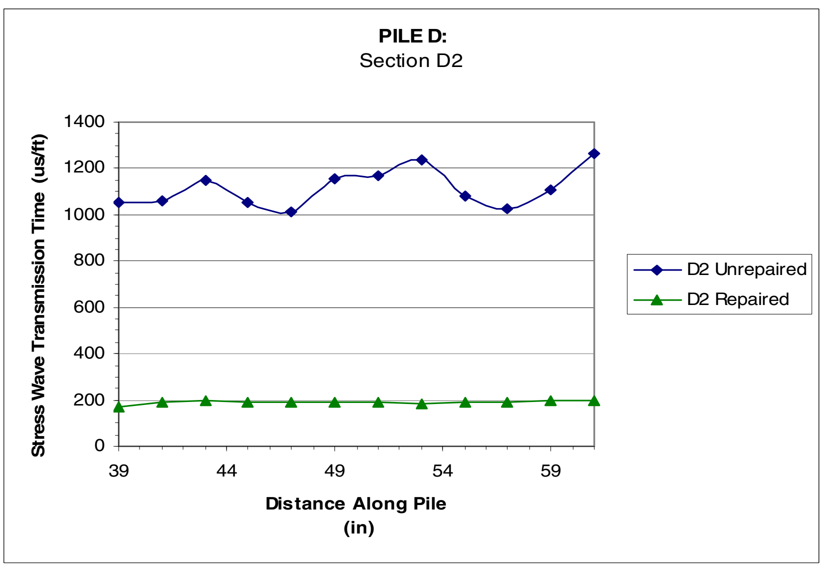

Figure 4.19. Average Stress Wave Transmission Time for Section D2

PILE E

Pile E is the middle pile in Figure 4.20. Cracks can be seen running throughout the pile length. The pile is well intact and was not damaged a great deal during extraction. Pile E was a length of 111.5 inches and the largest diameter recorded was 13.6 inches before repair. Figure 4.21 shows a map of the stress wave transmission time throughout Pile E. The highest recorded SWTT was over 1300µs/ft. The left end has a lot of cracks; this is why the SWTT values are high. Most of SWTT for Pile E are between 400-500µs/ft.

Figure 4.20. Photo of Pile E

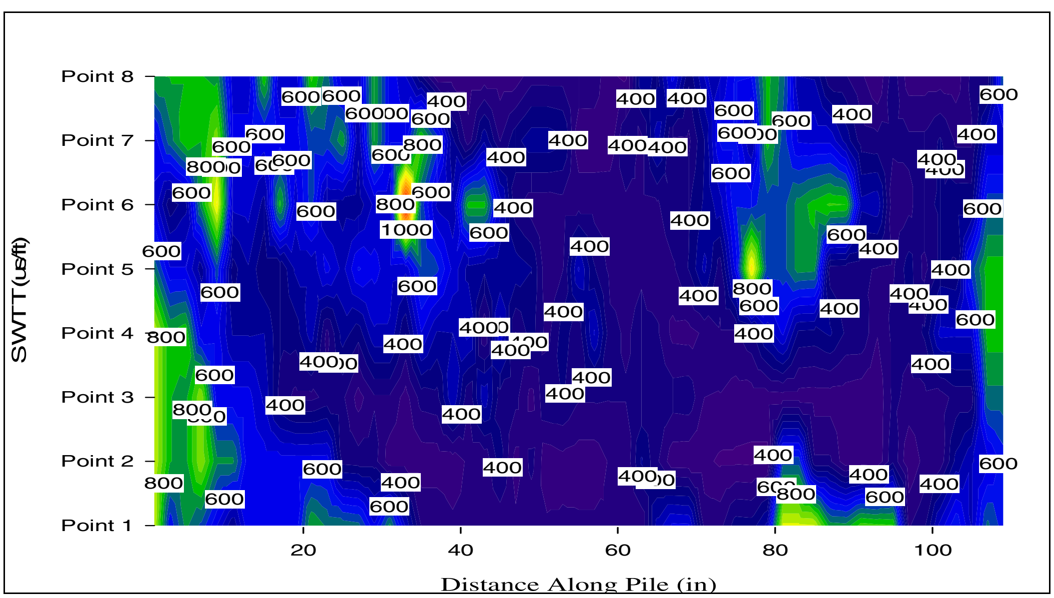

Figure 4.21. Stress Wave Transmission Time for Pile E

Figure 4.22 illustrates the average SWTT values. The ends have the highest stress wave times, and the middle from 45 inches to 75 inches seems to be sound wood.

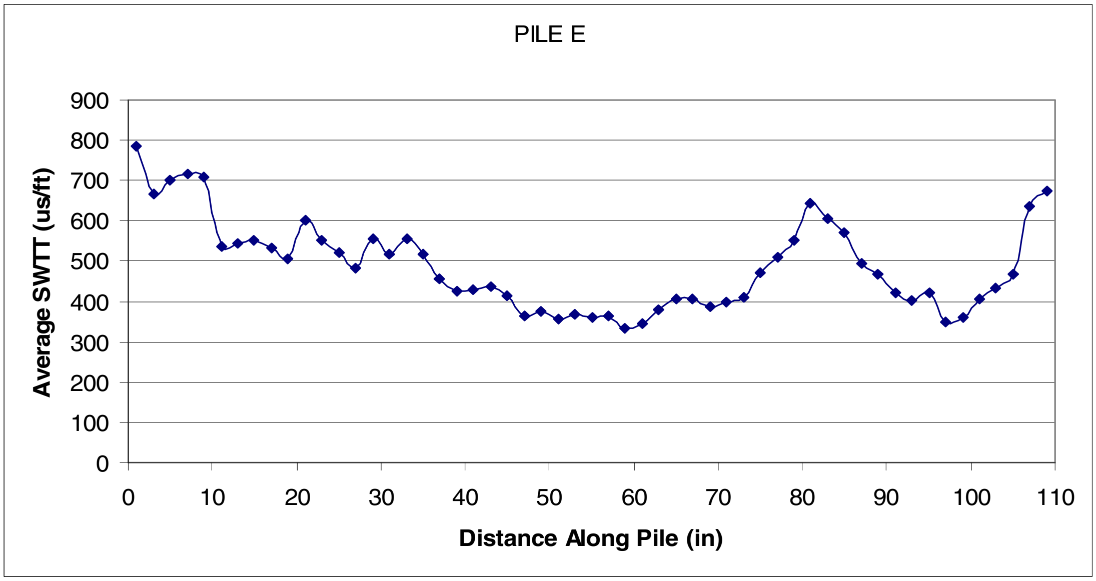

Figure 4.22. Average Stress Wave Transmission Time for Pile E

Section E2 was taken at 39 inches to 63 inches and the results can be seen above. Two sections from Pile E were repaired. Section E1 was repaired with the fiberglass wrap and aggregate/epoxy core. Section E3 was repaired with the fiberglass wrap. The results of the SWTT values are in Figure 4.23 and Figure 4.24. The stress wave times have been decreased to about 200µs/ft throughout the pile length. Section E1 is similar to Section A1. The SWTT for the drilled cores were reduced. The reasons are materials were lost during drilling or the core was severely decayed. Much of the damaged outer surface was lost resulting in faster stress waves.

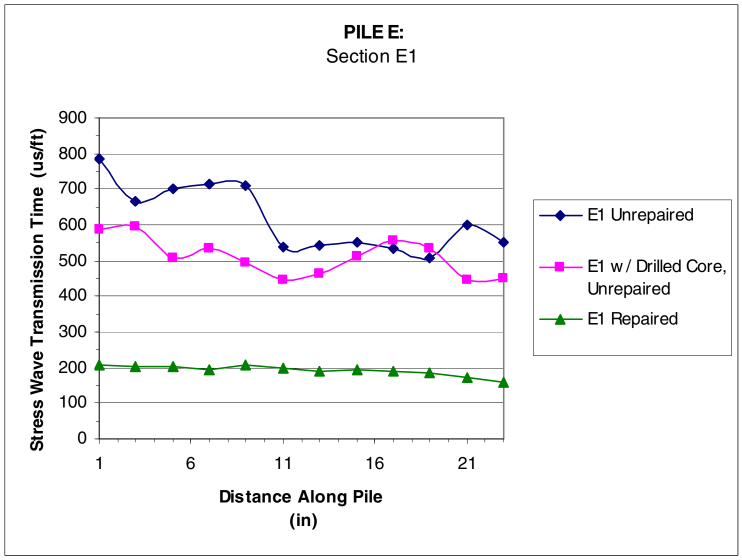

Figure 4.23. Average Stress Wave Transmission Time for Section E1

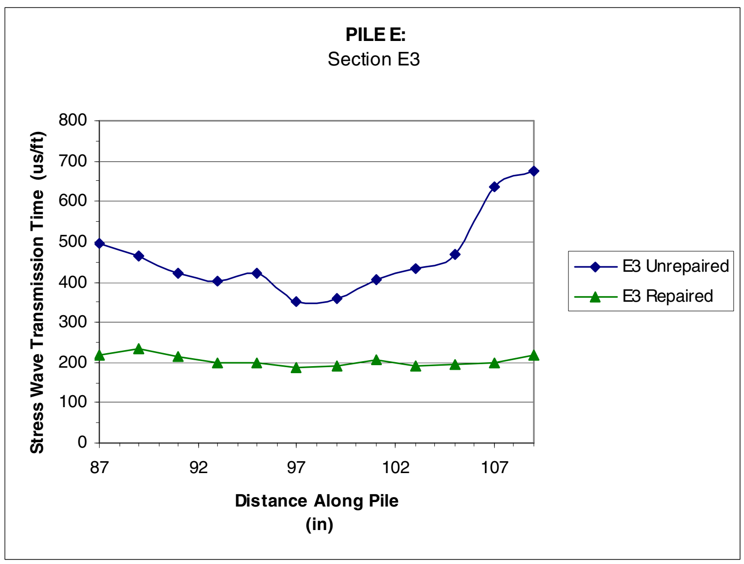

Figure 4.24. Average Stress Wave Transmission Time for Section E3

PILE F

Pile F was damaged on the right end of the pile and cracks could be seen. Some wood pieces have come off Pile F but no visible decay is present on the outer surface. A photo of Pile F can be seen in Figure 4.25. Pile F was measured to be a length of 91 inches. On one end of the pile the diameter was 14.0 inches and on the other end the diameter was 11.2 inches. Figure 4.26 on the following page has the layout of the stress wave transmission times. The end that was badly damaged has high SWTT values. The highest SWTT recorded was over 1600µs/ft. The pile has moderate decay with some regions of advance decay.

Figure 4.25. Photo of Pile F

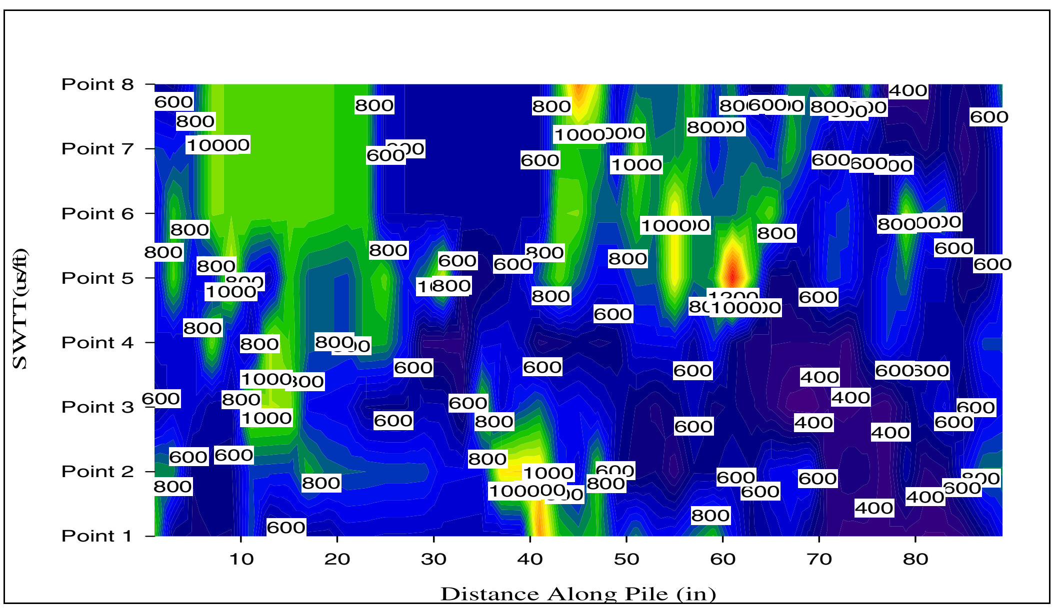

Figure 4.26. Stress Wave Transmission Time for Pile F

Sections F1 and F2 were the unrepaired sections. Section F1 was taken at 0 to 24 inches. Section F2 was taken at 24 inches to 48 inches. Results for sections F1 and F2 are in Figure 4.27. One section from Pile F was repaired. Section F3 was repaired with the fiberglass wrap, epoxy paste, and epoxy resin. The results of the average SWTT values are below in Figure 4.27. The stress wave times have been decreased by a factor of either three or four for the repaired section, F3. Results for section F3 are shown in Figure 4.28.

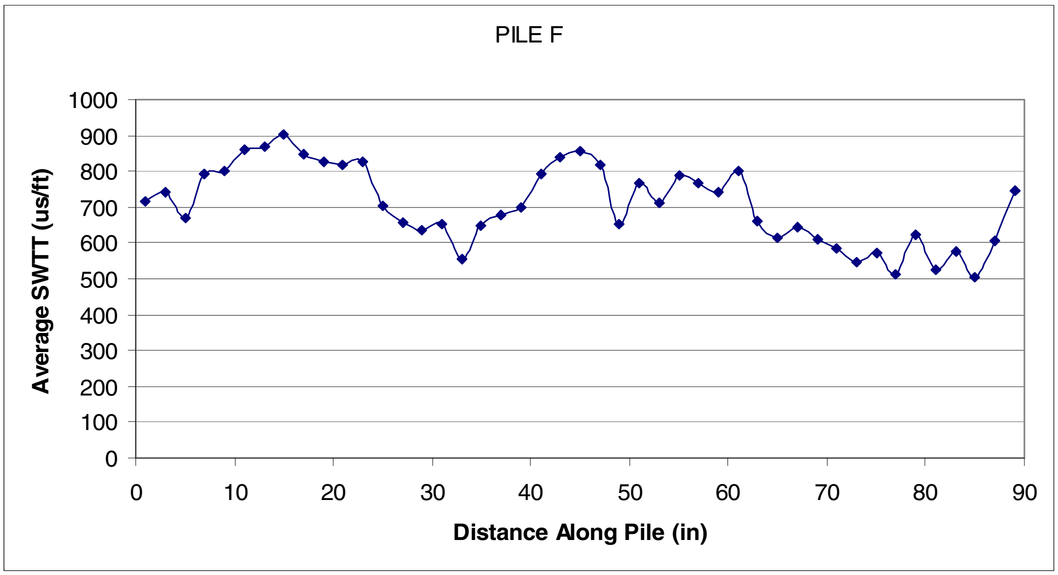

Figure 4.27. Average Stress Wave Time for Pile F

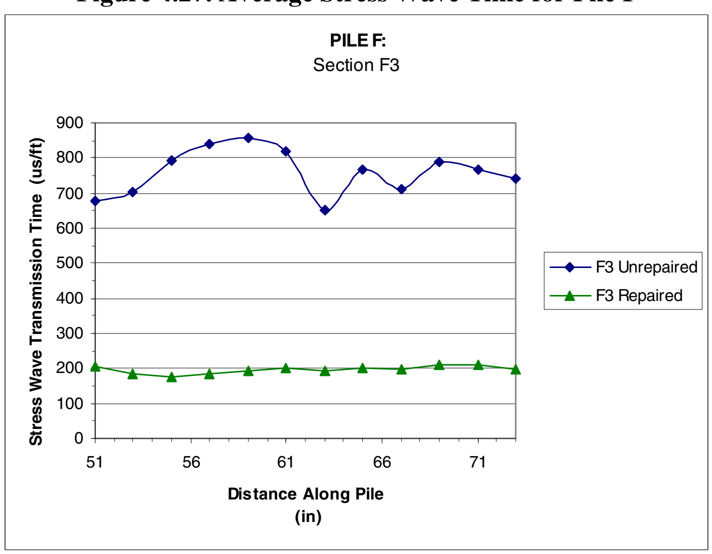

Figure 4.28. Average Stress Wave Transmission Time for Section F3

PILE G

The final three piles are the longest in length. The longest piles were damaged the most during removal from the bridge in Oklahoma. Pile G was measured to be 142.5 inches. A photo of Pile G is in Figure 4.29. Pile G was extremely damaged during extraction. Cracks can be seen all around the perimeter of the specimen. Most of the outer shell is weak and could be easily torn apart by hand. No visible decay is present on the outer surface. Figure 4.30 illustrates a layout of the stress wave transmission time throughout Pile G. There are some areas in the pile that has early decay. The early decay is present where the darker shade of blue can be seen in the figure. Around the regions of early decay are higher SWTT values, this seems to be moderate decay. The green, yellow and red regions seem to signify advance decay. The red region is at Point 2 and 80 inches in the figure.

Figure 4.29. Photo of Pile G

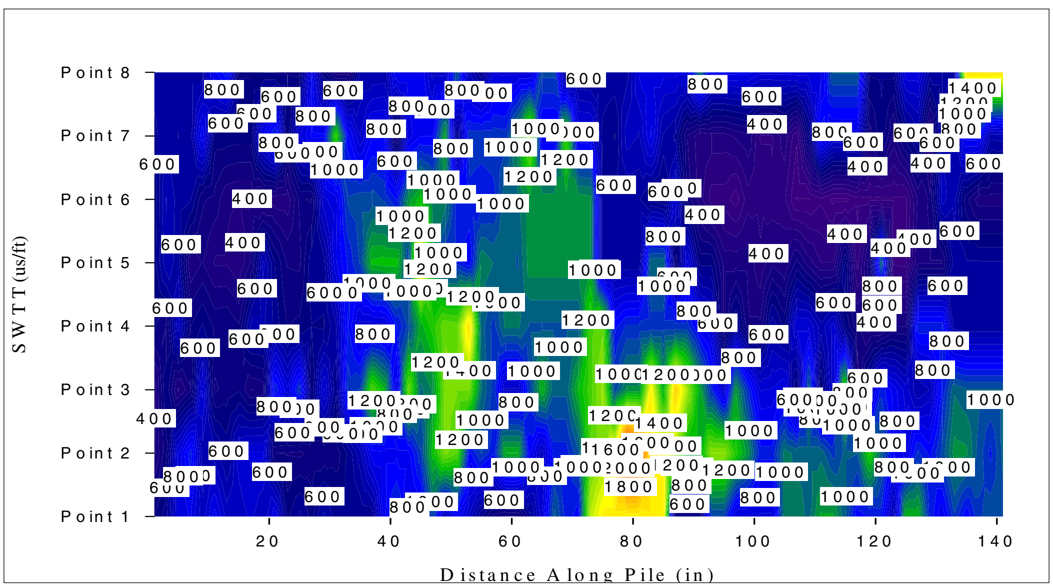

Figure 4.30. Stress Wave Transmission Time for Pile G

The average SWTT for Pile G are in Figure 4.31. There is no clear trendline for the stress waves in pile G. The SWTT for Pile G is scattered probably due to the damaged suffered during extraction. The results are as low as 500µs/ft to as high as 1100µs/ft. It is clear though that the pile has moderate to advance decay.

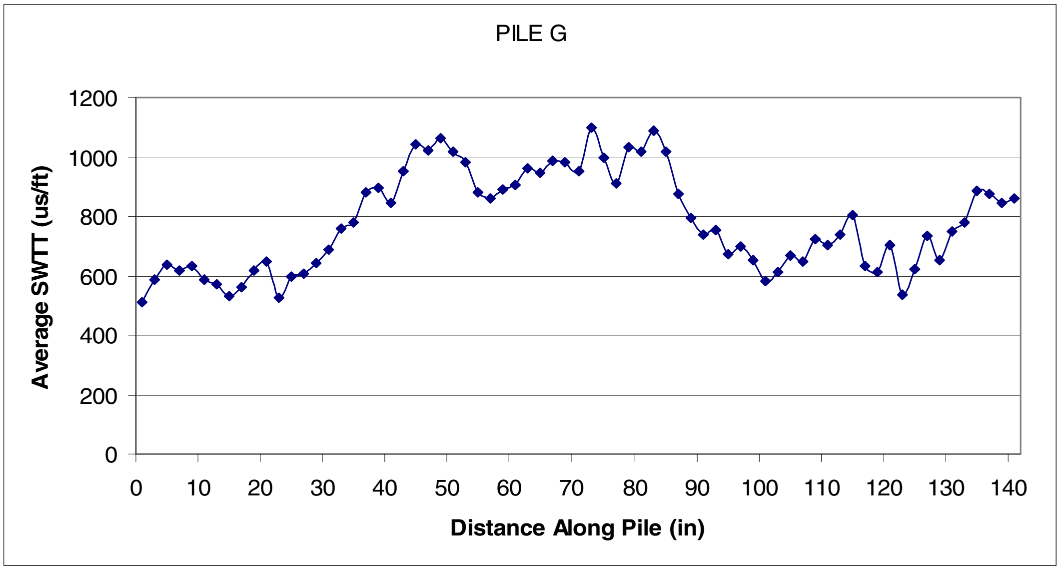

Figure 4.31. Average Stress Wave Transmission Time for Pile G

Six two-foot sections were taken from Pile G. Sections G2 to G6 were taken from 24 inches to 141 inches. The results are above in Figure 4.31. Only one section was repaired and that was Section G1. Section G1 was taken from the left end of Pile G. The remaining sections are control specimens for future evaluation. Figure 4.32 displays the results for Section G1. The transmission time for the stress waves were reduced to 200µs/ft. Section G1 was taken where moderate decay seems to be present. The repair technique has improved the SWTT values which should increase the dynamic modulus of elasticity and strength of the pile.

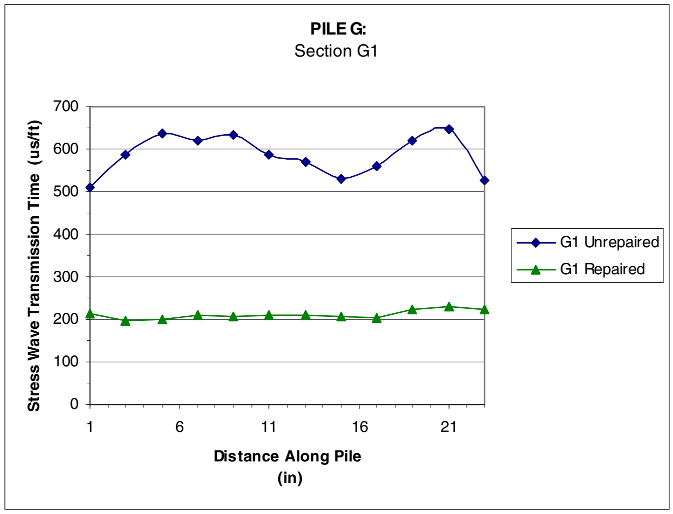

Figure 4.32. Average Stress Wave Transmission Time for Section G1

PILE H

As seen in the Figure 4.33, Pile H was severely damaged. Cracks and splits can be seen all around the perimeter of the pile. The right end was the area that was most severely damaged. The stress waves recorded from the middle to the right end were difficult to record. Perpendicular strikes to the wood were almost impossible due to the extent of the damaged on Pile H. Figure 4.34 illustrates that the highest SWTT for Pile H are in the middle of the pile. The right end also has high SWTT values even though the diameter was smallest in that region. The middle of the pile has advance decay. To the right of the advance decay seems to be early decay. The rest of the pile has moderate decay.

Figure 4.33. Photo of Pile H

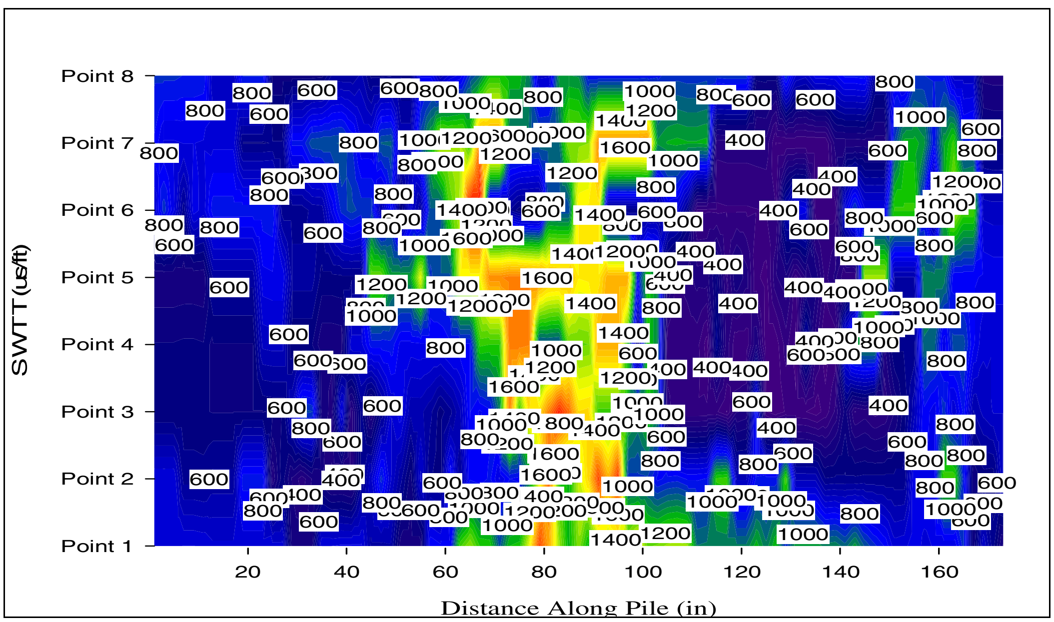

Figure 4.34. Stress Wave Transmission Time for Pile H

Figure 4.35 also illustrate that the highest SWTT of Pile H are in the middle. It is clearly seen that all of the pile has some type of decay.

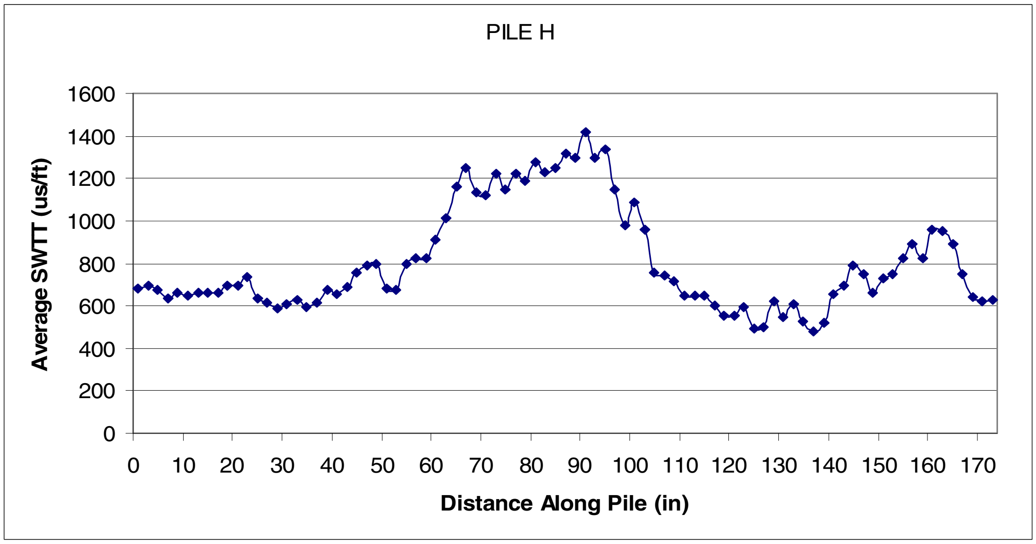

Figure 4.35. Average Stress Wave Transmission Travel Time for Pile H

Six sections were cut from Pile H with two sections being repaired. The rest of the sections are to be control specimens. Section H2 was taken from 24 inches to 48 inches. Section H6 was taken at 150 inches to 174 inches. Sections H3 and H4 were taken from 76 inches to 124 inches. The results for these four segments are in Figure 4.35. Section H5 was completely repaired. It was wrapped with fiberglass, injected with epoxy resin, and filled with an aggregate/epoxy core. Section H1 was repaired using the fiberglass wrap, and injected with epoxy resin. The results for both sections are in Figure 4.36 and Figure 4.37. All of the repaired sections from the previous piles have had the SWTT values reduced to 200µs/ft and the same goes for the two sections repaired from Pile H. The SWTT are lower for the pile with the drilled core. The reasons why the SWTT are lower were discussed earlier on page 22.

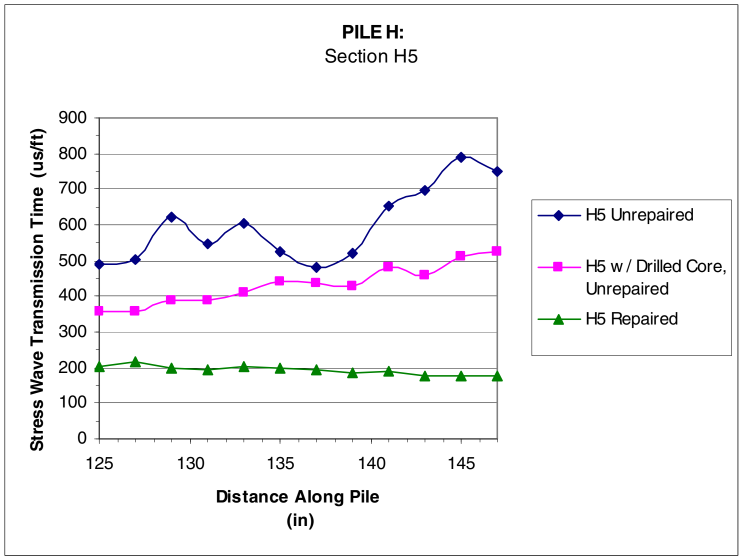

Figure 4.36. Average Stress Wave Transmission Time for Section H5

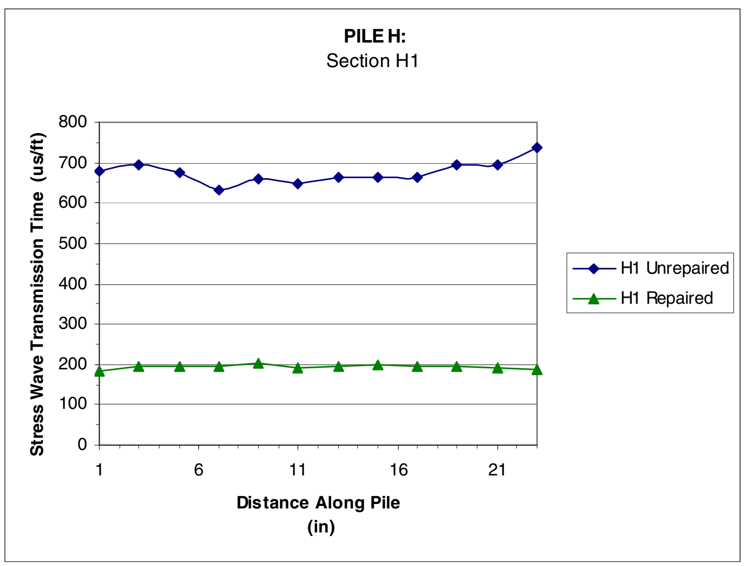

Figure 4.37. Average Stress Wave Transmission Time for Section H1

PILE I

Pile I is very similar to Pile H on the exterior. Photo of Pile I are in Figure 4.38 and in Figure 4.39. Pile I has lost a lot of its' outer shell. Figure 4.38 displays the damage the pile has endured on the left side. Even though the outer shell seems to be weak, the inner area seems well intact. The length of Pile I was the greatest at nearly 190 inches. The diameter of the pile ranges from 11.2 inches to 14.0 inches. Figure 4.40 illustrates the layout of the stress waves through Pile I. The left end of the pile has the slowest stress wave velocity and this is shown by the shades of green. The yellow/orange area has the highest values of stress waves recorded. The rest of the pile is in the blue region which signifies early decay.

Figure 4.38. End View of Pile I

Figure 4.39. Photos of Pile I

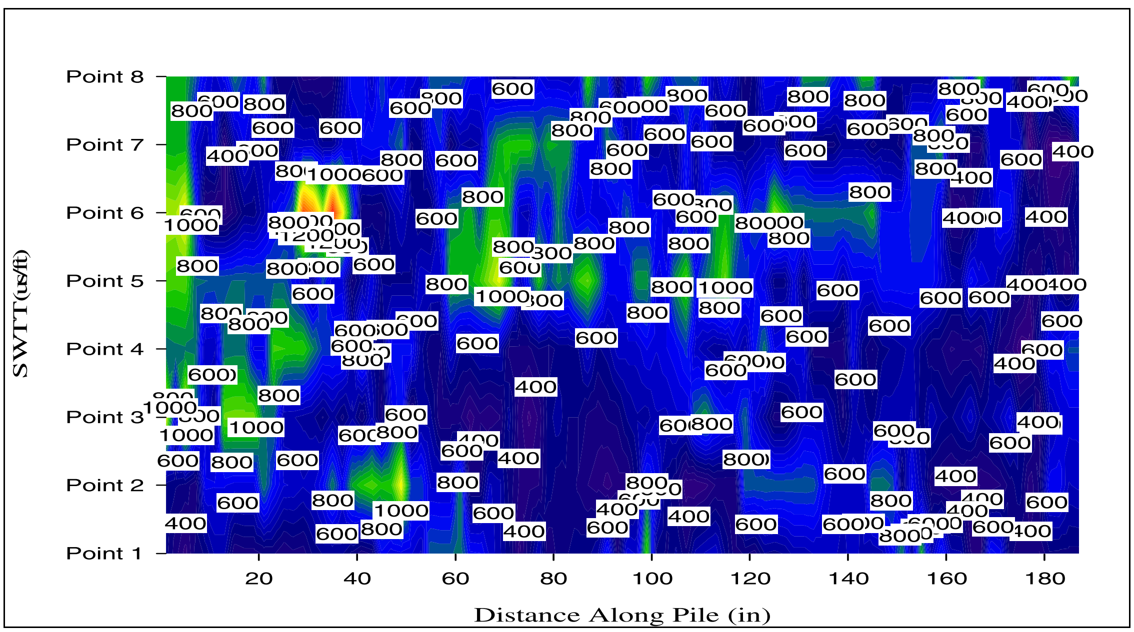

Figure 4.40. Stress Wave Transmission Time for Pile I

If a trend line is to be placed in Figure 4.41, it would approximately be between 600-700µs/ft. These are the values for moderate decay. The whole pile is above the sound wood criteria of 200-400µs/ft.

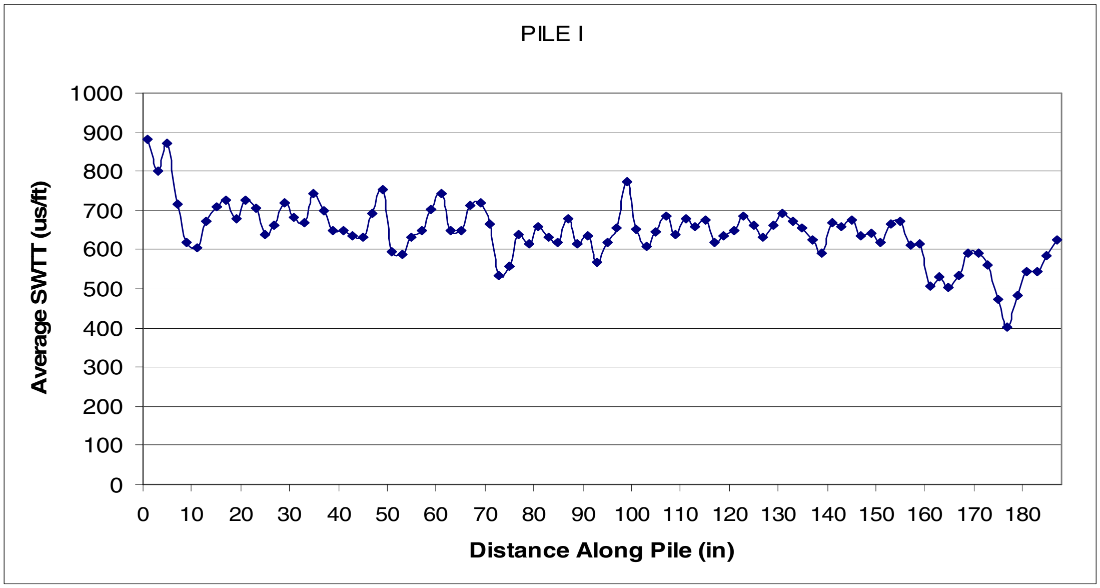

Figure 4.41. Average Stress Wave Transmission Time for Pile I

Six sections were taken from Pile I. Results for sections I1, I3, I4, and I5 can be seen in Figure 4.41. Section I1 was taken at 0 to 24 inches. Sections I3 and I4 were taken at 62 inches to 110 inches. Section I5 was taken from Pile I at 163 inches to 187 inches. Two sections were repaired from Pile I. Section I2 was repaired with fiberglass, epoxy resin and the core made up of aggregate/epoxy. Section I6 was repaired with fiberglass and epoxy resin. All of the sections repaired in this research as well as sections I2 and I6 have had the stress waves reduced to 200µs/ft. By reducing the stress wave time the velocity has been increased suggesting an increase of strength. Sections I2 with the hollow core, the SWTT are lower. The reasons why the SWTT are lower were discussed earlier on page 22.

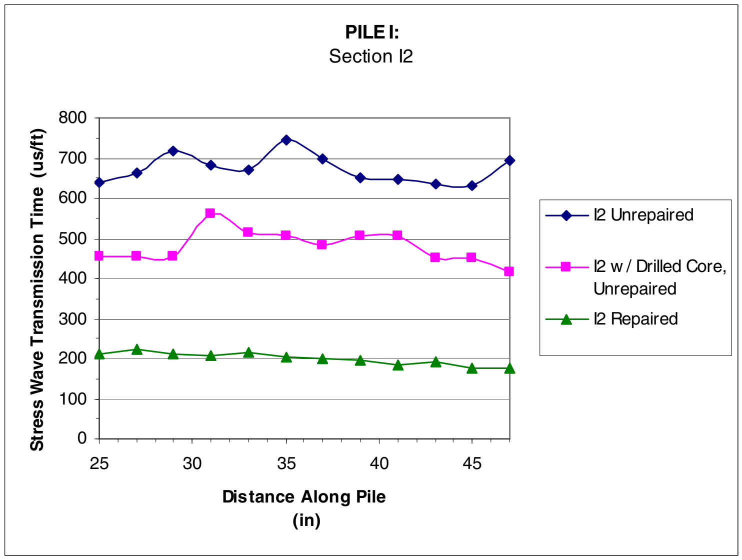

Figure 4.42. Average Stress Wave Transmission Time for Section I2

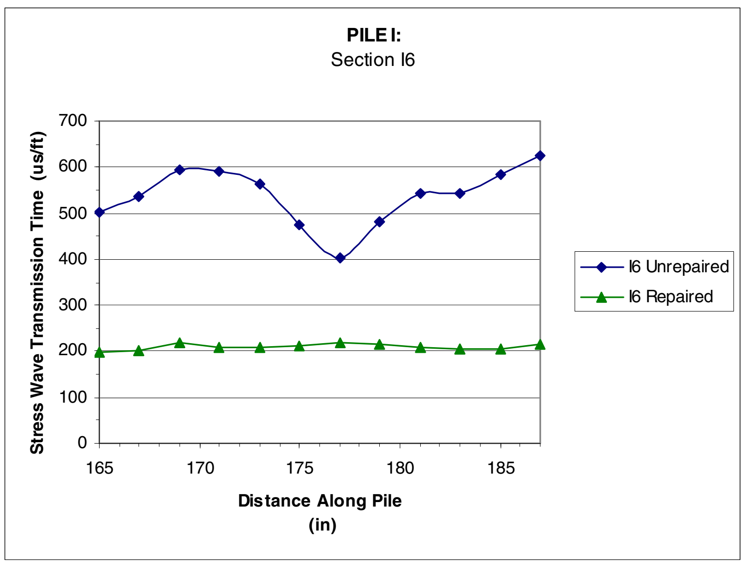

Figure 4.43. Average Stress Wave Transmission Time for Section I6

CORRELATION BETWEEN STRESS WAVE VELOCITY & REPAIR MATERIAL

One of the major objectives of this research was to correlate the nondestructive inspection to the quantity of repair materials. Regression analyses were performed to investigate how well the stress wave velocity (SWV) was correlated to the repair materials. To assess the correlation of the data, results from the SWV and repair material quantities were input into graphing program, SigmaPlot 10. Correlation coefficients, R^2, were calculated using Regression Wizard in SigmaPlot 10. The correlation coefficient measures how well a regression model describes the data. The closer R^2 is to 1.0 the better the regression model fits the data. There are various regression models including, but not limited to polynomial, three-dimensional, hyperbola, and exponential growth. Two types of regression models were chosen to evaluate the data. The first regression model performed was a simple linear regression model, and the second regression model performed was a three-dimension, plane regression model. These two regression models were simple and effective to evaluate the data. The two regression models were chosen since they were similar to regression analyses documented by Emerson (1999). Emerson conducted nondestructive evaluation on timber bridges for identifying decay. He correlated decay and NDE with two types of regression models which were simple and multi linear regression models.

SIMPLE LINEAR REGRESSION

Simple linear regressions were performed between the repair materials and average SWV of the unrepaired piles. To perform a simple linear regression model, two variables are required: (1) dependent predicted variables and (2) independent predictor variables. The repair materials were used as the dependent predicted variables. The average SWV or pile dimensions were used as the independent predictor variables. The two variables are needed to predict correlation coefficients. Simple linear regressions were performed with six sets of data. The six sets of data were used to create five linear regression models. The six sets of data used in the regression models are surface area, pile volume, average SWV, fiberglass length, Sikadur 30 and Pro-Poxy 100 LV.

The first linear regression model created was Sikadur 30 versus average SWV. The faster the stress wave velocity, the sounder the wood. It is expected that as velocity increases the amount of repair material decreases. This was true for Sikadur 30 versus stress wave velocity. Results for Sikadur 30 versus average SWV are in Figure 4.44.

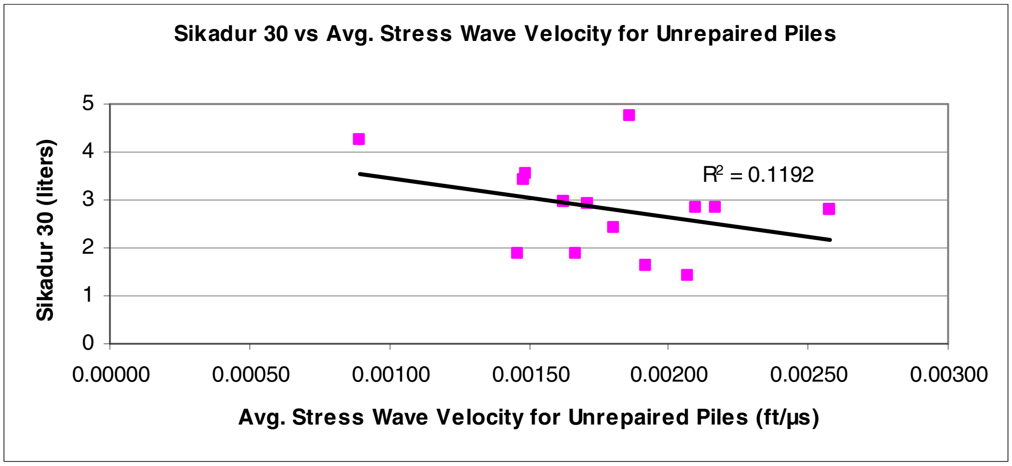

Figure 4.44. Relationship Between Sikadur 30 & Avg. Stress Wave Velocity

It is seen in the figure above as the SWV increases the amount of Sikadur 30 decreases. This was expected since the piles with higher velocities are expected to have less decay, splits, voids and cracks than the piles with slower velocities. The correlation coefficient in Figure 4.44 is 0.1192, indicating a low correlation between Sikadur 30 and SWV. Therefore, the regression model does not represent the data well.

The Pro-Poxy 100 LV versus SWV also resulted in what was expected; as the SWV velocity increases, the amount of Pro-Poxy decreases. Results of Pro-Poxy 100 LV versus SWV are in Figure 4.45. Once again the correlation coefficient is low in the figure, signifying a low correlation between Pro-Poxy and SWV. R^2 equals zero when the values of the independent variables do not allow any prediction of the dependent variables.

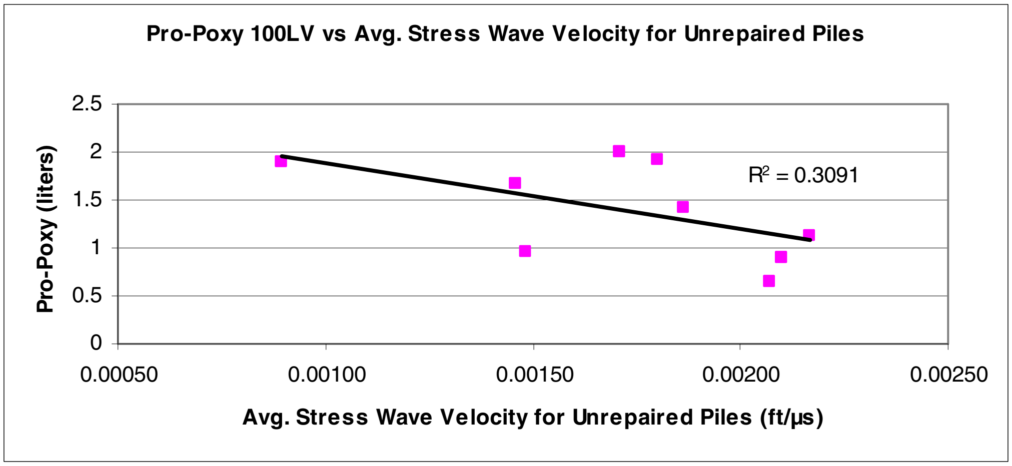

Figure 4.45. Relationship Between Pro-Poxy 100 LV & Avg. SWV

The next couple of figures correlate repair materials with pile dimensions. The relationship between Pro-Poxy and Pile Volume is in Figure 4.46. The relationship between Sikadur 30 and Surface Area is in Figure 4.47. It was expected that as pile dimensions increase the amount of Sikadur 30 and Pro-Poxy increase. The results are contrary of what was expected, because the repair material is decreasing as pile dimensions increase. The figures show linear regression lines decreasing. The reason may be that the piles that had the least amounts of volume and surface area were the piles that were damaged the most and have the lowest stress wave velocities. Since the smaller diameter piles contained damage a greater amount of repair material was needed. The piles that were not severely damaged had the least amount of repair materials. The correlation coefficients for Figure 4.46 and Figure 4.47 are 0.0137 and 0.0100 showing little correlation between repair materials and pile dimensions.

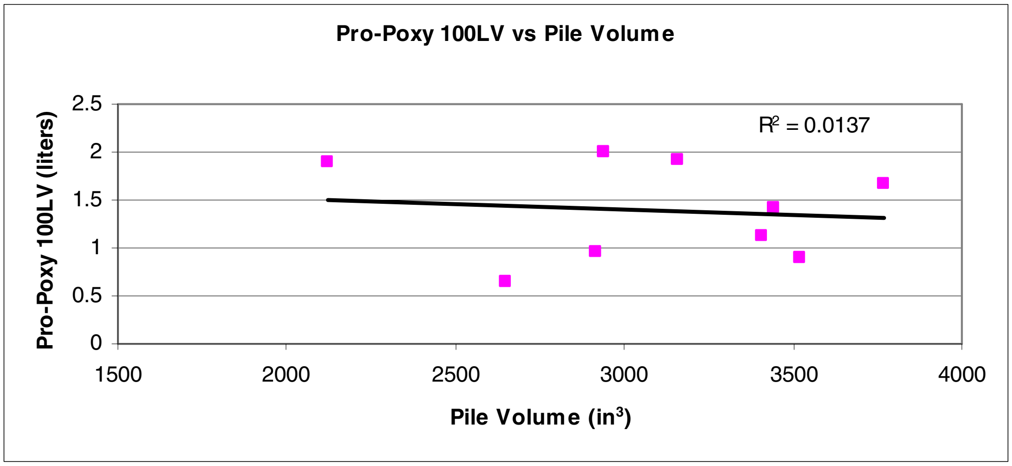

Figure 4.46. Relationship Between Pro-Poxy & Pile Volume

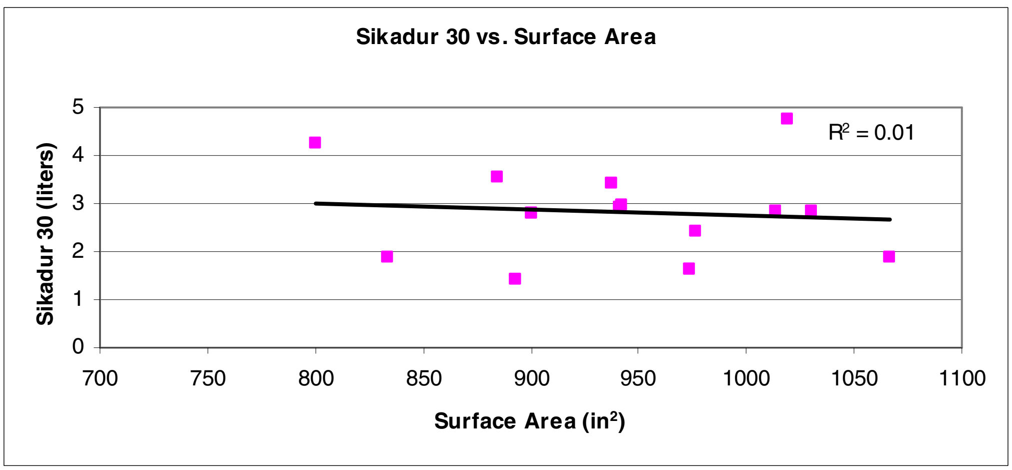

Figure 4.47. Relationship Between Sikadur 30 & Surface Area

The final simple linear regression model created was between fiberglass length and surface area. The fiberglass is directly proportional to the surface area so it is expected and known that as surface area increases the length of the fiberglass wrap increases. Figure 4.48 has the highest correlation of all the simple linear regression models created.

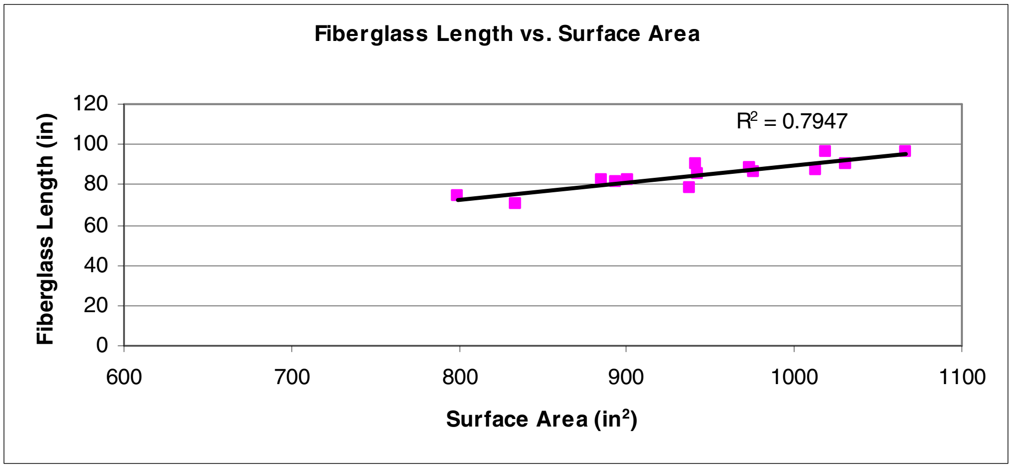

Figure 4.48. Fiberglass Length vs. Surface Area

All of the simple linear regression models did not accurately correlate the repair material and stress wave velocity with the exception of fiberglass length versus surface area. A three-dimensional regression model is performed between SWV and repair materials in the next section to establish better correlations.

3-D, PLANE REGRESSION MODEL

All of the simple linear regression models created in the preceding section gave low correlations with one exception, fiberglass length versus surface area. To find better correlations 3-D, plane regression models were created. Three-dimension, plane regression models were performed between the repair materials and both the average SWV of the deteriorated and repaired piles. To perform a 3-D, plane regression model, three variables are required: one dependent predicted variable, and two independent predictor variables. The repair materials were used as the dependent predicted variables. The stress wave velocities and pile dimensions were used as the independent predictor variables. The variables were chosen from ten sets of data. The ten sets of data used in the regression models are highlighted in Table 4.1 and Table 4.2. The other remaining sets of data in Table 4.1 were not chosen to establish correlations since the data can be easily calculated with simple measurements in the field.

Table 4.1. Variables for 3-D, Plane Regression Model

	Piles	Sikadur 30 Sikadur A/B 3:1 Epoxy Paste (liters)	SikaWrap HEX 100G Fiberglass Length (inches)	Sikadur 300 A/B Sikadur A/B 1:1 Epoxy (liters)	Pro-Poxy 100 LV Sikadur A/B 2:1 (liters)	PeaGravel #6 Aggregate (oz)	Surface Area (in^2)	Pile Volume (in^3)
Piles w/ Drilled Core	A1	1.61	88	1.18	4.39	152	974	3145
	B2	2.78	82	1.06	4.54	152	900	2688
	E1	2.95	85	1.18	3.79	152	942	2945
	H5	1.89	70	1.01	2.93	152	834	2305
	I2	3.53	82	1.18	3.29	152	885	2595
Piles Fully Intact	A3	2.84	90	1.18	0.89	-	1030	3521
	B1	1.42	81	1.48	0.65	-	893	2647
	C2	2.43	86	1.42	1.92	-	976	3161
	D2	4.26	74	1.42	1.89	-	800	2121
	E3	2.84	87	1.12	1.12	-	1013	3406
	F3	1.89	96	1.24	1.66	-	1066	3770
	G1	2.9	90	1.42	2.00	-	941	2937
	H1	3.43	78	1.06	0.95	-	937	2914
	I6	4.73	96	1.12	1.42	-	1019	3444

Table 4.2. Variable for 3-D, Plane Regression Model Continued

	Piles	Avg. SW (µs)	Avg. SWV for Unrepaired Piles (ft/µs)	Avg. SWV for Unrepaired Piles w/ Hollow Core (ft/µs)	Avg. SWV for Unrepaired Piles, Combined (ft/µs)	Avg. SWV for Repaired Piles w/o Agg/Epx Core (ft/µs)	Avg. SWV for Repaired Piles w/ Agg/Epx Core (ft/µs)	Avg. SWV for Repaired Piles, Combined (ft/µs)
Piles w/ Drilled Core	A1	561	0.00192	0.00187	0.00187	-	0.00558	0.00558
	B2	386	0.00258	0.00204	0.00204	-	0.00548	0.00548
	E1	643	0.00162	0.00222	0.00222	-	0.00520	0.00520
	H5	551	0.00167	0.00190	0.00190	-	0.00517	0.00517
	I2	658	0.00149	0.00241	0.00241	-	0.00501	0.00501
Piles Fully Intact	A3	543	0.00210	-	0.00210	0.00491	-	0.00491
	B1	478	0.00207	-	0.00207	0.00523	-	0.00523
	C2	599	0.00180	-	0.00180	0.00491	-	0.00491
	D2	985	0.00090	-	0.00090	0.00529	-	0.00529
	E3	517	0.00217	-	0.00217	0.00488	-	0.00488
	F3	807	0.00146	-	0.00146	0.00509	-	0.00509
	G1	609	0.00171	-	0.00171	0.00474	-	0.00474
	H1	700	0.00148	-	0.00148	0.00516	-	0.00516
	I6	604	0.00186	-	0.00186	0.00478	-	0.00478

The variables from the ten sets of data were used interchangeably to create correlations between the data. The correlation coefficient, R^2, was calculated to see which combinations had the best correlations. The best correlation coefficients where then used to develop equations to predict the dependent variables. Table 4.3 list some of the correlation coefficients calculated using the 3-D, plane regression model. The rest of the correlations can be seen in APPENDIX B. The table lists the correlations coefficients in descending order.

Table 4.3. Combination of Variables Using Average SWV for Unrepaired Piles

x (independent variable)	y (independent variable)	z (dependent variable)	R^2
Avg. SWV for Unrepaired Piles	Surface Area	Pro-Poxy 100 LV of Piles w Agg/Epx core	0.993
Avg. SWV for Unrepaired Piles	Pile Volume	Pro-Poxy 100 LV of Piles w Agg/Epx core	0.991
Avg. SWV for Unrepaired Piles w/ hollow core	Pile Volume	Sikadur 30	0.921
Avg. SWV for Unrepaired Piles w/ hollow core	Surface Area	Sikadur 30	0.920
Avg. SWV for Unrepaired Piles, Combined	Pile Volume	Pro-Poxy 100 LV of Piles w Agg/Epx core	0.572
Pile Volume	Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100 LV of Piles w Agg/Epx core	0.572
Pile Volume	Avg. SWV for Unrepaired Piles	Pro-Poxy 100 LV of Piles w/o Agg/Epx core	0.354
Avg. SWV for Unrepaired Piles	Surface Area	Sikadur 30	0.097
Avg. SWV for Unrepaired Piles, Combined	Surface Area	Sikadur 30	0.046

The previous table shows several results of the best and worst correlations found between the stress wave velocity, pile dimensions and repair material quantities. The first four combinations of variables in Table 4.3 have the highest R^2. R^2 ranges from 0.920 to 0.993. The correlations are found using the average stress wave velocities of the unrepaired piles. The best predicted repair materials are Pro-Poxy 100 LV and Sikadur 30. These two dependent variables have correlation coefficients, R^2, close to the value one. R^2 equals one when the regression model accounts for 100 percent of the variability of the dependent predicted variable.

The highest correlations from Table 4.3 are expressed in terms of equations in Table 4.4. A three-dimension, plane regression equation is in the table below. The table has values of parameters used to predict the amount repair material for deteriorated piles. In the equation there are two independent variables (*x* and *y*), and three constants (*a*, *b*, and z_o). The variables are used to estimate the dependent variable *z*. Since the equation below can be used to predict the quantity of repair materials it can be used to double check the results obtained in Table 4.1 and Table 4.2.

Table 4.4. Parameter Values to Predict Dependent Variables

$z = z_o + ax + by$

z (dependent variable) (liters or μs)	z_o	a	x (independent variable) (μs or liters)	b	y (independent variable) (in^2, in^3, liters, or μs)
Pro-Poxy 100 LV of Piles w Agg/Epx core	-5.643	1089	Avg. SWV for Unrepaired Piles	0.0082	Surface Area
Pro-Poxy 100 LV of Piles w Agg/Epx core	-1.958	1096	Avg. SWV for Unrepaired Piles	0.0014	Pile Volume
Sikadur 30	-3.749	3269	Avg. SWV for Unrepaired Piles w/ hollow core	-0.0002	Pile Volume
Sikadur 30	-3.241	3302	Avg. SWV for Unrepaired Piles w/ hollow core	-0.0012	Surface Area

The only other repair quantity that is important to calculate that is not in Table 4.4 is the Pro-Poxy 100 LV for the piles without an aggregate/epoxy core. The correlation coefficient was low for all combinations that included Pro-Poxy 100 LV without the aggregate/epoxy core. An average for all the piles was estimated on how much Pro-Poxy

100 LV would go in a timber pile for a two foot section. Since the volume of the drilled core in the pile is known as well as the amount of aggregate that went into the core, one can calculate the amount of epoxy resin in the core. The amount of epoxy resin in the core then can be subtracted from the overall amount of Pro-Poxy 100 LV that went into the pile. This result is the amount of Pro-Poxy 100 LV that is in the pile not including the epoxy resin in the aggregate/epoxy core. By knowing this result, the amount of Pro-Poxy 100 LV was averaged for all the piles and it came out to be approximately 1.62 liters for every two-foot section. The standard deviation was equal to 0.64 liters; therefore, the Pro-Poxy 100 LV ranges from 1.0 liter to 2.25 liters for every two-foot segment for deteriorated piles. The results of the amount of Pro-Poxy 100 LV not including the aggregate core can be seen in APPENDIX A.

CHAPTER 5

INSPECTION OF REPAIRED TIMBER PILES IN-SERVICE USING STRESS WAVE TIMING

INTRODUCTION

Stress Wave Timing was employed in a field study of repaired timber piles in Cotton County, Oklahoma. The repair method was to improve the strength of the timber piles. To do this the decayed was drilled out, replaced with aggregate and injected with epoxy. The timber piles were then wrapped with fiber reinforcement. Eleven of the twelve piles supporting the state highway bridge were repaired. The nondestructive evaluation of the timber piles was to observe if the repair technique was adequate and to locate any flaws throughout the piles.

DATA COLLECTION

Data was collected for twelve piles in the form of stress wave times. Piles on the west end of the bridge are designated as piles W1-W6, while piles on the east end of the bridge are designated as piles E1-E6 (see Figure 5.1).

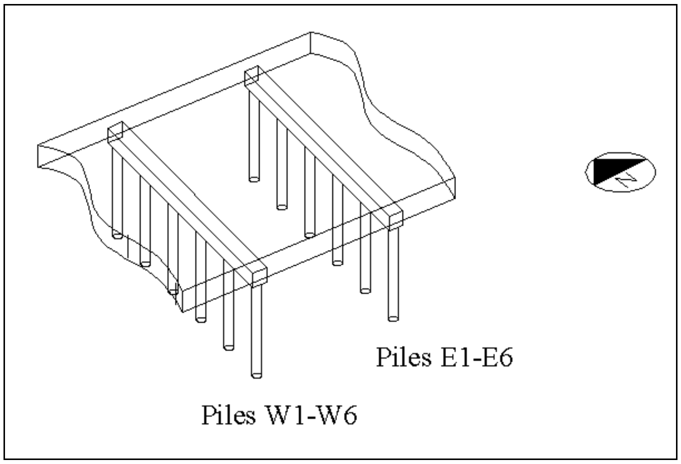

Figure 5.1. Pile Layout

Data points were taken on each pile at every half foot (six inches) vertically. Two points were taken at each level as shown in Figure 5.2; one in the north-south direction and one in the east-west direction.

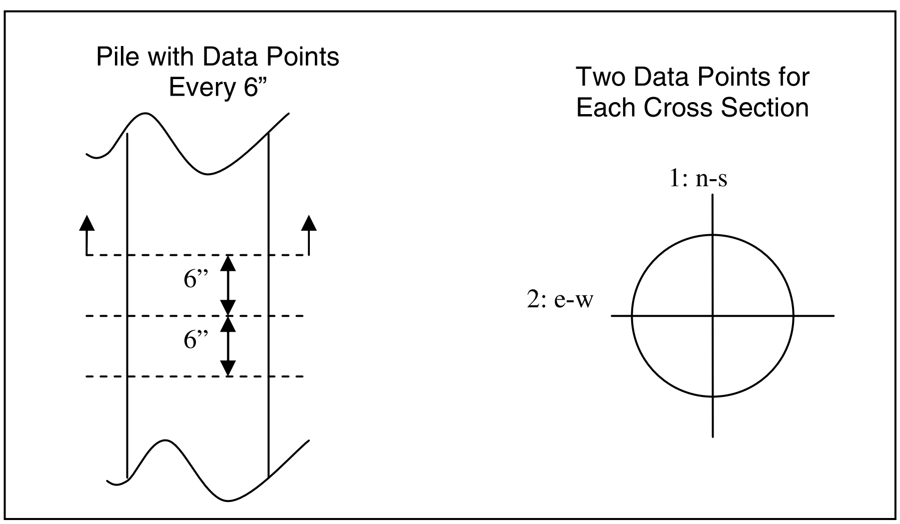

Figure 5.2. Two Data Points Every Six Inches Along Pile

The two values were averaged for each cross section. (At some cross sections, bracing prevented a data reading in one direction. For these locations, the one stress wave time obtained is used as the average value.) The data points were taken at every six inches, but the circumference were measured at every foot. Interpolation was then used to obtain the circumference for the points that were not measured on the piles. The circumference was used to calculate the pile diameter, which was then used in determination of the stress wave velocity.

To record stress wave times, a hammer with a built-in accelerometer is used to strike the pile and induce a stress wave. Upon impact, a start signal is sent to a timer. The stress wave propagates through the pile until it contacts a second accelerometer on the opposite side of the pile, at which point a stop signal is sent to the timer. The elapsed time is the stress wave time, and the known distance (the pile diameter) is used to calculate the stress wave velocity. The procedure and apparatus are shown in Figure 5.3 (note the two accelerometers; one in the form of a hammer and one in the form of a receiver pressed to the pile). Data plots for each pile are provided in the following pages. Complete data tables can be found in APPENDIX C.

Figure 5.3. Accelerometers Used in Stress Wave Timing

DATA PLOTS AND COMMENTS

The east-west and north-south stress wave velocities were averaged for each cross section on each pile. Average velocities (average being the "average of averages;" it is the average of all resulting north-south/east-west averages for the pile) and standard deviations for each pile are gathered in the table below, while full plots for each pile are presented on the following pages. The results are plotted on the following pages. Two vertical lines in each plot represent the upper and lower bounds for stress wave velocities that can be expected in sound Douglas-fir at a moisture content of 12%, according to Rutherford 1987, as printed in Ross, et al. Although moisture content was not measured in the tested piles, the bounds provided by Rutherford should provide a reasonable estimate for how the tested piles compare to sound wood. The lower bound is 0.036 in/μs, and the upper bound is 0.063 in/μs. The third vertical line in each plot represents the average of the values plotted for that pile.

Table 5.1. Data Summary

Pile	Avg. Velocity (in/μs)	Std. Dev. (in/μs)	Lower Bound for Sound Wood (in/μs)	Upper Bound for Sound Wood (in/μs)
W1	0.062	0.0071	0.036	0.063
W2	0.066	0.0061	‘’	‘’
W3	0.067	0.0054	‘’	‘’
W4	0.035	0.0055	‘’	‘’
W5	0.058	0.0037	‘’	‘’
W6	0.069	0.0046	‘’	‘’
E1	0.060	0.0065	‘’	‘’
E2	0.055	0.0123	‘’	‘’
E3	0.061	0.0058	‘’	‘’
E4	0.060	0.0045	‘’	‘’
E5	0.055	0.0070	‘’	‘’
E6	0.059	0.0050	‘’	‘’

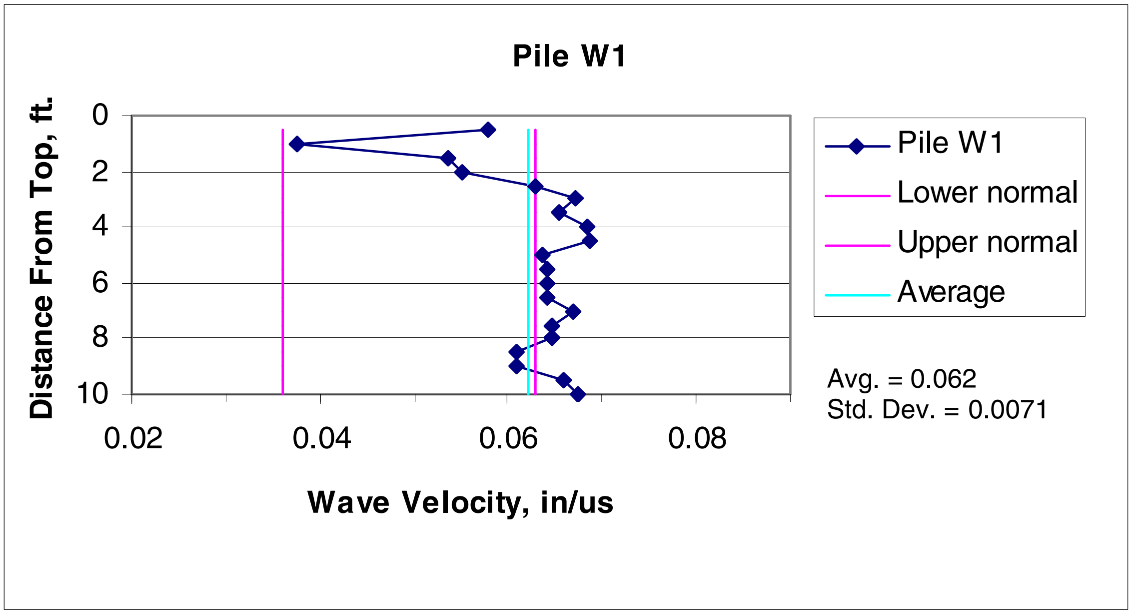

Figure 5.4. Stress Wave Velocity through Timber Pile, W1

Pile W1 appears to be in good shape. The average recorded wave velocity is right at the upper bound for sound wood. If the standard deviation is subtracted from the lowest plotted velocity (at 1' from the top of the pile), the result falls below the lower bounds of normal sound wood (0.037- 0.0071 = 0.0299). However, this point appears to be an anomaly. It was taken where bracing is present, so only the north-south reading was taken. Even though access remained to the east-west data point, the brace made it awkward to take the data reading and human error may have been introduced.

Even if the extreme nature of the velocity at 1ft. is ignored, the top two feet of the pile have generally lower velocities. These lower velocities may indicate a higher degree of wood deterioration. This may be a result of long-term exposure moisture that has permeated the bridge deck. Since the velocity at 1ft. does not appear to be valid, there are no apparent problems in pile W1.

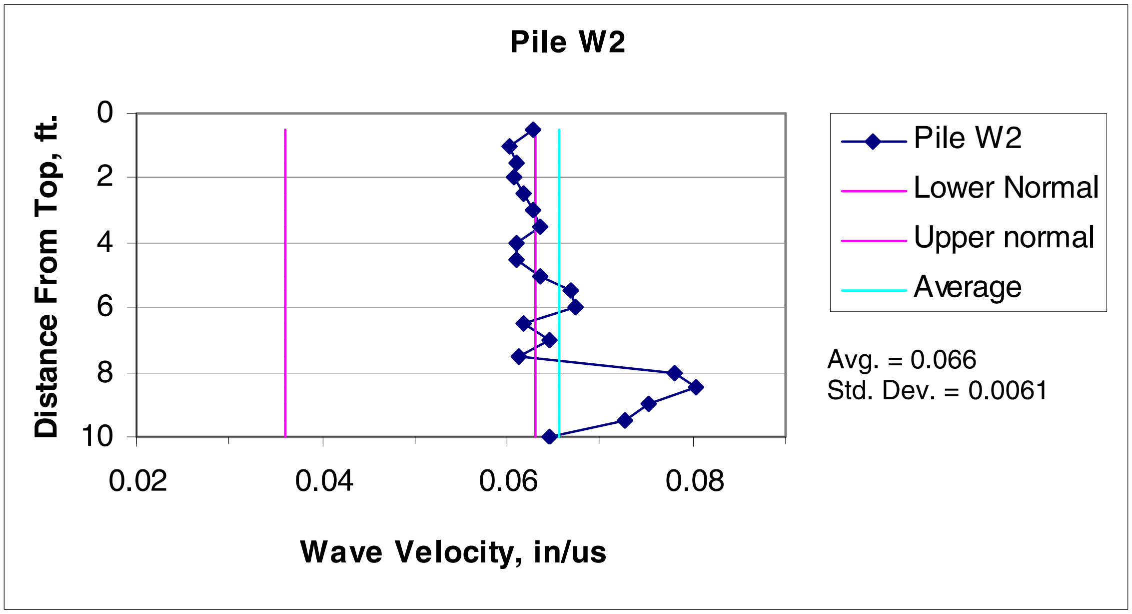

Figure 5.5. Stress Wave Velocity through Timber Pile, W2

Pile W2 appears to be in good condition as well. The average velocity for pile W2 and many of the individual plotted velocities are above the normal upper bound for sound Douglas-fir. If the standard deviation is subtracted from the lowest value (at 1ft. from the top of the pile, the result is still well within the bounds of normal sound wood (0.060-0.0061 = 0.0539).

Velocities indicate that an area about 1.5ft. long near the bottom of the pile is significantly denser than the rest of the pile. The bottom of the pile could have high long-term moisture exposure through ground contact, which should lead to greater deterioration and decreased density. This may indeed have been the case--if this area of the pile had advanced deterioration, much of it would have been drilled out and replaced with epoxy during the repair operation. If the majority of the cross section now consists of epoxy and aggregate instead of wood, the wave velocities will indeed be higher than those expected for sound wood (Bray and Stanley, 1997). The data do not indicate any problems with pile W2.

The fact that the average velocity is higher that the upper bound expected for sound wood is somewhat surprising. Piles W3 and W6 also exhibit this behavior. This gives rise to the possibility that the sound wave could travel more quickly through the fiberglass/epoxy shell than the wooden pile. It would then be possible that the times recorded were actually the time required for the wave to pass halfway around the pile through the shell, rather than directly through the wooden pile. However, if this were the case, the average velocity should remain consistent for all repaired piles (the fiberglass shell is a more uniform material than the wooden piles; results should vary little regardless of the condition of the pile within the shell). Since the average velocity is higher than the upper bound for sound wood in only 2 of 11 repaired piles, it appears that the waves were indeed passing through the pile and not around it.

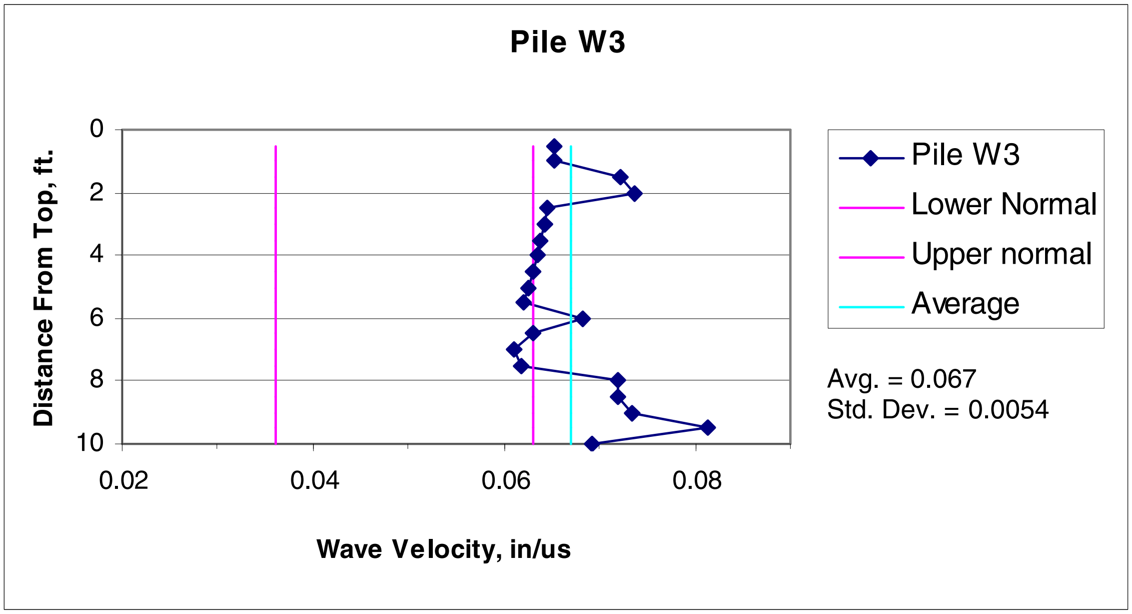

Figure 5.6. Stress Wave Velocity through Timber Pile, W3

Pile W3 is much like pile W2; the average velocity and the majority of individual velocities are actually higher than those predicted for sound wood. As with pile W2, there are localized areas of higher velocities. These areas may be the result of excessive epoxy as previously mentioned, or they could simply indicate local inconsistencies in the pile (such as large knots) which cause an increase in density. Pile W3 appears to be structurally sound.

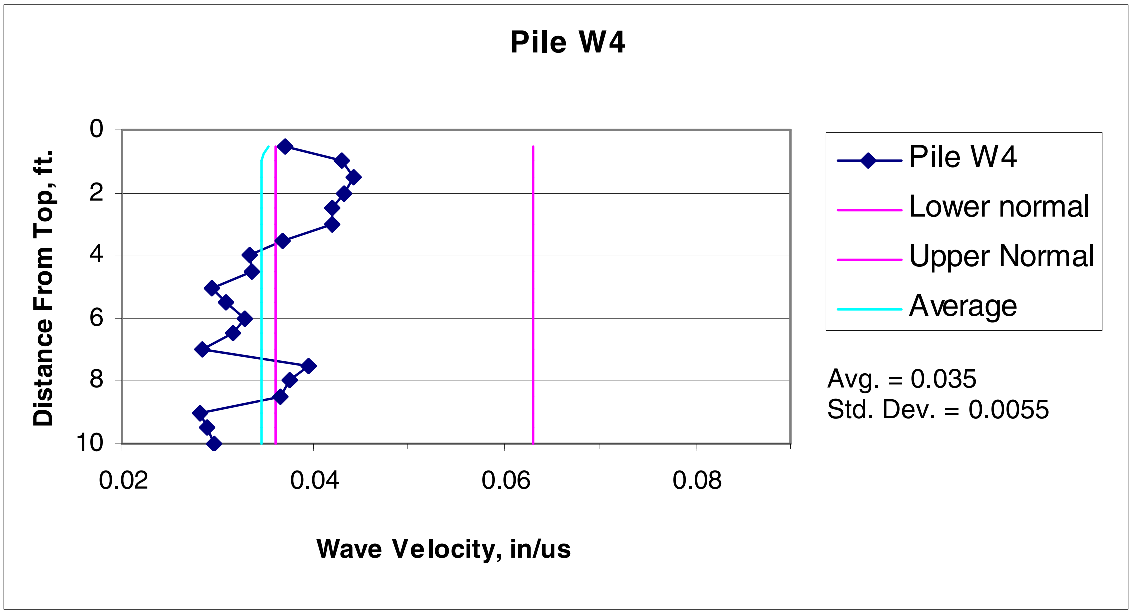

Figure 5.7. Stress Wave Velocity through Timber Pile, W4

Pile W4 was unrepaired (there was no fiberglass and epoxy wrap). The average velocity is below the lower bound for sound wood, and many individual values are well below the lower bound. Pile W4 may well be structurally deficient, and probably should be repaired just like the other eleven piles. The average velocity for the un-repaired pile is approximately half that of the repaired piles. This indicates that the repaired piles may be thoroughly saturated with epoxy, causing the majority of each repaired pile to be much denser than the aged wood present in pile W4.

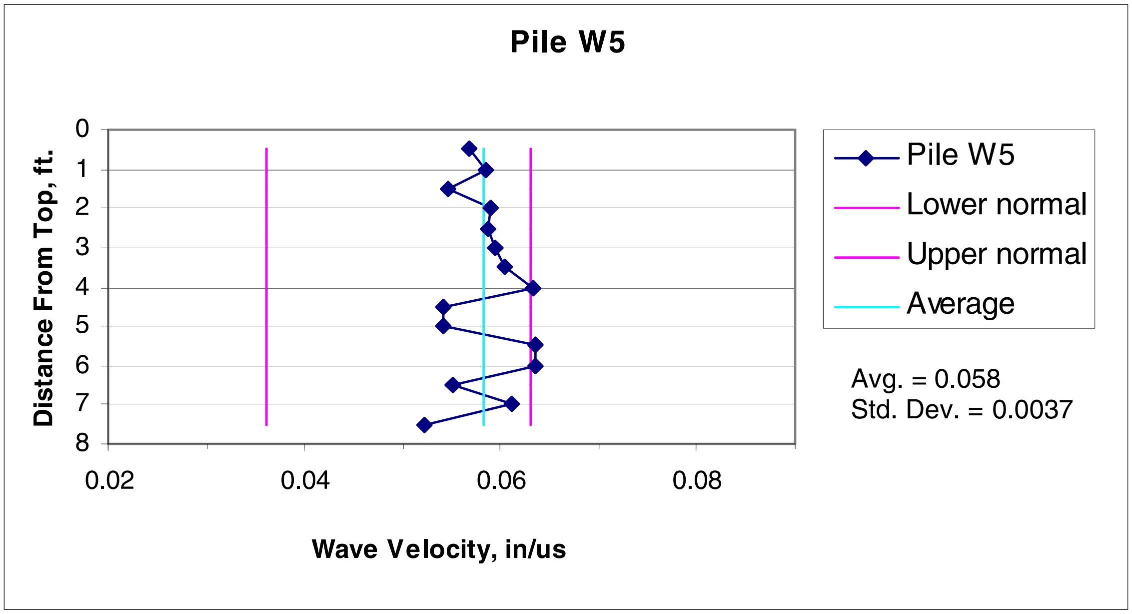

Figure 5.8. Stress Wave Velocity through Timber Pile, W5

Pile W5 yields very reasonable velocities. The average falls nicely within the bounds expected for normal sound wood. No individual velocity minus the standard deviation falls below the lower bound, so there do not appear to be any problem areas within pile W5.

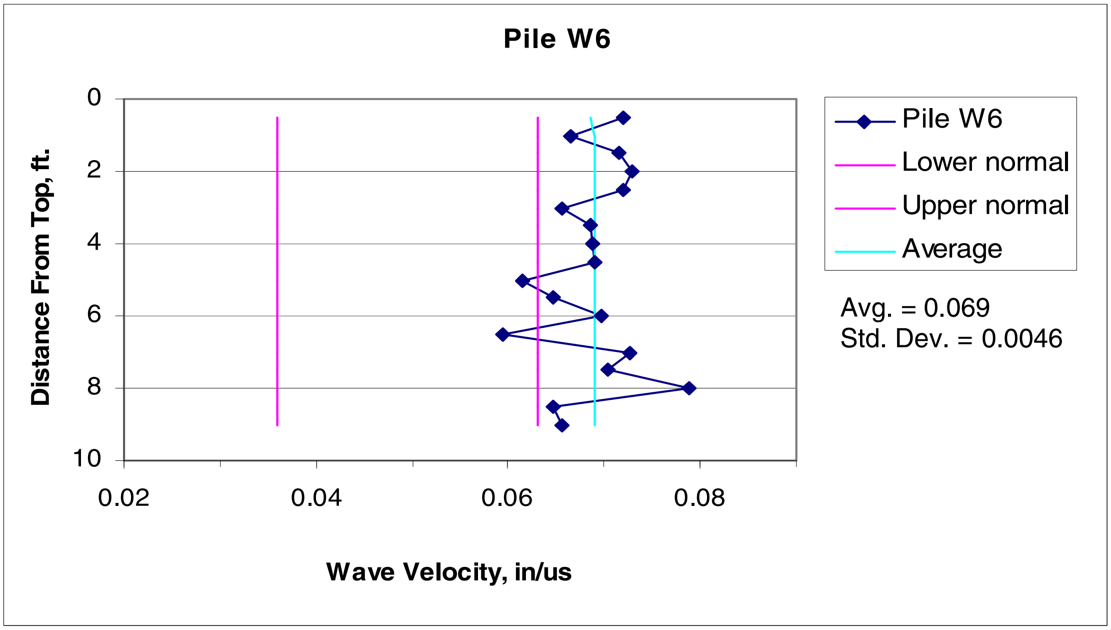

Figure 5.9. Stress Wave Velocity through Timber Pile, W6

Pile W6, like piles W2 and W3, displays an average velocity above the upper bound expected for sound wood. Only two individual values are even low enough to fall within the bounds for sound wood. Pile W6 was likely severely deteriorated before repair, and now contains large amounts of epoxy. It should currently be more than structurally adequate.

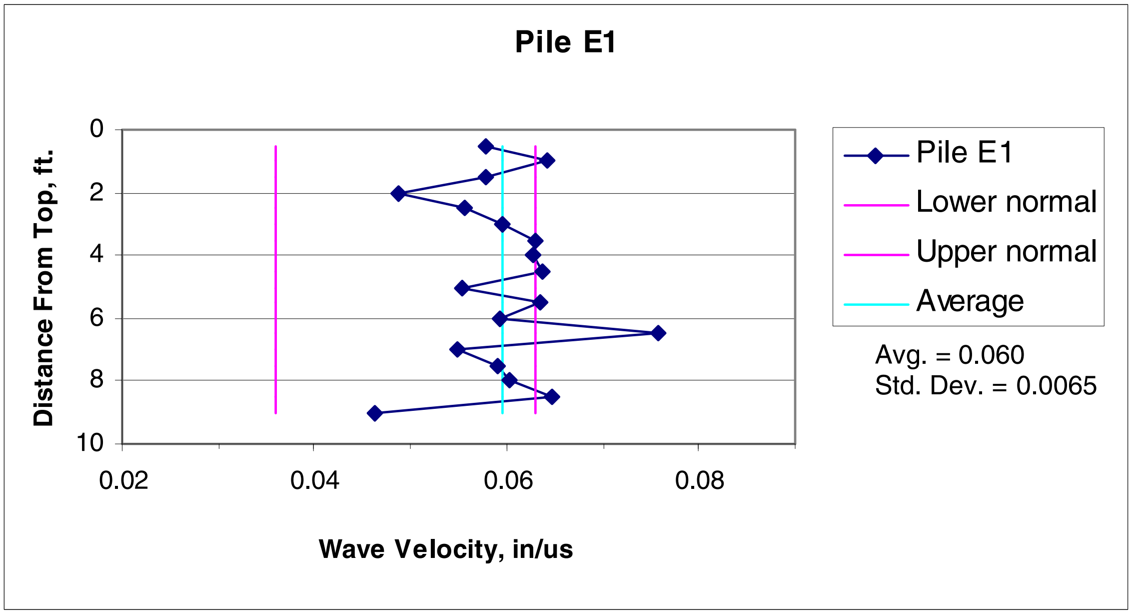

Figure 5.10. Stress Wave Velocity through Timber Pile, E1

The velocities for pile E1 appear to be widely scattered, and E1 does exhibit one of the higher standard deviations. However, the lowest velocity minus the standard deviation yields a value that still falls within the bounds for sound wood (0.046 - 0.0065 = 0.0395). The fact that the velocity at 8.5ft. from the top of the pile is so much different than the value just 0.5ft. lower suggests the possibility of an erroneous data point at 9.0ft. Otherwise, the low velocity may be a result of decayed wood that was not fixed during the repair process. The high velocity at 6.5ft. from the top is difficult to explain. However, bracing was present at 5.5ft. and 6.0ft., so the awkward access to data points in those areas could have introduced human error in the data acquisition.

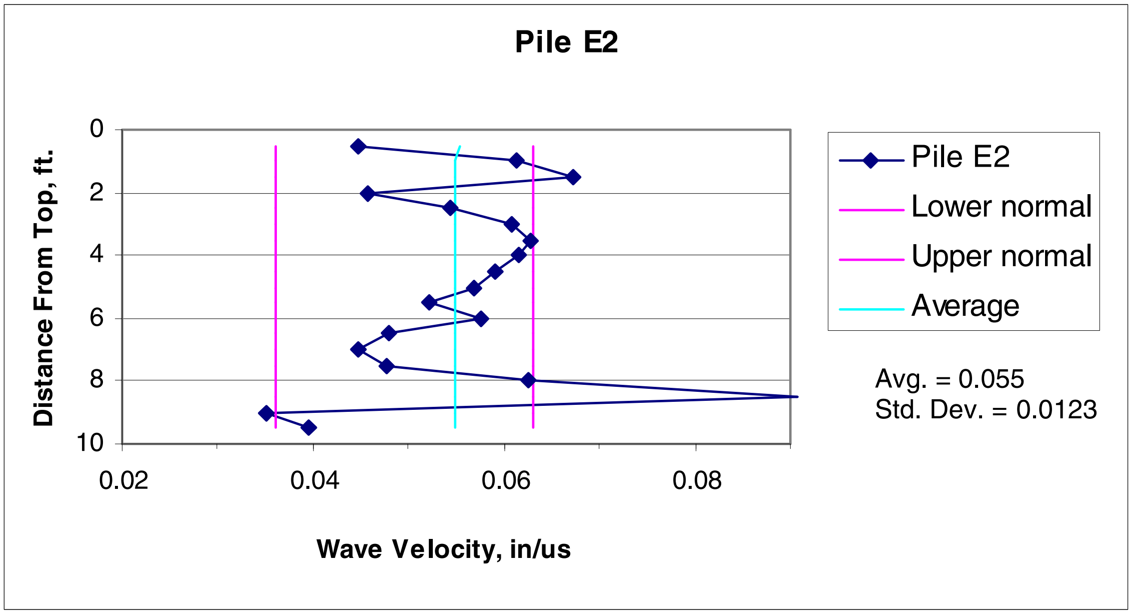

Figure 5.11. Stress Wave Velocity through Timber Pile, E2

Pile E2 shows very erratic results and has the highest standard deviation. Fluctuations in wave velocities in the top 8ft. of the pile may be a result of any previously mentioned conditions. The bottom three data points appear to be unreliable, as they contain both the highest and lowest velocities at adjacent points. The bottom three data points were also taken where bracing is present. As previously mentioned, human error is more likely near the brace points. Also, the attachment of the brace may cause fluctuations in the data. The bottom three data points are also a major cause of the high standard deviation. If these data points were excluded, the standard deviation would be 0.0074. At that standard deviation, the remaining data indicate that the pile is still sound. However, it might be advisable to re-examine this pile in the near future.

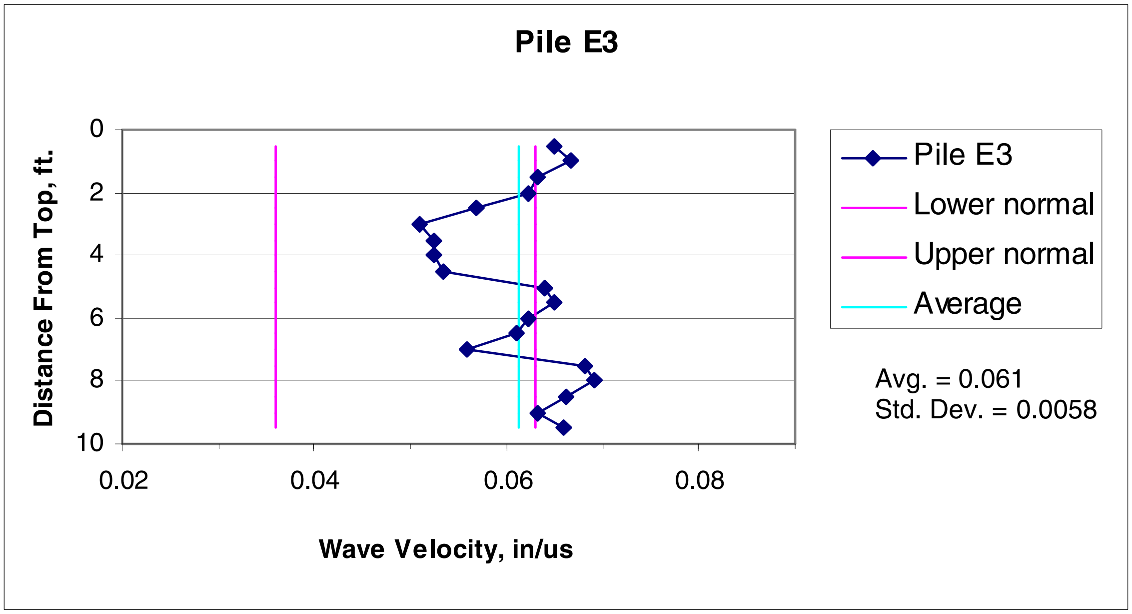

Figure 5.12. Stress Wave Velocity through Timber Pile, E3

Pile E3 also shows scattered data, but the average velocity is near the upper bound expected for sound wood. The lowest value minus the standard deviation is still within the bounds for sound wood (0.051- 0.0058 = 0.0452). This indicates that although some regions are more solid than others, there are not problem areas in pile E3.

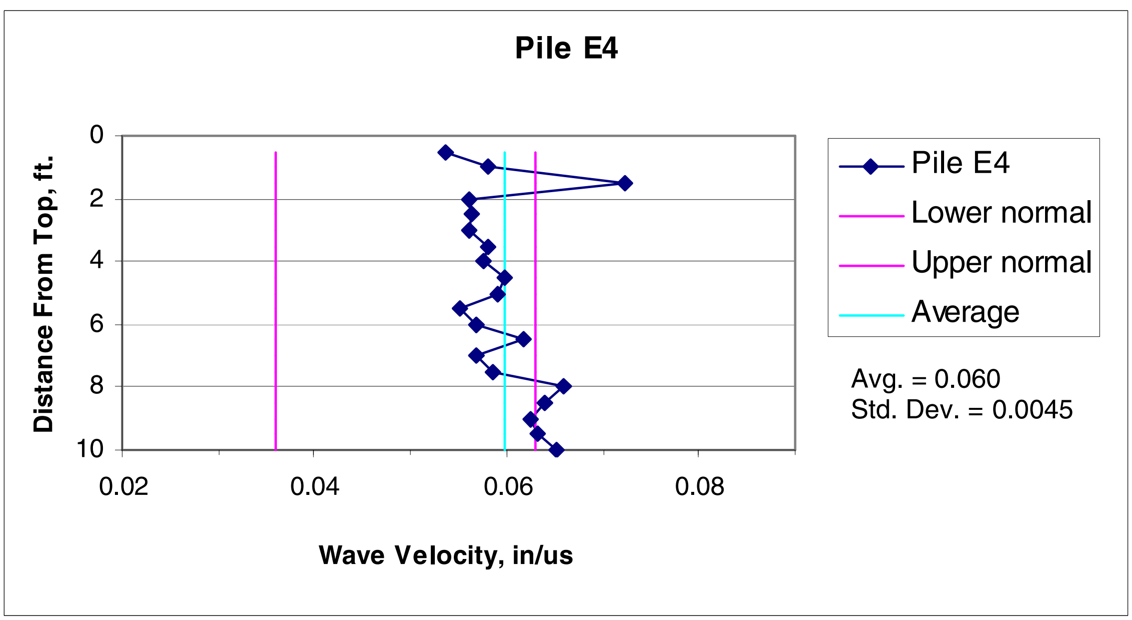

Figure 5.13. Stress Wave Velocity through Timber Pile, E4

Pile E4 exhibits relatively consistent data, with one of the lower standard deviations. Again, the average velocity is near the upper bound expected for normal sound wood. The lowest value minus the standard deviation is still well within the bounds for normal wood (0.054 - 0.0045 = 0.0495), which again indicates that there are no problem areas within pile E4. The high velocity at 1.5ft. down from the top likely indicates a locally hard area in the pile, such as a large knot in the cross section. The rest of the velocities generally tend to increase down the pile. This may indicate that the pile originally suffered from steadily worsening decay down its length. After repair, the pile contains steadily increasing epoxy content down its length which accounts for the increasing velocities.

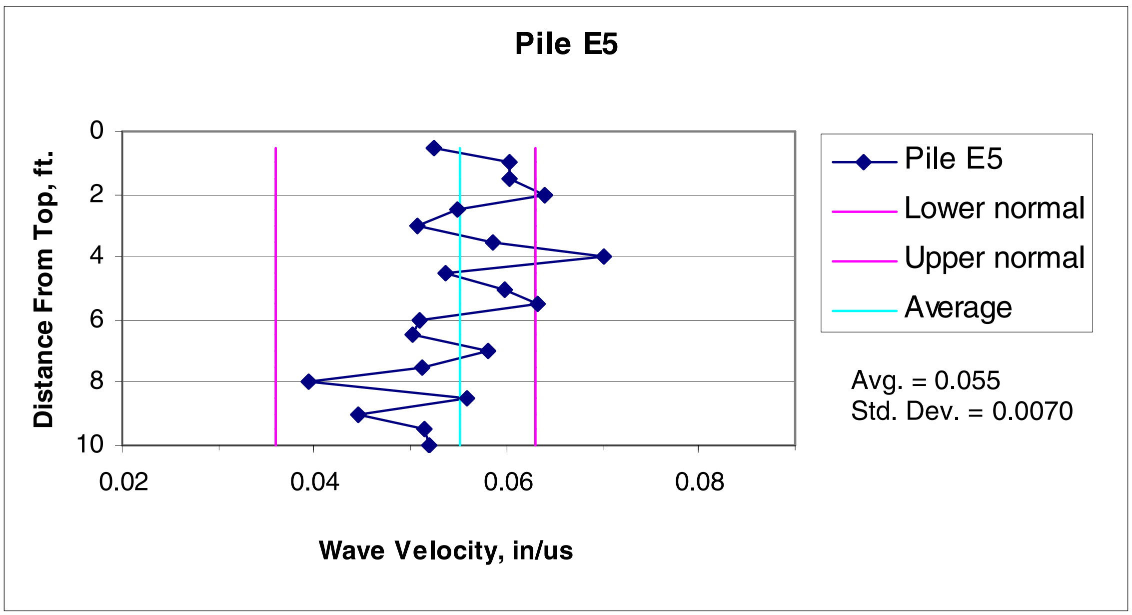

Figure 5.14. Stress Wave Velocity through Timber Pile, E5

Pile E5 exhibits widely scattered data, with one of the higher standard deviations. The average velocity falls within the bounds expected for normal sound wood, but the lowest velocity minus the standard deviation falls below the bounds for sound wood (0.039 - .0070 = 0.032). This indicates a point of concern at 8ft. down the pile. This area of the pile should probably be rechecked at regular intervals to ensure no further deterioration occurs.

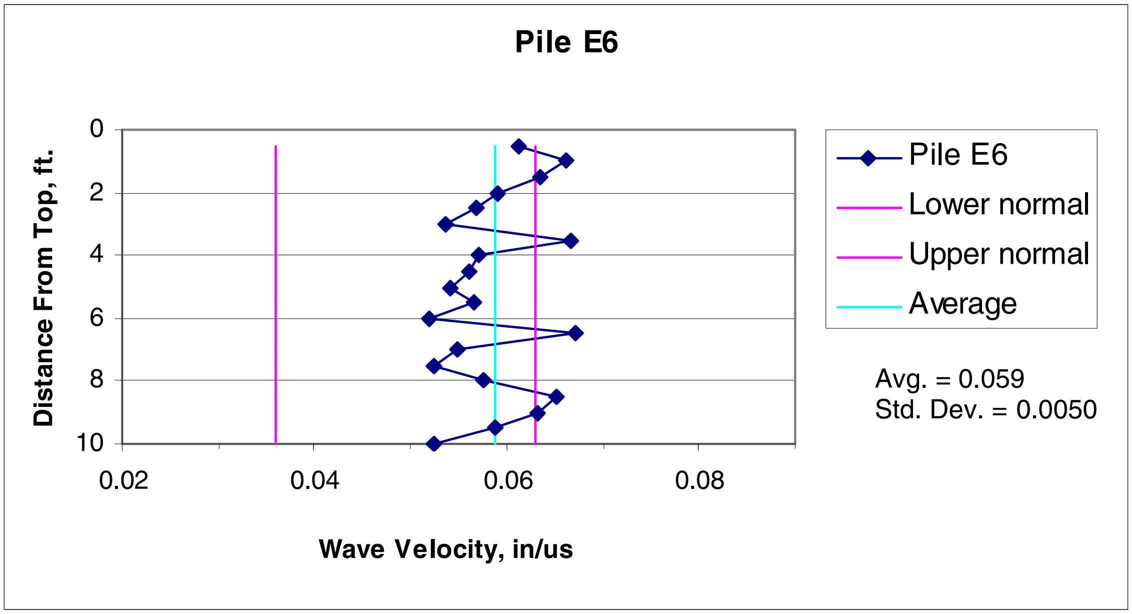

Figure 5.15. Stress Wave Velocity through Timber Pile, E6

Pile E6 is in good condition. The average velocity falls toward the high end of the range expected for normal sound wood. No individual velocities are even within one standard deviation of the lower bound. The above average velocities in the top 2ft. of the pile may well indicate wood that was still in good condition, while the trend for increasing velocity around 9ft. down likely indicates an abundance of epoxy after repair. The high velocities recorded at 3.5ft. and 6.5ft. must indicate either naturally occurring local hard spots or erroneous data.

CONCLUSION

Timber bridges are constantly exposed to various environmental conditions. As a result the timber tends to age and decay faster if not treated properly. Cotton County Bridge was repaired by replacing the decay within the piles with aggregate injected with epoxy and wrapping the circumference with fiber reinforcement. A way to monitor the repaired piles is through nondestructive evaluation using stress waves. By using stress waves one can locate any defects within the wood.

Overall, a majority of the piles gave results that concluded that the velocity through the timber piles had increased compared to published values. The increased velocity shows that the decayed wood may have been completely replaced with the aggregate core. Each pile had specific locations that produced data that was well above or below the average velocity values. Some of the piles should be re-examined for example pile W4. Pile W4, which was the only un-repaired pile has the lowest velocity. The un-repaired pile should probably be repaired before the decay progresses. Pile E2 has the greatest deviation in velocity and it may be reasonable to take further test on the pile in the near future.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

SUMMARY

Thousands of timber bridge piles support hundreds of bridges in the state of Oklahoma. Over time bridge piles become deteriorated and eventually have to be repaired or replaced. High costs spent each year on bridge foundations have resulted in development of new evaluation and repair techniques. A cost effective technique to evaluate both deteriorated and repaired timber piles is stress wave timing. Stress wave timing can be used to determine if decay is present in a timber pile. If decay is detected, stress wave timing can then be used to determine the degree of decay present in the pile. Stress wave timing can also be applied on repaired timber piles. In this study the stress wave velocity was significantly lower in the repaired piles than in the deteriorated piles.

A series of nondestructive evaluations via visual inspection and stress wave timing were carried out to develop simplistic methods for estimating repair material quantities and evaluate the effectiveness of the repair techniques. The repair materials used for the repair are cost effective and simplistic. The repair materials consist of fiberglass, epoxy resin, and if needed aggregate/epoxy cores. A destructive test was not conducted on the piles but from a previous study at OSU it was proven that the repair technique restored the compression strength of decay timber piles well beyond the design values.

Correlations were established between stress wave velocity, physical dimensions, and repair material quantities. By establishing correlations, one can estimate the amount of repair material needed for the repair. Knowing the amount of repair materials required, a simplistic and quick cost estimate can be developed.

RECOMMENDATIONS

Stress wave timing has proven from this current study and other previous studies to be an adequate tool for evaluating deteriorated and repaired timber piles. As a result of this study, several recommendations are made:

- Many of the timber bridge piles obtained for this research were greatly damaged during extraction. For future tests great care should be considered when removing piles from the field. Stress wave timing is very sensitive to the outer dimensions of the wood.
- The stress wave velocity was faster for the repaired piles than the unrepaired piles. The most common use for SWV has been to obtain the modulus of elasticity (MOE) of the wood. Faster SWV predicts the MOE and strength of the pile increases. Destructive evaluations should be applied on the test specimens to prove that the strength of the piles was increased.
- All the results for the reduced stress wave times were approximately within the same range. The fiberglass wrap and epoxy resin had the greatest effect on the stress waves. The epoxy/aggregate core had little to no effect on the stress waves. Further tests should be conducted on timber piles with an epoxy/aggregate core and no fiberglass wrap.

- Correlations were established between SWT and the materials used for repair. The correlation coefficients were lower than expected for the simple linear regression models; therefore, a 3-D, plane regression model was created. The 3-D, plane regression model was used to predict the amount of repair materials. The three-dimension, plane regression was used to create equations to determine the quantity of materials needed to repair deteriorated timber piles. It is recommended to acquire additional test specimens and perform more analyses to see if the correlation coefficients can be improved in the simple linear regression model.
- Stress wave timing conducted on Cotton County Bridge was adequate to evaluate the repaired timber piles. Some of the piles should be re-examined which are piles W4 and E2. Pile W4 was the only unrepaired pile and had the lowest stress wave velocities. The pile should be repaired before decay progresses.

CONCLUSION

A new cost effective timber pile evaluation and repair technique is being developed and improved. Stress wave timing is an ongoing research topic and has been proven to be a dependable tool for evaluating timber piles. The developed repair technique results in significantly reducing the stress wave time and restoring the strength of the deteriorated piles. Correlations were established between the stress wave times and repair materials. The equations developed from the stress wave velocity and pile dimensions are adequate to estimate the amount of materials required to repair deteriorated piles. It is concluded that stress wave timing is a simplistic and cost effective technique to evaluate deteriorated and repaired timber piles.

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APPENDIXES

APPENDIX A

REPAIR MATERIALS AND QUANTITIES

Amount of Materials Used for Repair.

	Piles	Sikadur 30 Sikadur A/B 3:1 Epoxy Paste (liters)	SikaWrap HEX 100G Fiberglass Length (inches)	Sikadur 300 A/B Sikadur A/B 1:1 Epoxy (liters)	Pro-Poxy 100 LV Sikadur A/B 2:1 (liters)	PeaGravel #6 Aggregate (oz)
Piles w/ Drilled Core	A1	1.61	88	1.18	4.39	152
	B2	2.78	82	1.06	4.54	152
	E1	2.95	85	1.18	3.79	152
	H5	1.89	70	1.01	2.93	152
	I2	3.53	82	1.18	3.29	152
Piles Fully Intact	A3	2.84	90	1.18	0.89	-
	B1	1.42	81	1.48	0.65	-
	C2	2.43	86	1.42	1.92	-
	D2	4.26	74	1.42	1.89	-
	E3	2.84	87	1.12	1.12	-
	F3	1.89	96	1.24	1.66	-
	G1	2.9	90	1.42	2.00	-
	H1	3.43	78	1.06	0.95	-
	I6	4.73	96	1.12	1.42	-
	Σ =	**39.5**	**1185**	**17.1**	**31.4**	**760**
	AVG	**2.82**	**84.64**	**1.22**	**2.25**	**152.00**

AMOUNT OF PRO-POXY 100 LV not INCLUDING AGG/EPX CORE

Volume of Pro-Poxy 100 LV in Core (liters) = 1.76

	Piles	Pro-Poxy 100 LV (liters)	Volume of Pro-Poxy not in core (liters)
Piles w/ Drilled Core	A1	4.39	2.63
	B2	4.54	2.78
	E1	3.79	2.03
	H5	2.93	1.17
	I2	3.29	1.53
Piles Fully Intact	A3	-	0.89
	B1	-	0.65
	C2	-	1.92
	D2	-	1.89
	E3	-	1.12
	F3	-	1.66
	G1	-	2.00
	H1	-	0.95
	I6	-	1.42

average = 1.62

standard deviation = 0.64

Construction

Product Data Sheet
Edition 7.2003
Identification no. 332-15F
SikaWrap Hex 100G

SikaWrap Hex® 100G

Glass fiber fabric for structural strengthening

Description

SikaWrap Hex 100G is a unidirectional E-glass fiber fabric. Material is field laminated using Sikadur 300, Sikadur Hex 300 or Sikadur Hex 306 epoxy to form a glass fiber reinforced polymer (GFRP) used to strengthen structural elements.

Where to Use

- Load increases
- Seismic strengthening of columns and masonry walls
- Damage to structural parts
- Temporary strengthening
- Change in structural system
- Design or construction defects

Advantages

- Approved by ICBO/ICC ER-5558.
- Used for shear, confinement or flexural strengthening.
- Flexible, can be wrapped around complex shapes.
- Light weight.
- Non-corrosive.
- Acid resistant.
- Low aesthetic impact.
- Economical.

Possible Applications

- Bridges
- Parking Structures
- Buildings
- Marine Structures
- Civil/Environmental Facilities

Packaging

Rolls: 50 in. x 30 ft., 50 in. x 150 ft. **Kits:** Pre-measured kits containing 50 in. x 30 ft. (125 $ft.^2$) roll of fabric and 4 gallons of Sikadur Hex 300/306 epoxy.

How to Use

Surface Preparation

Surface must be clean and sound. It may be dry or damp, but free of standing water and frost. Remove dust, laitance, grease, curing compounds, impregnations, waxes, foreign particles, disintegrated materials and other bond inhibiting materials from the surface. Consult Sikadur 300, Sikadur Hex 300/306 and Sikadur 330 technical data sheets for additional information on surface preparation.
Existing uneven surfaces must be filled with an appropriate repair mortar. The adhesive strength of the concrete must be verified following surface preparation by random pull-off testing (ACI 503R) at the discretion of the engineer. Minimum tensile strength, 200 psi (1.4 MPa) with concrete substrate failure.
Preparation Work: Concrete - Blast clean, shotblast or use other approved mechanical means to provide an open roughened texture.
In certain applications and at the engineer's discretion, the intimate contact between the substrate and the fabric may be determined to be non-critical. In these cases, a thorough cleaning of the substrate using low pressure sand or water blasting is sufficient.

Typical Data

Storage Conditions	Store dry at 40°-95°F (4°-35°C)
Color	White
Primary Fiber Direction	0° (unidirectional)
Weight Per Square Yard	27 oz. (913 g/m^2)

Fiber Properties

Tensile Strength	3.3×10^5 psi (2,276 MPa)
Tensile Modulus	10.5×10^6 psi (72,413 MPa)
Elongation	4%
Density	0.092 $lbs./in.^3$ (2.54 g/cc)

Construction

Cured Laminate Properties with Sikadur Hex 300 Epoxy
Properties after standard cure followed by standard post cure
[70°-75°F (21°-24°C) - 5 days, 48 hours at 140°F (60°C)]

Property	Average Value[1] US Units psi	Average Value[1] SI Units MPa	Design Value[2] US Units psi	Design Value[2] SI Units MPa	ASTM Test Method
Tensile Strength*	88,800	612	81,000	558	D-3039
Tensile Modulus*	3,790,800	26,119	3,547,800	24,444	D-3039
Tensile % Elongation*	2.45	2.45	2.23	2.23	D-3039
140°F - Tensile Strength	79,900	551	77,100	531	D-3039
140°F - Tensile Modulus	3,728,000	25,690	3,390,600	23,361	D-3039
140°F - % Elongation	2.28	2.28	2.14	2.14	D-3039
Compressive Strength	86,600	597	78,600	542	D-695
Compressive Modulus	4,312,700	29,715	3,700,100	25,494	D-695
90 deg Tensile Strength	4,400	30	3,400	24	D-3039
90 deg Tensile Modulus	965,000	6,649	916,800	6,317	D-3039
90 deg % Tensile Elongation	0.46	0.46	0.34	0.34	D-3039
Shear Strength +/-45 in. Plane	5,800	40	5,000	34	D-3518
Shear Modulus +/-45 in. Plane	335,900	2,314	306,300	2,110	D-3518
Ply Thickness (inch/mm)	0.04	1.016	---	---	---

Cured Laminate Properties with Sikadur Hex 306 Epoxy
Properties after standard cure followed by standard post cure
[70°-75°F (21°-24°C) - 5 days, 48 hours at 140°F (60°C)]

Property	Average Value[1] US Units psi	Average Value[1] SI Units MPa	Desing Value[2] US Units psi	Desing Value[2] SI Units MPa	ASTM Test Method
Tensile Strength*	83,400	575	74,600	514	D-3039
Tensile Modulus*	3,672,000	25,300	3,163,400	21,796	D-3039
Tensile % Elongation*	2.31	2.31	2.03	2.03	D-3039
140°F - Tensile Strength	69,300	477	64,700	446	D-3039
140°F - Tensile Modulus	3,306,400	22,781	3,082,600	21,239	D-3039
140°F - % Elongation	2.19	2.19	2.01	2.01	D-3039
Compressive Strength	75,000	517	68,200	470	D-695
Compressive Modulus	4,248,200	29,270	3,551,000	24,466	D-695
90 deg Tensile Strength	5,000	34	3,800	26	D-3039
90 deg Tensile Modulus	819,800	5,648	746,800	5,145	D-3039
90 deg % Tensile Elongation	0.66	0.66	0.52	0.52	D-3039
Shear Strength +/-45 in. Plane	6,100	42	5,700	39	D-3518
Shear Modulus +/-45 in. Plane	337,200	2,323	310,800	2,141	D-3518
Ply Thickness (inch/mm)	0.04	1.016	---	---	---

* 24 sample coupons per test series; all other values based on 6 coupon test series
[1] Average value of test series
[2] Average value minus 2 standard deviations

Mixing

Consult either Sikadur 300 or Sikadur Hex 300/306 data sheets for information on epoxy resins.

Application

Prior to placing the fabric, the concrete surface is sealed using Sikadur 300 or Sikadur Hex 300 epoxy. Material may be applied by spray, brush or roller. SikaWrap Hex 100G can be impregnated using either the Sikadur 300, Sikadur Hex 300 or Sikadur Hex 306 epoxy. For best results on larger projects, the impregnation process should be accomplished using a mechanically driven fabric saturator or similar device. In special cases where the size of the project does not justify the use of a saturator, the fabric may be saturated by hand using a roller prior to placement. In either case, installation of this system should be performed only by a specially trained, approved contractor.

For overhead and vertical applications, prime concrete with Sikadur 30 or Sikadur 330 to improve tack. Saturate fabric with Sikadur 300, Sikadur Hex 300 or Sikadur Hex 306. Coat the exposed surface of final fabric layer using Sikagard 670W or Sikagard 62.

Cutting SikaWrap

Fabric can be cut to appropriate length by using a commercial quality heavy duty scissor. Since dull or worn cutting implements can damage, weaken or fray the fiber their use should be avoided. Consult MSDS for proper handling procedures.

Limitations

- Design calculations must be made and certified by an independent licensed professional engineer.
- System is a vapor barrier. Concrete should not be encapsulated in areas of freeze/thaw.

Caution

SikaWrap fabric is non-reactive. However, caution must be used when handling since a fine "glass dust" may be present on the surface. Gloves must therefore be worn to protect against skin irritation. Caution must also be used when cutting SikaWrap fabric to protect against airborne glass dust generated by the cutting procedure. Use of an appropriate, properly fitted NIOSH approved respirator is recommended.

KEEP CONTAINER TIGHTLY CLOSED — KEEP OUT OF REACH OF CHILDREN
NOT FOR INTERNAL CONSUMPTION — FOR INDUSTRIAL USE ONLY
CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

Visit our website at www.sikausa.com — 1-800-933-SIKA NATIONWIDE

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Fax: 52 42 25 0537

QUALITY ISO 9001 9002 ACHIEVEMENT

Quality Certification Numbers: Lyndhurst: FM 69711 (ISO 9000), FM 70421 (QS 9000), Marion: FM 69715, Kansas City: FM 69107, Santa Fe Springs: FM 69408

UNITEX® CHEMICALS FOR CONCRETE CONSTRUCTION

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PRO-POXY 100 LV

Low-viscosity injection resin and mortar binder

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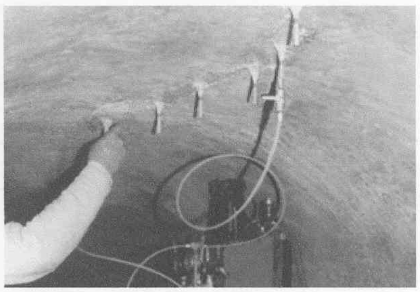

Compliances

ASTM-C-881: Types I, II, IV & V, Grade 1, Class B, C
Meets USDA specifications for use in food processing areas

Test Data

Download **this catalog page** (88 kb PDF)
Download **the MSDS** (14.8 kb PDF)
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Features

- Structurally restores integrity of concrete
- Low viscosity
- Moisture insensitive
- Ideal for adverse conditions

Description

A solvent-free, moisture-insensitive, low-viscosity, high-strength, two-component injection resin. It meets ASTM-C-881 Types I, II, IV & V, Grade 1, Classes B & C. It also meets USDA specifications for use in food processing areas.

An excellent epoxy adhesive for use in crack grouting by pressure injection or gravity-feed, and for making epoxy mortars and grouts.

Usage

- Pressure-injection of cracks in structural concrete, masonry, wood, etc.
- Gravity-feed of cracks in horizontal concrete and masonry
- Epoxy resin binder for epoxy mortar patching and overlay of interior, horizontal surfaces

Appearance

Component A: Clear
Component B: Amber
Shelf Life: 1 year in original unopened container
Storage Conditions: Store at 40-95°F (5-35°C).
Condition material to 65-85°F (18-29°C) before using
Gel Time (60 g. mass): 30 min. at 73°F ?° (23°C)

Coverage

1 gal./3.8 L of mixed epoxy yields 231 cu. in./.0037 cu. m of epoxy.
1 gal./3.8 L of mixed epoxy combined with 5 gal./18.9 L of aggregate yields 808.5 cu. in./.013 cu. m of mortar.

Packaging

150 ml x 300 ml cartridges
1 gal./3.8 L units
3 gal./11.4 L units
15 gal./56.8 L units
165 gal./624.6 L units

Application

TO PRESSURE INJECT CRACKS: Flushing cracks is detrimental and should not usually be done. Use automatic injection equipment for 2:1 ratio epoxy that will absolutely stay on ratio while under pressure. Carefully set surface or countersink ports on face of crack. Be sure the crack is open where ports are placed and not impacted with debris. Set the ports with PRO-POXY 300, 300 FAST or 300 PASTE, being careful not to obstruct the crack with epoxy. If feasible, also seal the back side of crack with PRO-POXY 300, 300 FAST or 300 PASTE. The PRO-POXY 300, 300 FAST or 300 PASTE is a cap sealing compound when used in this application.

A successful and profitable injection job depends largely on carefully placing the cap seal and ports allowing the injection to proceed smoothly with no leaks. Allow the cap seal to fully cure. Cure time will depend on temperature and which cap sealing compound was used. Inject PRO-POXY 100, always starting at the lowest port. If the back side of the crack has been sealed, stay on a port as long as it is accepting epoxy. Cap adjoining ports as epoxy extrudes out of them staying on the original port until the pump stalls out or the crack is completely filled.
TO BIND MORTAR AND GROUT FOR PATCHING: Premix entire unit of A and B or exact portions, 2 parts A to 1 part B by volume, with low speed Jiffy mixer for 3 minutes. Hold back some neat resin for priming patch. Paint concrete to be patched with just enough neat resin to wet out the surface. Slowly add oven-dried aggregate (typically 4-5 parts of aggregate to 1 part epoxy) to the mixed epoxy while mixing with a slow speed Jiffy mixer, being careful not to mix in air. Prepared mortar must be

View packaging & accessories

placed before primer becomes tack-free. Epoxy mortar may be placed and leveled with trowels. Do not disturb patch until it is fully cured. Ultra-violet light will darken epoxy. Oven-dried aggregate may be sprinkled to refusal on top of mortar to protect from UV. Brush off excess after epoxy has cured.

TO GRAVITY-FEED CRACKS: Seal underside of slab prior to filling if cracks reflect through. Pour neat PRO-POXY 100 into vee-notched crack. Continue placement until completely filled.

Limitations

- Minimum substrate temperature is 40°F (5°C).
- Do not thin. Solvents will prevent proper cure.
- Use oven-dried aggregate only.
- Minimum age of concrete must be 21-28 days, depending on curing and drying conditions, for mortar.
- Do not seal slabs on grade with product. PRO-POXY 100 is a vapor barrier.
- Maximum epoxy mortar thickness is 1.5 in./3.8 cm. per lift.

Cleanup

EQUIPMENT: Uncured material can be removed with Unitex CITRI-CLEAN or other approved solvent. Cured material can only be removed mechanically.

MATERIAL: Collect with absorbent material. Flush area with water. Dispose of in accordance with local, state and federal disposal regulations.

First Aid

EYE CONTACT: Flush immediately with water for at least 15 minutes. Contact physician immediately.
RESPIRATORY CONTACT: Remove person to fresh air.
SKIN CONTACT: Remove any contaminated clothing. Remove epoxy immediately with a dry cloth or paper towel. Solvents should not be used as they carry the irritant into the skin. Wash skin thoroughly with soap and water.
CURED EPOXY RESINS ARE INNOCUOUS.

Cautions

- Component A: Irritant
- Component B: Corrosive
- Product is a strong sensitizer. Use of safety goggles and chemical resistant gloves are recommended.
- Use of a NIOSH/MSHA organic vapor respirator is recommended if ventilation is inadequate.
- Avoid breathing vapors.
- Avoid skin contact.

UNITEX® CHEMICALS FOR CONCRETE CONSTRUCTION

Test Data: PRO-POXY 100 LV

ASTM C-881 | Types I, II, IV & V | Grade 1, Classes B& C
Download PDF (19 Kb PDF)

Laboratory Tests	Results	Specifications	
C-881 Brookfield Visc.	500 cps	2000 cps	Maximum
C-881 Gel Time	30 min.	30 min.[1,2,4,5]	Minimum
C-882 Bond Strength (2-day cure)	2,380 psi	1,000 psi[1,4]	Minimum
C-882 Bond Strength (14-day cure)	3,035 psi	1,500 psi[1,2,4,5]	Minimum
D-570 Absorption	0.84%	1.0%[1,2,4,5]	Maximum
D-648 Heat Deflection Temperature	50°C	49°C[4,5]	Minimim
D-2566 Linear Coefficient of Shrinkage	0.0043	0.005[1,2,4,5]	Maximum
D-695 Compressive Strength	12,385 psi	5,000 psi[2] 8,000 psi[1,5] 10,000 psi[4]	Minimum
D-695 Compressive Modulus	267,586 psi	90,000 psi 150,000 psi[1,5] 200,000 psi[4]	Minimum
D-638 Tensile Strength	7,168 psi	2,000 psi[2] 5,000 psi[1] 6,000 psi[5] 7,000 psi[4]	Minimum
D-638 % Elongation at Break	2.3%	1.0%[1,2,4,5]	Minimum
C-881 Filler Content	0.0%	None	
C-883 Shrinkage	Pass	None	
D-732 Shear Strength	8,500 psi	None	
D-790 Flexural Strength	8,700 psi	None	
C-884 Thermal Compatibility	Pass	None	

[1]ASTM C-881 Type I
[2]ASTM C-881 Type II
[4]ASTM C-881 Type IV
[5]ASTM C-881 Type V

Product Data Sheet
Edition 8.2003
Identification no. 347
Sikadur 300

Sikadur® 300

High-modulus, high-strength, impregnating resin

Description	Sikadur 300 is a two-component 100% solids, moisture-tolerant, high strength, high modulus epoxy.
Where to use	■ For use as an impregnating resin with SikaWrap Structural Strengthening System. ■ Sikadur 300 is used as a seal coat and impregnating resin for horizontal and vertical applications.
Advantages	■ Long pot life. ■ Long open time. ■ Easy to mix. ■ Tolerant of moisture before, during and after cure. ■ High strength, high modulus adhesive. ■ Excellent adhesion to concrete, masonry metals, wood and most structural materials. ■ Fully compatible and developed specifically for the SikaWrap System. ■ High temperature resistance. ■ High creep resistance under permanent load. ■ High abrasion and shock resistance. ■ Solvent-free, VOC compliant.
Coverage	As a sealer: 100 ft.^{2}/gal. As an impregnating resin: 60 ft^2/gal.
Packaging	4 gallon units.

How to Use

Surface Preparation

The concrete surface should be prepared to a minimum concrete surface profile (CSP) 3 as defined by the ICRI-surface-profile chips. Localized out-of-plane variations, including form lines, should not exceed 1/32 in. (1 mm). Substrate must be clean, sound, and free of surface moisture. Remove dust, laitance, grease, oils, curing compounds, waxes, impregnations, foreign particles, coatings and disintegrated materials by mechanical means, i.e. (sandblasting). For best results, substrate should be dry. However, a saturated surface dry condition is acceptable.

Typical Data *(Material and curing conditions @ 73°F (23°C) and 50% R.H.)*

Shelf Life	2 years in original, unopened container.
Storage Conditions	Store dry at 40°-95°F (4°-35°C). **Condition material to 65°-75°F (18°-24°C) before using.**
Color	Clear, amber.
Mixing Ratio	Mix entire unit, do not batch.
Viscosity (mixed)	approx. 500 cps
Reactivity	6-7 hours (time to reach 10,000 cps)
Tack Free (30 mils) ByK Drying Recorder	14-16 hours
Service Temperature Range	-40°F to 140°F (-40°C to 60°C)

Mechanical Properties *(14 day cure @73°F (23°C) and 50% R.H.)*

Tensile Strength (ASTM D-638)	8,000 psi (55 MPa)
Tensile Modulus (ASTM D-638)	2.5 x 10^5 psi (1,724 MPa)
Elongation @ Break (ASTM D-638)	3%
Flexural Strength (ASTM D-790)	11,500 psi (79 MPa)
Flexural Modulus (ASTM D-790)	500,000 psi (3,450 MPa)

Construction

Sika®

Construction

Mixing

Pre-mix each component. Mix entire unit, do not batch. Pour contents of part B to part A. Mix thoroughly for 5 minutes on low using a paddle style mixer on low speed (400-600 rpm) drill until uniformly blended.

Application

As a sealer: Apply mixed Sikadur 300 epoxy to a properly prepared substrate using a brush, roller or airless sprayer. Sikadur 300 should be applied at a sufficient rate to fully saturate the substrate without producing a surface film. Coverage rates are based on a substrate with normal porosity.

As an impregnating resin: As an impregnating resin for vertical and horizontal applications, use Sikadur 300. Resins may be applied to fabric by either manual or automatic means. For further information, consult installation guidelines.

Limitations

- Minimum substrate and ambient temperature 50°F (10°C).
- Do not thin with solvents.
- Material is a vapor barrier after cure.
- Minimum age of concrete must be 21-28 days depending on curing and drying conditions.

Caution

Danger: Component 'A' - Irritant; Sensitizer - Contains epoxy resin. Skin and eye irritant. May cause sensitization after prolonged or repeated contact. High concentrations of vapor may cause respiratory irritation. Harmful if swallowed. Avoid skin contact. Use only with adequate ventilation. Use of safety goggles and chemical resistant gloves is recommended. In case of exceedance of PELs, use an appropriate, properly fitted NIOSH approved respirator. Remove contaminated clothing. Consult MSDS for more detailed information.

Component 'B' - Corrosive; Sensitizer - Contains amines. Contact with eyes or skin causes severe burns. Can cause sensitization after prolonged or repeated contact. Skin and eye irritant. High concentrations of vapor may cause respiratory irritation. Harmful if swallowed. Avoid skin contact. Use only with adequate ventilation. Use of safety goggles and chemical resistant gloves is recommended. In case of exceedance of PELs, use an appropriate, properly fitted NIOSH approved respirator. Remove contaminated clothing. Consult MSDS for more detailed information.

First Aid

Eyes: Hold eyelids apart and flush thoroughly with water for 15 minutes. **Skin:** Remove contaminated clothing. Wash skin thoroughly for 15 minutes with soap and water. **Inhalation:** Remove person to fresh air. **Ingestion:** Do not induce vomiting. **In all cases, contact a physician immediately if symptoms persist.**

Handling and Storage:

Avoid direct contact. Use chemical resistant clothing/gloves/goggles. Use only with adequate general and local ventilation. In absence of adequate ventilation, use properly fitted NIOSH respirator. Wash thoroughly after handling product. Remove contaminated clothing and launder before reuse. Store at 40°-95°F (4°-35°C) under dry conditions. Condition material to 65°-75°F (18°-24°C) before using. Keep container tightly closed.

Clean Up

Confine spill. Collect with absorbent material and transfer to sealed containers. Uncured material can be removed with approved solvent. Follow solvent manufacturer's handling and safety instructions. Cured material can only be removed mechanically. Dispose of in accordance with current, applicable local, state and federal regulations. Cured material can only be removed mechanically.

KEEP CONTAINER TIGHTLY CLOSED
NOT FOR INTERNAL CONSUMPTION
KEEP OUT OF REACH OF CHILDREN
FOR INDUSTRIAL USE ONLY
CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

Sika warrants this product for one year from date of installation to be free from manufacturing defects and to meet the technical properties on the current technical data sheet if used as directed within shelf life. User determines suitability of product for intended use and assumes all risks. Buyer's sole remedy shall be limited to the purchase price or replacement of product exclusive of labor or cost of labor.

NO OTHER WARRANTIES EXPRESS OR IMPLIED SHALL APPLY INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. SIKA SHALL NOT BE LIABLE UNDER ANY LEGAL THEORY FOR SPECIAL OR CONSEQUENTIAL DAMAGES.

Visit our website at www.sikausa.com **1-800-933-SIKA NATIONWIDE**

Regional Information and Sales Centers. For the location of your nearest Sika sales office, contact your regional center.

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QUALITY ISO 9001 9002 ACHIEVEMENT

Edition 7.22.2005
Identification no. 332-15
Sikadur 30

Construction

Sikadur® 30

High-modulus, high-strength, structural epoxy paste adhesive for use with Sika CarboDur® reinforcement.

Description

Sikadur 30 is a 2-component, 100% solids, moisture-tolerant, high-modulus, high-strength, structural epoxy paste adhesive. It conforms to the current ASTM C-881 and AASHTO M-235 specifications.

Where to use

- Adhesive for bonding external reinforcement to concrete, masonry, steel, wood, stone, etc.
- Structural bonding of composite laminates (Sika CarboDur CFRP) to concrete.
- Structural bonding of steel plates to concrete.
- Suitable for use in vertical and overhead configurations.
- As a binder for epoxy mortar repairs.

Advantages

- Long pot life.
- Long open time.
- Tolerant of moisture before, during and after cure.
- High strength, high modulus, structural paste adhesive.
- Excellent adhesion to concrete, masonry, metals, wood and most structural materials.
- Fully compatible and excellent adhesion to Sika CarboDur CFRP composite laminate.
- Paste consistency ideal for vertical and overhead applications.
- High creep resistance under permanent load.
- High abrasion and shock resistance.
- Convenient easy mix ratio A:B=3:1 by volume.
- Solvent-free.
- Color-coded components to ensure proper mixing control.

Coverage

Type S 512 CarboDur: approx. 50 LF/gal.; Type S 812 CarboDur: approx. 32 LF/gal.; Type S 1012 CarboDur: approx. 22 LF/gal.

Packaging

1 gal. units.

Typical Data *(Material and curing conditions @ 73°F {23°C} and 50% R.H.)*

Shelf Life 2 years in original, unopened containers.

Storage Conditions Store dry at 40°-95°F (4°-35°C). **Condition material to 65°-85°F (18°-29°C) before using.**

Color Light gray

Mixing Ratio Component 'A': Component 'B' = 3:1 by volume.

Consistency Non-sag paste.

Pot Life Approximately 70 minutes @ 73°F (23°C) (1 qt.)

Tensile Properties (ASTM D-638)

7 day	Tensile Strength	3,600 psi (24.8 MPa)
	Elongation at Break	1%
	Modulus of Elasticity	6.5 X 10^5 psi (4,482 MPa)

Flexural Properties (ASTM D-790)

14 day	Flexural Strength (Modulus of Rupture)	6,800 psi (46.8 MPa)
	Tangent Modulus of Elasticity in Bending	1.7 X 10^6 psi (11,721 MPa)

Shear Strength (ASTM D-732) **14 day** Shear Strength 3,600 psi (24.8 MPa)

Bond Strength (ASTM C-882): Hardened Concrete to Hardened Concrete

2 day (moist cure)	Bond Strength	2,700 psi (18.6 MPa)
2 day (dry cure)	Bond Strength	3,200 psi (22.0 MPa)
14 day (moist cure)	Bond Strength	3,100 psi (21.3 MPa)
	Hardened Concrete to Steel	2,600 psi (17.9 MPa)
2 day (moist cure)	Bond Strength	3,000 psi (20.6 MPa)
2 day (dry cure)	Bond Strength	2,600 psi (17.9 MPa)
14 day (moist cure)	Bond Strength	

Heat Deflection Temperature (ASTM D-648)

7 day [fiber stress loading=264 psi (1.8 MPa)] 118°F (47°C)

Water Absorption (ASTM D-570) 7 day (24 hour immersion) 0.03%

Compressive Properties (ASTM D-695) - Compressive Strength, psi (MPa)

	40°F* (4°C)	73°F* (23°C)	90°F* (32°C)
4 hour	-	-	5,500 (37.9)
8 hour	-	3,500 (24.1)	6,700 (46.2)
16 hour	-	6,700 (46.2)	7,400 (51.0)
1 day	750 (5.1)	7,800 (53.7)	7,800 (53.7)
3 day	6,800 (46.8)	8,300 (57.2)	8,300 (57.2)
7 day	8,000 (55.1)	8,600 (59.3)	8,600 (59.3)
14 day	8,500 (58.6)	8,600 (59.3)	8,900 (61.3)
28 day	8,500 (58.6)	8,600 (59.3)	9,000 (62.0)

Compressive Modulus **7 day** 3.9 x 10^5 psi (2,689 MPa)

*Material cured and tested at the temperatures indicated.

C120

Construction

How to Use

Surface Preparation

The concrete surface should be prepared to a minimum concrete surface profile (CSP) 3 defined by the ICRI surface-profile chips. Localized out-of-plane variations, including form lines, should not exceed 1/32 in. (1 mm). Surface must be clean and sound. It may be dry or damp, but free of standing water and frost. Remove dust, laitance, grease, curing compounds, impregnations, waxes, foreign particles, disintegrated materials, and other bond inhibiting materials from the surface. Existing uneven surfaces must be filled with an appropriate repair mortar (e.g., Sikadur 30 with the addition of 1 part oven-dried sand). The adhesive strength of the concrete must be verified after surface preparation by random pull-off testing (ACI 503R) at the discretion of the engineer. Minimum tensile strength, 200 psi (1.4 MPa) with concrete substrate failure.

Preparation work

Concrete - Blast clean, shotblast or use other approved mechanical means to provide an open roughened texture.

Steel - Should be cleaned and prepared thoroughly by blastcleaning to a white metal finish.

CarboDur - Wipe clean with appropriate cleaner (e.g. MEK).

Mixing

Pre-mix each component. Proportion 1 part Component 'B' to 3 parts Component 'A' by volume into a clean pail. Mix thoroughly for 3 minutes with Sika paddle on low-speed (400-600 rpm) drill until uniform in color. Mix only that quantity which can be used within its pot life.

To prepare an epoxy mortar: slowly add up to 1 part by loose volume of an oven-dried aggregate to 1 part of the mixed Sikadur 30 and mix until uniform in consistency.

Application

For bonded, external reinforcement:
Apply the neat mixed Sikadur 30 onto the concrete with a trowel or spatula to a nominal thickness of 1/16" (1.5 mm). Apply the mixed Sikadur 30 onto the CarboDur laminate with a "roof-shaped" spatula to a nominal thickness of 1/16" (1.5 mm). Within the open time of the epoxy, depending on the temperature, place the CarboDur laminate onto the concrete surface. Using a hard rubber roller, press the laminate into the epoxy resin until the adhesive is forced out on both sides. Remove excess adhesive. Glue line should not exceed 1/8 inch (3 mm). The external reinforcement must not be disturbed for a minimum of 24 hours. The epoxy will reach its design strength after 7 days.

For interior vertical and overhead patching: Work the material into the prepared substrate, filling the cavity. Strike off level. Lifts should not exceed 1 inch (25 mm).

Limitations

- Minimum substrate and ambient temperature is 40°F (4°C).
- Do not thin. Addition of solvents will prevent proper cure.
- Use oven-dried aggregate only.
- Maximum glue line of neat epoxy is 1/8 inch (3 mm).
- Maximum epoxy mortar thickness is 1 inch (25 mm) per lift.
- Minimum age of concrete must be 21-28 days, depending upon curing and drying conditions.
- Porous substrates must be tested for moisture vapor transmission prior to mortar applications.

Caution

Component 'A' - Irritant; Sensitizer - Contains epoxy resin and crystalline silica (sand). Can cause skin sensitization after prolonged or repeated contact. Skin and eye irritant. High concentrations of vapor may cause respiratory irritation. If sanded, crystalline silica dust may be generated and may cause delayed lung injury (silicosis) and is listed as a suspect carcinogen by NTP and IARC (2A). Use only with adequate ventilation. Use of safety goggles and chemical resistant gloves is recommended. In case of exceedance of PELs, use an appropriate, properly fitted NIOSH approved respirator. Remove contaminated clothing. Consult MSDS for more detailed information.

Component 'B' - Corrosive; Sensitizer - Contains amines and crystalline silica (sand). Contact with eyes or skin may cause severe burns. Can cause skin and/or respiratory sensitization after prolonged or repeated contact. Skin and eye irritant. High concentrations of vapor may cause respiratory irritation. Overexposure may cause liver, kidney, and/or central nervous system effects. If sanded, crystalline silica dust may be generated and may cause delayed lung injury (silicosis) and is listed as a suspect carcinogen by NTP and IARC (2A). Avoid skin contact. Use only with adequate ventilation. Use of safety goggles and chemical resistant gloves is recommended. In case of exceedance of PELs, use an appropriate, properly fitted NIOSH approved respirator. Remove contaminated clothing. Consult MSDS for more detailed information.

First Aid

Eyes: Hold eyelids apart and flush thoroughly with water for 15 minutes. **Skin:** Remove contaminated clothing. Wash skin thoroughly for 15 minutes with soap and water. **Inhalation:** Remove person to fresh air. **Ingestion:** Do not induce vomiting. **In all cases, contact a physician immediately if symptoms persist.**

Clean Up

In case of spills or leaks, wear suitable protective equipment, contain spill, collect with absorbent material, and transfer to suitable container. Ventilate area. Avoid contact. Dispose of in accordance with current, applicable local, state and federal regulations. Uncured material can be removed with approved solvent. Cured material can only be removed mechanically.

KEEP CONTAINER TIGHTLY CLOSED — KEEP OUT OF REACH OF CHILDREN
NOT FOR INTERNAL CONSUMPTION — FOR INDUSTRIAL USE ONLY
CONSULT MATERIAL SAFETY DATA SHEET FOR MORE INFORMATION

Sika warrants this product for one year from date of installation to be free from manufacturing defects and to meet the technical properties on the current Technical Data Sheet if used as directed within shelf life. User determines suitability of product for intended use and assumes all risks. Buyer's sole remedy shall be limited to the purchase price or replacement of product exclusive of labor or cost of labor.

NO OTHER WARRANTIES EXPRESS OR IMPLIED SHALL APPLY INCLUDING ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. SIKA SHALL NOT BE LIABLE UNDER ANY LEGAL THEORY FOR SPECIAL OR CONSEQUENTIAL DAMAGES. SIKA SHALL NOT BE RESPONSIBLE FOR THE USE OF THIS PRODUCT IN A MANNER TO INFRINGE ON ANY PATENT OR ANY OTHER INTELLECTUAL PROPERTY RIGHTS HELD BY OTHERS.

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QUALITY ISO 9001 9002 ACHIEVEMENT

Quality Certification Numbers: Lyndhurst: FM 69711 (ISO 9000), FM 70421 (QS 9000), Marion: FM 69715, Kansas City: FM 69107, Santa Fe Springs: FM 69408

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1-800-259-8721

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Oklahoma City, OK 73127
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PEA GRAVEL

SIEVE SIZE	% RETAINED	% PASSING
3/8	0	100.0
4	15.8	84.2
8	97.8	2.2
16	100.0	0.0

SW= 517

APPENDIX B

CORRELATIONS BETWEEN AVG. SWV & REPAIR MATERIALS

Correlation Coefficients Using Average SWV for Unrepaired Piles

x (independent variable)	y (independent variable)	z (dependent variable)	R^2
Avg. SWV for Unrepaired Piles	Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	0.993
Avg. SWV for Unrepaired Piles	Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	0.991
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles	Surface Area	0.984
Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w Agg/Epx core	Surface Area	0.984
Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles	0.982
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles	Pile Volume	0.982
Pile Volume	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles	0.982
Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w Agg/Epx core	Pile Volume	0.979
Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100LV of Piles w Agg/Epx core	Sikadur 30	0.936
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles w/ hollow core	Sikadur 30	0.926
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	Sikadur 30	0.926
Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	Sikadur 30	0.926
Pile Volume	Avg. SWV for Unrepaired Piles w/ hollow core	Sikadur 30	0.921
Avg. SWV for Unrepaired Piles w/ hollow core	Pile Volume	Sikadur 30	0.921
Avg. SWV for Unrepaired Piles	Pile Volume	Sikadur 30	0.921
Surface Area	Avg. SWV for Unrepaired Piles w/ hollow core	Sikadur 30	0.920
Avg. SWV for Unrepaired Piles w/ hollow core	Surface Area	Sikadur 30	0.920
Pile Volume	Sikadur 30	Avg. SWV for Unrepaired Piles w/ hollow core	0.919
Sikadur 30	Pile Volume	Avg. SWV for Unrepaired Piles w/ hollow core	0.919
Sikadur 30	Surface Area	Avg. SWV for Unrepaired Piles w/ hollow core	0.918
Surface Area	Sikadur 30	Avg. SWV for Unrepaired Piles w/ hollow core	0.918
Surface Area	Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100LV of Piles w Agg/Epx core	0.586
Surface Area	Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	0.586
Avg. SWV for Unrepaired Piles w/ hollow core	Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	0.586
Avg. SWV for Unrepaired Piles, Combined	Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	0.586
Avg. SWV for Unrepaired Piles, Combined	Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	0.575
Pile Volume	Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100LV of Piles w Agg/Epx core	0.572
Pile Volume	Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	0.572
Avg. SWV for Unrepaired Piles w/ hollow core	Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	0.572
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles w/ hollow core	Surface Area	0.557
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	Surface Area	0.557
Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100LV of Piles w Agg/Epx core	Surface Area	0.557
Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	Surface Area	0.557
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles w/ hollow core	Pile Volume	0.543
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	Pile Volume	0.543
Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100LV of Piles w Agg/Epx core	Pile Volume	0.543
Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	Pile Volume	0.543
Pile Volume	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	0.531
Sikadur 30	Avg. SWV for Unrepaired Piles w/ hollow core	Pile Volume	0.531
Surface Area	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles	0.486
Pile Volume	Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.354
Sikadur 30	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles	0.351
Sikadur 30	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	0.351
Surface Area	Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.340
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles	Pile Volume	0.330
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles,Combined	Pile Volume	0.330
Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Pile Volume	0.330
Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Pile Volume	0.330
Sikadur 30	Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.320
Avg. SWV for Unrepaired Piles	Sikadur 30	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.320
Avg. SWV for Unrepaired Piles, Combined	Sikadur 30	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.320
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles	Surface Area	0.264
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles,Combined	Surface Area	0.264
Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Surface Area	0.264
Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Surface Area	0.264
Sikadur 30	Avg. SWV for Unrepaired Piles w/ hollow core	Pro-Poxy 100LV of Piles w Agg/Epx core	0.208
Pile Volume	Sikadur 30	Avg. SWV for Unrepaired Piles	0.204
Sikadur 30	Pile Volume	Avg. SWV for Unrepaired Piles	0.204
Sikadur 30	Surface Area	Avg. SWV for Unrepaired Piles	0.165
Surface Area	Sikadur 30	Avg. SWV for Unrepaired Piles	0.165
Sikadur 30	Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	0.161
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles	Sikadur 30	0.120
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Unrepaired Piles,Combined	Sikadur 30	0.120
Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Sikadur 30	0.120
Avg. SWV for Unrepaired Piles, Combined	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Sikadur 30	0.120
Pile Volume	Avg. SWV for Unrepaired Piles	Sikadur 30	0.120
Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles w/ hollow core	0.110
Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	0.110
Sikadur 30	Avg. SWV for Unrepaired Piles	Pile Volume	0.104
Avg. SWV for Unrepaired Piles	Sikadur 30	Pile Volume	0.104
Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles w/ hollow core	0.098
Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles, Combined	0.098
Surface Area	Avg. SWV for Unrepaired Piles	Sikadur 30	0.097
Avg. SWV for Unrepaired Piles	Surface Area	Sikadur 30	0.097
Avg. SWV for Unrepaired Piles w/ hollow core	Sikadur 30	Surface Area	0.093
Sikadur 30	Avg. SWV for Unrepaired Piles	Surface Area	0.085
Avg. SWV for Unrepaired Piles	Sikadur 30	Surface Area	0.085
Sikadur 30	Avg. SWV for Unrepaired Piles w/ hollow core	Surface Area	0.083
Sikadur 30	Pile Volume	Avg. SWV for Unrepaired Piles, Combined	0.080
Pile Volume	Sikadur 30	Avg. SWV for Unrepaired Piles, Combined	0.080
Avg. SWV for Unrepaired Piles w/ hollow core	Sikadur 30	Pile Volume	0.074
Pile Volume	Avg. SWV for Unrepaired Piles, Combined	Sikadur 30	0.059
Avg. SWV for Unrepaired Piles, Combined	Pile Volume	Sikadur 30	0.059
Sikadur 30	Surface Area	Avg. SWV for Unrepaired Piles, Combined	0.058
Surface Area	Sikadur 30	Avg. SWV for Unrepaired Piles, Combined	0.058
Surface Area	Avg. SWV for Unrepaired Piles, Combined	Sikadur 30	0.046
Avg. SWV for Unrepaired Piles, Combined	Surface Area	Sikadur 30	0.046
Sikadur 30	Avg. SWV for Unrepaired Piles, Combined	Pile Volume	0.034
Avg. SWV for Unrepaired Piles, Combined	Sikadur 30	Pile Volume	0.034
Sikadur 30	Avg. SWV for Unrepaired Piles, Combined	Surface Area	0.028
Avg. SWV for Unrepaired Piles, Combined	Sikadur 30	Surface Area	0.028
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Unrepaired Piles	Sikadur 30	0.028
Avg. SWV for Unrepaired Piles	Pro-Poxy 100LV of Piles w Agg/Epx core	Sikadur 30	0.028

Correlations Coefficients Using Average SWV of Repaired Piles

x (independent variable)	y (independent variable)	z (dependent variable)	R^2
Sikadur 30	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles, Combined	0.991
Sikadur 30	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	0.991
Sikadur 30	Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	0.986
Sikadur 30	Avg. SWV for Repaired Piles w/ Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	0.986
Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	Surface Area	0.984
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	Sikadur 30	0.967
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles, Combined	Sikadur 30	0.967
Avg. SWV for Repaired Piles w/ Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	Sikadur 30	0.967
Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	Sikadur 30	0.926
Surface Area	Avg. SWV for Repaired Piles w/ Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	0.815
Surface Area	Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	0.815
Avg. SWV for Repaired Piles, Combined	Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	0.815
Avg. SWV for Repaired Piles w/ Agg/Epx	Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	0.815
Pile Volume	Avg. SWV for Repaired Piles w/ Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	0.808
Pile Volume	Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	0.808
Avg. SWV for Repaired Piles, Combined	Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	0.808
Avg. SWV for Repaired Piles w/ Agg/Epx	Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	0.808
Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	0.737
Surface Area	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles, Combined	0.737
Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	0.735
Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles, Combined	0.735
Surface Area	Sikadur 30	Avg. SWV for Repaired Piles w/ Agg/Epx	0.644
Sikadur 30	Surface Area	Avg. SWV for Repaired Piles w/ Agg/Epx	0.644
Pile Volume	Sikadur 30	Avg. SWV for Repaired Piles w/ Agg/Epx	0.638
Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	Surface Area	0.557
Avg. SWV for Repaired Piles w/ Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	Surface Area	0.557
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	Surface Area	0.544
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles, Combined	Surface Area	0.544
Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w Agg/Epx core	Pile Volume	0.532
Avg. SWV for Repaired Piles w/ Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	Pile Volume	0.532
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	Pile Volume	0.532
Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles, Combined	Pile Volume	0.532
Surface Area	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles w/o Agg/Epx	0.475
Surface Area	Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.470
Avg. SWV for Repaired Piles, Combined	Surface Area	Sikadur 30	0.470
Avg. SWV for Repaired Piles w/ Agg/Epx	Surface Area	Sikadur 30	0.470
Sikadur 30	Avg. SWV for Repaired Piles w/o Agg/Epx	Surface Area	0.460
Avg. SWV for Repaired Piles w/o Agg/Epx	Sikadur 30	Surface Area	0.460
Pile Volume	Avg. SWV for Repaired Piles w/ Agg/Epx	Sikadur 30	0.458
Avg. SWV for Repaired Piles w/ Agg/Epx	Pile Volume	Sikadur 30	0.458
Surface Area	Sikadur 30	Avg. SWV for Repaired Piles w/o Agg/Epx	0.451
Sikadur 30	Surface Area	Avg. SWV for Repaired Piles w/o Agg/Epx	0.451
Pile Volume	Pro-Poxy 100LV of Piles w Agg/Epx core	Avg. SWV for Repaired Piles w/o Agg/Epx	0.449
Pile Volume	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles, Combined	0.449
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles w/o Agg/Epx	Surface Area	0.445
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles, Combined	Surface Area	0.445
Sikadur 30	Avg. SWV for Repaired Piles w/o Agg/Epx	Pile Volume	0.432
Avg. SWV for Repaired Piles w/o Agg/Epx	Sikadur 30	Pile Volume	0.432
Sikadur 30	Pile Volume	Avg. SWV for Repaired Piles w/ Agg/Epx	0.425
Sikadur 30	Avg. SWV for Repaired Piles w/ Agg/Epx	Surface Area	0.425
Avg. SWV for Repaired Piles, Combined	Sikadur 30	Surface Area	0.425
Avg. SWV for Repaired Piles w/ Agg/Epx	Sikadur 30	Surface Area	0.425
Sikadur 30	Pile Volume	Avg. SWV for Repaired Piles w/o Agg/Epx	0.425
Pile Volume	Sikadur 30	Avg. SWV for Repaired Piles w/o Agg/Epx	0.425
Sikadur 30	Avg. SWV for Repaired Piles w/ Agg/Epx	Pile Volume	0.420
Avg. SWV for Repaired Piles w/ Agg/Epx	Sikadur 30	Pile Volume	0.420
Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Pile Volume	0.415
Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Pile Volume	0.415
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles w/o Agg/Epx	Pile Volume	0.415
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles, Combined	Pile Volume	0.415
Surface Area	Sikadur 30	Avg. SWV for Repaired Piles, Combined	0.336
Sikadur 30	Surface Area	Avg. SWV for Repaired Piles, Combined	0.336
Sikadur 30	Avg. SWV for Repaired Piles, Combined	Pile Volume	0.336
Sikadur 30	Pile Volume	Avg. SWV for Repaired Piles, Combined	0.335
Pile Volume	Sikadur 30	Avg. SWV for Repaired Piles, Combined	0.335
Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Surface Area	0.264
Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Surface Area	0.264
Sikadur 30	Avg. SWV for Repaired Piles, Combined	Surface Area	0.238
Avg. SWV for Repaired Piles, Combined	Sikadur 30	Pile Volume	0.236
Surface Area	Avg. SWV for Repaired Piles, Combined	Sikadur 30	0.212
Avg. SWV for Repaired Piles, Combined	Pile Volume	Sikadur 30	0.209
Pile Volume	Avg. SWV for Repaired Piles, Combined	Sikadur 30	0.209
Surface Area	Avg. SWV for Repaired Piles w/o Agg/Epx	Sikadur 30	0.188
Avg. SWV for Repaired Piles w/o Agg/Epx	Surface Area	Sikadur 30	0.188
Pile Volume	Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.182
Pile Volume	Avg. SWV for Repaired Piles w/o Agg/Epx	Sikadur 30	0.172
Avg. SWV for Repaired Piles w/o Agg/Epx	Pile Volume	Sikadur 30	0.172
Sikadur 30	Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.120
Avg. SWV for Repaired Piles, Combined	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Sikadur 30	0.120
Avg. SWV for Repaired Piles w/o Agg/Epx	Sikadur 30	Pro-Poxy 100LV of Piles w/o Agg/Epx core	0.120
Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Sikadur 30	0.120
Sikadur 30	Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles w/o Agg/Epx	0.083
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles w/ Agg/Epx	Sikadur 30	0.081
Pro-Poxy 100LV of Piles w/o Agg/Epx core	Avg. SWV for Repaired Piles, Combined	Sikadur 30	0.081
Avg. SWV for Repaired Piles w/o Agg/Epx	Pro-Poxy 100LV of Piles w Agg/Epx core	Sikadur 30	0.028

APPENDIX C

DATA TABLES; STRESS WAVE VELOCITIES FROM COTTON COUNTY BRIDGE

Pile W1:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (µs)	North-South Direction Velocity (in/µs)	East-West Direction Stress Wave Time (µs)	East-West Direction Velocity (in/µs)	Avg. Velocity (in/µs)
0.5	39.69	12.63	200	0.0632	240	0.0526	0.058
1.0	39.56	12.59	336	0.0375	NA	-	0.037
1.5	39.44	12.55	300	0.0418	192	0.0654	0.054
2.0	39.47	12.56	232	0.0542	224	0.0561	0.055
2.5	39.50	12.57	200	0.0629	200	0.0629	0.063
3.0	39.50	12.57	176	0.0714	200	0.0629	0.067
3.5	39.50	12.57	192	0.0655	192	0.0655	0.065
4.0	39.59	12.60	184	0.0685	184	0.0685	0.068
4.5	39.69	12.63	184	0.0687	184	0.0687	0.069
5.0	40.00	12.73	200	0.0637	NA	-	0.064
5.5	40.31	12.83	200	0.0642	NA	-	0.064
6.0	40.28	12.82	200	0.0641	200	0.0641	0.064
6.5	40.25	12.81	200	0.0641	200	0.0641	0.064
7.0	40.44	12.87	192	0.0670	192	0.0670	0.067
7.5	40.63	12.93	200	0.0647	200	0.0647	0.065
8.0	40.63	12.93	200	0.0647	200	0.0647	0.065
8.5	40.63	12.93	216	0.0599	208	0.0622	0.061
9.0	40.63	12.93	216	0.0599	208	0.0622	0.061
9.5	40.63	12.93	200	0.0647	192	0.0674	0.066
10.0	40.63	12.93	192	0.0674	192	0.0674	0.067

Pile W2:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	38.63	12.29	192	0.0640	200	0.0615	0.063
1.0	38.50	12.25	208	0.0589	200	0.0613	0.060
1.5	38.38	12.22	200	0.0611	NA	-	0.061
2.0	38.19	12.16	200	0.0608	NA	-	0.061
2.5	38.00	12.10	200	0.0605	192	0.0630	0.062
3.0	38.13	12.14	194	0.0626	192	0.0632	0.063
3.5	38.25	12.18	184	0.0662	200	0.0609	0.064
4.0	38.27	12.18	200	0.0609	NA	-	0.061
4.5	38.29	12.19	200	0.0609	NA	-	0.061
5.0	38.31	12.20	200	0.0610	184	0.0663	0.064
5.5	38.59	12.28	192	0.0640	176	0.0698	0.067
6.0	38.88	12.37	176	0.0703	192	0.0644	0.067
6.5	38.88	12.37	200	0.0619	200	0.0619	0.062
7.0	38.88	12.37	192	0.0644	192	0.0644	0.064
7.5	39.03	12.42	192	0.0647	216	0.0575	0.061
8.0	39.19	12.47	160	0.0780	160	0.0780	0.078
8.5	39.28	12.50	160	0.0781	152	0.0823	0.080
9.0	39.38	12.53	152	0.0825	184	0.0681	0.075
9.5	39.09	12.44	160	0.0778	184	0.0676	0.073
10.0	38.81	12.35	184	0.0671	200	0.0618	0.064

Pile W3:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	40.94	13.03	200	0.0652	200	0.0652	0.065
1.0	40.97	13.04	192	0.0679	208	0.0627	0.065
1.5	41.00	13.05	160	0.0816	208	0.0627	0.072
2.0	40.79	12.98	176	0.0738	176	0.0738	0.074
2.5	40.57	12.91	200	0.0646	NA	-	0.065
3.0	40.31	12.83	200	0.0642	200	0.0642	0.064
3.5	40.14	12.78	200	0.0639	NA	-	0.064
4.0	39.97	12.72	200	0.0636	NA	-	0.064
4.5	39.63	12.61	200	0.0631	200	0.0631	0.063
5.0	39.34	12.52	200	0.0626	200	0.0626	0.063
5.5	39.06	12.43	200	0.0622	200	0.0622	0.062
6.0	39.31	12.51	176	0.0711	192	0.0652	0.068
6.5	39.56	12.59	192	0.0656	208	0.0605	0.063
7.0	39.19	12.47	208	0.0600	200	0.0624	0.061
7.5	38.81	12.35	200	0.0618	200	0.0618	0.062
8.0	38.81	12.35	168	0.0735	176	0.0702	0.072
8.5	38.81	12.35	176	0.0702	168	0.0735	0.072
9.0	38.75	12.33	168	0.0734	168	0.0734	0.073
9.5	38.69	12.31	160	0.0770	144	0.0855	0.081
10.0	38.63	12.29	160	0.0768	200	0.0615	0.069

Pile W4:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	39.63	12.61	256	0.0493	512	0.0246	0.037
1.0	38.91	12.38	248	0.0499	344	0.0360	0.043
1.5	38.19	12.16	256	0.0475	296	0.0411	0.044
2.0	38.10	12.13	280	0.0433	280	0.0433	0.043
2.5	38.01	12.10	288	0.0420	NA	-	0.042
3.0	37.93	12.07	288	0.0419	NA	-	0.042
3.5	37.84	12.04	328	0.0367	NA	-	0.037
4.0	37.75	12.02	360	0.0334	360	0.0334	0.033
4.5	37.91	12.07	360	0.0335	360	0.0335	0.034
5.0	38.06	12.12	416	0.0291	408	0.0297	0.029
5.5	38.06	12.12	400	0.0303	384	0.0316	0.031
6.0	38.06	12.12	368	0.0329	368	0.0329	0.033
6.5	38.00	12.10	328	0.0369	456	0.0265	0.032
7.0	37.94	12.08	384	0.0314	472	0.0256	0.029
7.5	37.84	12.05	280	0.0430	336	0.0359	0.039
8.0	37.75	12.02	328	0.0366	312	0.0385	0.038
8.5	37.78	12.03	304	0.0396	360	0.0334	0.036
9.0	37.81	12.04	384	0.0313	480	0.0251	0.028
9.5	37.84	12.05	448	0.0269	392	0.0307	0.029
10.0	37.88	12.06	480	0.0251	352	0.0342	0.030

Pile W5:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (µs)	North-South Direction Velocity (in/µs)	East-West Direction Stress Wave Time (µs)	East-West Direction Velocity (in/µs)	Avg. Velocity (in/µs)
0.5	37.00	11.78	216	0.0545	200	0.0589	0.057
1.0	37.19	11.84	224	0.0528	184	0.0643	0.059
1.5	37.10	11.81	216	0.0547	NA	-	0.055
2.0	37.02	11.78	200	0.0589	NA	-	0.059
2.5	36.94	11.76	200	0.0588	200	0.0588	0.059
3.0	36.66	11.67	192	0.0608	200	0.0583	0.060
3.5	36.38	11.58	192	0.0603	192	0.0603	0.060
4.0	36.56	11.64	184	0.0633	184	0.0633	0.063
4.5	36.75	11.70	216	0.0542	NA	-	0.054
5.0	36.75	11.70	216	0.0542	216	0.0542	0.054
5.5	36.75	11.70	184	0.0636	184	0.0636	0.064
6.0	36.75	11.70	184	0.0636	184	0.0636	0.064
6.5	36.75	11.70	216	0.0542	208	0.0562	0.055
7.0	36.75	11.70	184	0.0636	200	0.0585	0.061
7.5	36.75	11.70	216	0.0542	232	0.0504	0.052

Pile W6:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	38.00	12.10	168	0.0720	NA	-	0.072
1.0	38.44	12.24	184	0.0665	NA	-	0.066
1.5	38.88	12.37	178	0.0695	168	0.0737	0.072
2.0	38.44	12.24	168	0.0728	168	0.0728	0.073
2.5	38.00	12.10	168	0.0720	168	0.0720	0.072
3.0	37.97	12.09	184	0.0657	184	0.0657	0.066
3.5	37.94	12.08	176	0.0686	176	0.0686	0.069
4.0	38.06	12.12	176	0.0688	176	0.0688	0.069
4.5	38.19	12.16	176	0.0691	176	0.0691	0.069
5.0	38.58	12.28	200	0.0614	NA	-	0.061
5.5	38.98	12.41	192	0.0646	192	0.0646	0.065
6.0	39.38	12.53	184	0.0681	176	0.0712	0.070
6.5	39.31	12.51	232	0.0539	192	0.0652	0.060
7.0	39.25	12.49	168	0.0744	176	0.0710	0.073
7.5	38.94	12.39	176	0.0704	176	0.0704	0.070
8.0	38.63	12.29	152	0.0809	160	0.0768	0.079
8.5	38.25	12.18	184	0.0662	192	0.0634	0.065
9.0	37.88	12.06	184	0.0655	184	0.0655	0.066

Pile E1:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	40.63	12.93	224	0.0577	NA	-	0.058
1.0	40.28	12.82	200	0.0641	NA	-	0.064
1.5	39.94	12.71	192	0.0662	256	0.0497	0.058
2.0	39.84	12.68	224	0.0566	312	0.0406	0.049
2.5	39.75	12.65	240	0.0527	216	0.0586	0.056
3.0	39.63	12.61	216	0.0584	208	0.0606	0.060
3.5	39.50	12.57	200	0.0629	200	0.0629	0.063
4.0	39.34	12.52	200	0.0626	200	0.0626	0.063
4.5	39.19	12.47	192	0.0650	200	0.0624	0.064
5.0	39.54	12.59	200	0.0629	264	0.0477	0.055
5.5	39.90	12.70	200	0.0635	NA	-	0.063
6.0	40.25	12.81	216	0.0593	NA	-	0.059
6.5	40.00	12.73	168	0.0758	168	0.0758	0.076
7.0	39.75	12.65	272	0.0465	200	0.0633	0.055
7.5	39.22	12.48	200	0.0624	224	0.0557	0.059
8.0	38.69	12.31	208	0.0592	200	0.0616	0.060
8.5	38.69	12.31	176	0.0700	208	0.0592	0.065
9.0	38.69	12.31	312	0.0395	232	0.0531	0.046

Pile E2:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	39.75	12.65	304	0.0416	264	0.0479	0.045
1.0	40.13	12.77	208	0.0614	208	0.0614	0.061
1.5	40.50	12.89	192	0.0671	NA	-	0.067
2.0	40.13	12.77	280	0.0456	NA	-	0.046
2.5	39.75	12.65	264	0.0479	208	0.0608	0.054
3.0	39.63	12.61	200	0.0631	216	0.0584	0.061
3.5	39.50	12.57	200	0.0629	200	0.0629	0.063
4.0	40.19	12.79	200	0.0640	216	0.0592	0.062
4.5	40.09	12.76	216	0.0591	NA	-	0.059
5.0	40.05	12.75	224	0.0569	NA	-	0.057
5.5	40.00	12.73	240	0.0531	248	0.0513	0.052
6.0	40.31	12.83	240	0.0535	208	0.0617	0.058
6.5	40.63	12.93	248	0.0521	296	0.0437	0.048
7.0	40.28	12.82	264	0.0486	312	0.0411	0.045
7.5	39.94	12.71	312	0.0407	232	0.0548	0.048
8.0	40.47	12.88	248	0.0519	176	0.0732	0.063
8.5	41.00	13.05	144	0.0906	NA	-	0.091
9.0	39.75	12.65	360	0.0351	NA	-	0.035
9.5	39.75	12.65	320	0.0395	NA	-	0.040

Pile E3:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	40.75	12.97	192	0.0676	208	0.0624	0.065
1.0	40.25	12.81	192	0.0667	192	0.0667	0.067
1.5	39.75	12.65	200	0.0633	200	0.0633	0.063
2.0	39.13	12.45	200	0.0623	200	0.0623	0.062
2.5	38.50	12.25	216	0.0567	NA	-	0.057
3.0	38.38	12.22	240	0.0509	NA	-	0.051
3.5	38.25	12.18	232	0.0525	NA	-	0.052
4.0	38.13	12.14	232	0.0523	NA	-	0.052
4.5	38.00	12.10	248	0.0488	208	0.0582	0.053
5.0	38.56	12.27	200	0.0614	184	0.0667	0.064
5.5	39.13	12.45	192	0.0649	192	0.0649	0.065
6.0	39.13	12.45	200	0.0623	200	0.0623	0.062
6.5	39.13	12.45	208	0.0599	200	0.0623	0.061
7.0	39.19	12.47	216	0.0577	232	0.0538	0.056
7.5	39.25	12.49	192	0.0651	176	0.0710	0.068
8.0	39.13	12.45	176	0.0708	184	0.0677	0.069
8.5	39.00	12.41	184	0.0675	192	0.0647	0.066
9.0	38.94	12.39	200	0.0620	192	0.0646	0.063
9.5	38.88	12.37	192	0.0644	184	0.0673	0.066
10.0	-	-	-	-	-	-	

Pile E4:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	39.75	12.65	272	0.0465	208	0.0608	0.054
1.0	39.38	12.53	208	0.0603	224	0.0560	0.058
1.5	39.00	12.41	176	0.0705	168	0.0739	0.072
2.0	38.50	12.25	168	0.0729	312	0.0393	0.056
2.5	38.30	12.19	216	0.0564	NA	-	0.056
3.0	38.10	12.13	216	0.0561	NA	-	0.056
3.5	37.90	12.06	208	0.0580	NA	-	0.058
4.0	37.70	12.00	208	0.0577	NA	-	0.058
4.5	37.50	11.94	200	0.0597	200	0.0597	0.060
5.0	37.44	11.92	184	0.0648	224	0.0532	0.059
5.5	37.38	11.90	224	0.0531	208	0.0572	0.055
6.0	37.69	12.00	224	0.0536	200	0.0600	0.057
6.5	38.00	12.10	200	0.0605	192	0.0630	0.062
7.0	37.75	12.02	224	0.0536	200	0.0601	0.057
7.5	37.50	11.94	200	0.0597	208	0.0574	0.059
8.0	38.06	12.12	184	0.0658	184	0.0658	0.066
8.5	38.63	12.29	224	0.0549	168	0.0732	0.064
9.0	38.41	12.23	192	0.0637	200	0.0611	0.062
9.5	38.19	12.16	224	0.0543	168	0.0724	0.063
10.0	38.19	12.16	160	0.0760	224	0.0543	0.065

Pile E5:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (µs)	North-South Direction Velocity (in/µs)	East-West Direction Stress Wave Time (µs)	East-West Direction Velocity (in/µs)	Avg. Velocity (in/µs)
0.5	39.50	12.57	240	0.0524	NA	-	0.052
1.0	39.44	12.55	208	0.0604	NA	-	0.060
1.5	39.38	12.53	208	0.0603	208	0.0603	0.060
2.0	39.31	12.51	208	0.0602	184	0.0680	0.064
2.5	39.25	12.49	216	0.0578	240	0.0521	0.055
3.0	39.44	12.55	256	0.0490	240	0.0523	0.051
3.5	39.63	12.61	208	0.0606	224	0.0563	0.058
4.0	39.69	12.63	176	0.0718	184	0.0687	0.070
4.5	39.75	12.65	240	0.0527	232	0.0545	0.054
5.0	39.75	12.65	224	0.0565	200	0.0633	0.060
5.5	39.75	12.65	200	0.0633	NA	-	0.063
6.0	39.75	12.65	248	0.0510	248	0.0510	0.051
6.5	39.75	12.65	248	0.0510	256	0.0494	0.050
7.0	40.13	12.77	216	0.0591	224	0.0570	0.058
7.5	40.50	12.89	240	0.0537	264	0.0488	0.051
8.0	40.13	12.77	296	0.0431	360	0.0355	0.039
8.5	39.75	12.65	208	0.0608	248	0.0510	0.056
9.0	39.75	12.65	280	0.0452	288	0.0439	0.045
9.5	39.75	12.65	200	0.0633	320	0.0395	0.051
10.0	39.75	12.65	248	0.0510	240	0.0527	0.052

Pile E6:

Location from Top (ft)	Circumference (in)	Diameter (in)	North-South Direction Stress Wave Time (μs)	North-South Direction Velocity (in/μs)	East-West Direction Stress Wave Time (μs)	East-West Direction Velocity (in/μs)	Avg. Velocity (in/μs)
0.5	39.25	12.49	200	0.0625	208	0.0601	0.061
1.0	39.00	12.41	184	0.0675	192	0.0647	0.066
1.5	38.33	12.20	192	0.0636	NA	-	0.064
2.0	38.67	12.31	208	0.0592	NA	-	0.059
2.5	38.50	12.25	208	0.0589	224	0.0547	0.057
3.0	38.38	12.22	200	0.0611	264	0.0463	0.054
3.5	38.25	12.18	168	0.0725	200	0.0609	0.067
4.0	38.00	12.10	208	0.0582	216	0.0560	0.057
4.5	38.04	12.11	216	0.0561	NA	-	0.056
5.0	38.08	12.12	224	0.0541	NA	-	0.054
5.5	38.13	12.14	184	0.0660	256	0.0474	0.057
6.0	38.44	12.24	240	0.0510	232	0.0527	0.052
6.5	38.75	12.33	184	0.0670	184	0.0670	0.067
7.0	38.75	12.33	184	0.0670	288	0.0428	0.055
7.5	38.75	12.33	224	0.0551	248	0.0497	0.052
8.0	39.03	12.42	216	0.0575	216	0.0575	0.058
8.5	39.31	12.51	192	0.0652	192	0.0652	0.065
9.0	38.91	12.38	200	0.0619	192	0.0645	0.063
9.5	38.50	12.25	208	0.0589	208	0.0589	0.059
10.0	38.50	12.25	200	0.0613	280	0.0438	0.053

VITA

Victor Rangel Cueto

Candidate for the Degree of

Master of Science

Thesis: STRESS WAVE TIMING, A SIMPLISTIC AND COST EFFECTIVE METHOD TO EVALUATE DETERIORATED AND REPAIRED TIMBER BRIDGE PILES

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Amherst, Texas, on June 27, 1980, the son of Edmundo and Rakel Cueto.

Education: Graduated from Amherst High School, Amherst, Texas in May 1999; received Bachelor of Science in Civil Engineering from Texas Tech University, Lubbock, Texas in May, 2005. Completed the requirements for the Master of Science degree with a major in Civil Engineering at Oklahoma State University in July, 2007.

Experience: Employed by Oklahoma State University, Department of Civil Engineering as a graduate teaching assistant, Fall 2005 to Summer 2006. Employed by Oklahoma State University, Department of Civil Engineering as a research assistant, Summer 2006 to Spring 2007. Employed by Department of Transportation as an Engineering Tech. IV, Summer 2003 and Summer 2004.

Professional Memberships: Precast/Prestressed Concrete Institute.

ABSTRACT

Name: Victor Rangel Cueto Date of Degree: July, 2007

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: STRESS WAVE TIMING, A SIMPLISTIC AND COST EFFECTIVE METHOD TO EVALUATE DETERIORATED AND REPAIRED TIMBER BRIDGE PILES

Pages in Study: 111 Candidate for the Degree of Master of Science

Major Field: Civil Engineering

Scope and Method of Study: The purpose of this study was to develop a simplistic and cost effective technique to evaluate deteriorated and repaired timber piles. Stress wave timing was conducted on two bridges. Nine deteriorated timber piles were extracted from a bridge on State Highway 76 in Oklahoma and evaluated at Oklahoma State University. The nine deteriorated timber piles were inspected for decay and were repaired using cost effective materials. An important objective was to correlate the amount of materials needed to repair the deteriorated piles to stress wave timing and physical dimensions. A second bridge was evaluated in a field inspection located in Cotton County, Oklahoma. Eleven of the twelve timber piles were repaired in-service and all were evaluated via stress wave timing. The objective was to observe if the repair technique was adequate and to see if the decay and voids were removed during repair.

Findings and Conclusions: Stress wave timing was found to be an adequate tool to evaluate deteriorated and repaired timber piles. All of the timber piles were repaired with materials that consisted of fiberglass wrap, epoxy resin and if needed aggregate/epoxy injections. The repair technique resulted in significantly reducing the stress wave travel timing in the piles, proving the decay removal and filling in of the voids was successful. For the bridge located on State Highway 76, equations were developed between stress wave timing and repair materials. The equations can be used to estimate the amount of material needed to repair deteriorated piles. Therefore, stress wave timing can be used to analyze the amount of material required to return the structural integrity of deteriorated timber piles. The repair method on Cotton County Bridge was concluded to be structurally sound and the pile left unrepaired should be re-evaluated and repaired before decay progresses.

Advisor's Approval: Robert N. Emerson