NDE SYSTEM FOR DETERMINING WOOD GUARDRAIL POST INTEGRITY

FINAL PROJECT REPORT

by

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16. Abstract

Wood guardrail posts degrade over time and a nondestructive evaluation (NDE) inspection system is needed to determine the condition of the nearly 2 million posts along our highways to prioritize future investments in maintenance. A robust, cost-effective stress wave technique was developed that addressed deficiencies in current equipment with regard to accuracy, ease of use and worker safety; efficient ways to acquire/store/transmit data; along with heuristics to interpret data and guide decision-making on guardrail maintenance and replacement.

The stress wave timing (SWT) technique was judged most promising, and a prototype device was developed with an industrial partner. The system includes wireless communication features and can be operated with a smart phone app. The system was validated with over 200 guardrail posts that were removed from service and tested at the WSU campus. Field-testing of the device occurred on December 18, 2014 with WSDOT personnel in a western Washington location. Internal conditions of the posts were accurately detected in 86% of the specimens. The device also successfully detected the internal condition of all posts inspected during a field test. An inspection procedure was recommended for implementation using SWT in conjunction with drilling of posts that are suspected to have decay. Field inspection protocol, training materials and final report were developed and presented to WSDOT staff in Olympia on June 1, 2015. A final project report was submitted to WSDOT on June 29, 2015.

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Executive Summary

During the initial stages of this project, a survey was sent to departments of transportation (DOTs) across the United States and Canada. The responses revealed that many of these departments had minimal or no procedures for regular inspection of guardrail systems utilizing wood posts. Nevertheless, among DOTs that had observed issues with longevity or performance of wood posts, decay and deterioration were typically cited as the primary concerns. The survey results also showed that the majority of responding DOTs, including the Washington State Department of Transportation (WSDOT), allowed the installation of new guardrail systems with wood posts. These results led to the conclusion that a quick and reliable way to assess the decay and deterioration condition of wood guardrail systems would be useful for WSDOT and many other DOTs. Based on available research, stress wave timing was selected as the most appropriate technology to accomplish this goal due to its accuracy, ease of use, portability, low cost, and rapid testing capabilities.

The WSU researchers worked with a local industrial partner, Metriguard, Inc., to develop a new stress wave timing prototype that built upon previous stress wave technology and improved measurement accuracy, repeatability, and reliability. Additional features were developed to allow interfacing, via Bluetooth, with portable computers or mobile phones for data acquisition and storage as well as cloud connectivity.

The instrument was validated through a series of nondestructive and destructive tests of 193 posts of varying ages and internal conditions from multiple locations across Washington State. The prototype accurately characterized approximately 86% of the posts tested. This accuracy could be further improved in the field by using a testing procedure that combines stress

wave timing and drilling to confirm results. Additionally, nine of the 193 posts failed to meet AASHTO standards for post strength during destructive testing. The prototype successfully identified that each of those particular test specimens had advanced decay.

After laboratory testing, the prototype was taken into the field to characterize interior post condition at a location in western Washington that was scheduled for maintenance. Employees on a WSDOT maintenance crew and the researchers each attempted to identify posts with interior degradation and decay, based on visual inspection, sounding, and probing. Sounding tests indicated several posts might have internal decay. Then, the same posts were tested with the NDT prototype. The results indicated that all posts tested at the maintenance location were sound. After being tested with the stress wave timer, the posts were drilled and it was confirmed that no decay was present. The field tests demonstrated the superior accuracy of the prototype NDT device as compared to visual and sounding methods.

The results from field and laboratory testing suggest that the prototype is useful as a device to identify posts with potentially impaired performance due to decay. The device could also be used to identify sound posts that might otherwise be unnecessarily removed during routine repair or safety improvement work. From this research, the value and usefulness of the new stress wave prototype is apparent for WSDOT and for DOTs in general.

Chapter 1 Introduction

Washington State has an estimated 2000 to 2500 miles of installed highway guardrails. This corresponds to approximately 1.5 to 2 million guardrail posts, and many of those posts are wood. As these wood guardrail posts age, they can experience decay and deterioration that is not easy to detect through conventional inspection procedures. However, wood guardrail posts in Washington are currently replaced only when either the adjacent roadway is being repaved or there has been third-party damage. Other wood assets, such as timber bridge decks, undergo regular nondestructive evaluation inspections to determine when components need to be replaced. Unfortunately, the technologies used for these inspections are often too cumbersome or time-consuming to be used for testing a large number of wood posts. The goal of this project was to identify nondestructive evaluation techniques to assess conditions of wood guardrail posts. One of the most promising NDT technologies for this task, and the one selected for this project, was stress wave timing (SWT). With the use of SWT, it is possible to detect decay in wood guardrail posts before it can be detected with less sophisticated inspection procedures. This document is the final report for this project, and it includes background information on current inspection techniques and technologies used by departments of transportation (DOTs) throughout the United States and Canada. This information is based on a survey conducted by the Washington State Department of Transportation (WSDOT) at the beginning of this research project.

1.1 DOT Survey Results

This project began with a survey about practices related to wood post installation and maintenance, in North America, that was sent to all DOTs in the United States and Canada. The results showed that while 84% of respondents worked for agencies that allowed installation of new wood guardrail systems, about 43% of respondents had no regular guardrail inspection or maintenance. In addition, only five of the 21 DOT respondents indicated a guardrail inspection or maintenance schedule outside of construction or collision reports, and only five DOTs indicated using an inspection technique other than visual inspection. A map of the survey response is shown in figure 1.1.

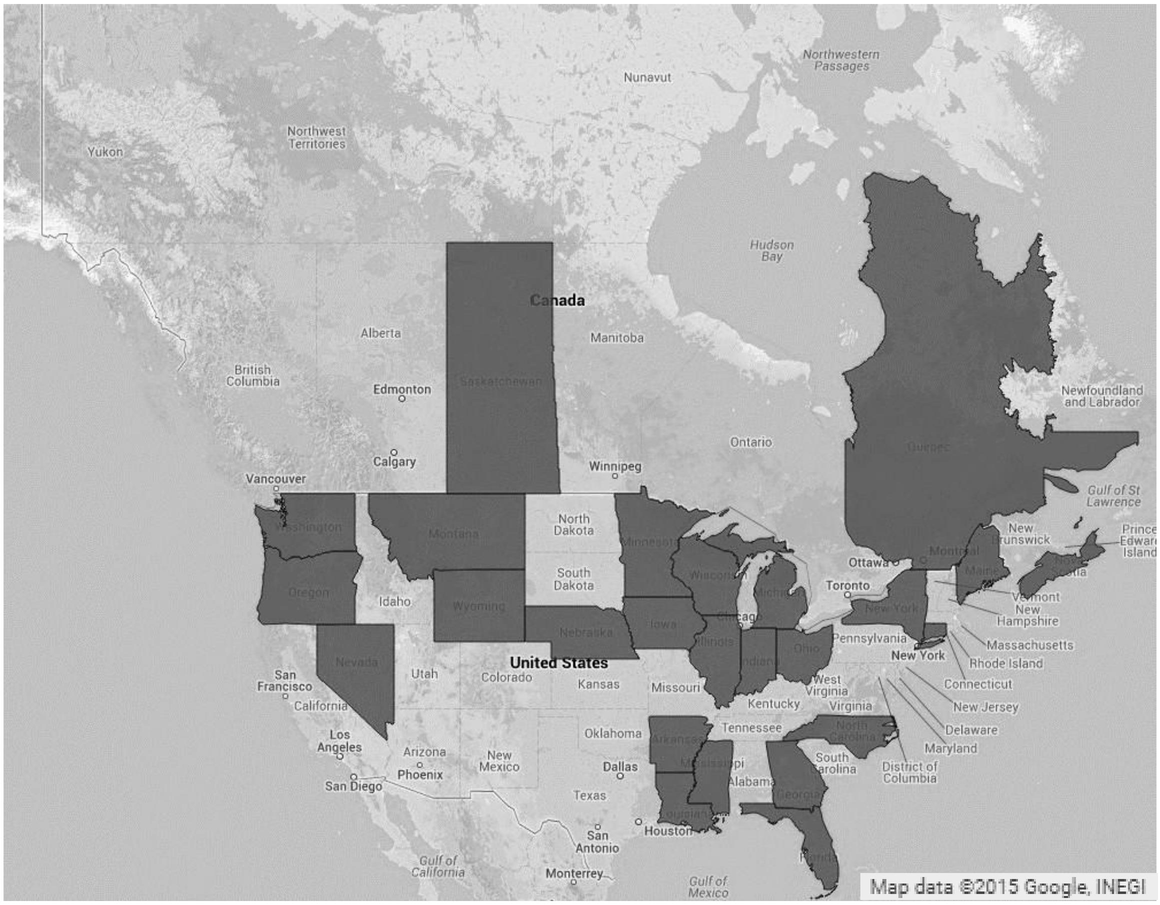


Figure 1.1 State and territory survey respondents

A comparison of the responses in figure 1.1 to the map of US decay regions in figure 1.2 indicates that the survey responses were collected from locations with varying decay hazard risks. The decay zones in figure 1.2 range from the least severe decay conditions in zone 1 to the most severe decay conditions in zone 5 (USDA 2013).

Figure 1.2 Decay severity zones for wood poles

The results of the survey are summarized in table 1.1.

Table 1.1 Summary of survey results

1a. Has your agency experienced significant issues with either the longevity or performance of either wood or steel guardrail posts?		#	%
a.	Yes	9	36%
b.	No	16	64%

1b. Issues			
a.	wood deteriorates/decays	6	67%
b.	wood shears off in landslides	1	11%
c.	wood is harder to install than steel	1	11%
d.	wood deteriorates/decays and steel corrodes	1	11%

1c. Mitigation techniques			
a.	replace damaged wood posts	3	33%
b.	replace damaged wood posts with steel	3	33%
c.	replace damaged wood posts and/or add cap	1	11%
d.	replace damaged wood posts when paving	1	11%
e.	no current mitigation strategy	1	11%

2a. Does your agency have a guardrail asset management system?			
a.	Yes	5	23%
b.	No	17	77%

2b. If yes, what software package does your agency use?			
a.	Excel/spreadsheets	2	40%
b.	AGILE	1	20%
c.	Custom bridge management system	1	20%
d.	Unknown	1	20%

2c. If yes, how are wood guardrail installations tracked and managed?			
a.	from data gathered during periodic inspections	1	33%
b.	Excel/spreadsheets	2	67%

2d. If yes, how is lifecycle calculated?			
a.	from data gathered during periodic inspections	1	33%
b.	using deterioration curves inside the BMS	1	33%
c.	it isn't	1	33%

3a. Do you have a dedicated funding mechanism to replace wood guardrails?			
a.	Yes	3	12%
b.	No	22	88%

3b. Further Comments on Funding			
a.	dedicated from safety or maintenance and ops	3	30%
b.	discretionary from capital or maintenance and ops	6	60%
c.	discretionary from pavement preservation projects	1	10%

4. Does your agency allow wood guardrails in new construction?			
a.	Yes	21	84%
b.	No	4	16%

5a. Does your agency perform a periodic inspection and maintenance of wood guardrail posts?			
a.	Yes	12	57%
b.	No	9	43%

5b. Inspection methods used			
a.	visual inspection	7	58%
b.	visual inspection and sounding or probing	2	17%
c.	visual inspection and occasional coring	1	8%
d.	inspection based on FHWA guidance	1	8%
e.	inspection based on department procedures	1	8%

6. What specification(s) do you use when procuring wood posts?
19 responses - all unique

7. Do you use or have you considered using a performance specification for posts?			
a.	Yes - TL-3	1	6%
b.	No	16	94%

8. When did your agency stop allowing use of wood guardrail posts?			
a.	within the past 10 years	2	40%
b.	within the past 20 years	0	0%
c.	within the past 30 years	2	40%
d.	unknown	1	20%

9. Why did your agency stop allowing use of wood guardrail posts?			
a.	maintenance issues/longevity concerns	2	40%
b.	constructability	0	0%
c.	cost of disposing of old posts	0	0%
d.	problematic transitions to bridge connections	0	0%
e.	a. & c.	1	20%
f.	a., b., and d.	1	20%
g.	unknown	1	20%

Chapter 2 Review of Previous Work

To supplement the results of this survey, technical literature was studied for both nondestructive testing (NDT) and destructive testing (DT) procedures and technologies that are suitable for timber members. Timber that is exposed to weather is typically pressure treated with preservative chemicals. The chemical can only penetrated a few centimeters, resulting in a protective shell of treated wood. Hence it is important that NDT techniques be used on wood components to avoid compromising the exterior treatment shell. NDT methods are also often faster than DT procedures or minimally invasive techniques. Of all the available techniques, the most widely used NDT and DT methods are briefly summarized below.

2.1 Visual Inspection

Visual inspection is a relatively quick and simple assessment of post condition based on appearance. It is difficult recognize signs of decay in wood guardrail posts by appearance alone, so some training or expertise is required for maximum effectiveness. Visual inspections are convenient for field work because no addition tools are required by the inspector. However, visual inspection alone is the least accurate method of those listed for assessing internal damage and decay. Pressure treatment on western timber species typically only penetrates through a small amount of the exterior of the post, leaving an interior, untreated core. Decay typically occurs in this untreated core, resulting in posts that may appear fine, with an external treated shell of wood, despite severe deterioration. For more information on the use and usefulness of visual inspection, see (USDA 2013) and (ODOT 2012).

2.2 Probing

Probing is another relatively quick and simple inspection technique. Like visual inspection, probing requires some training or expertise for maximum effectiveness in the field. Probing involves inserting a sharp object to probe or pick at wood, especially in areas of suspected decay. Soft wood or minimal resistance indicates possible decay or damaged wood. This test can be used only near the surface of a wood specimen, so, without additional drilling, it is not particularly accurate for detecting internal deterioration. For more information on probing, see (ODOT 2012), (USFS 1990, Ch. 13 1990), and (Seavey and Larson 2002).

2.3 Drilling and Coring

Both drilling and coring are minimally invasive and involve drilling into specimens. Drilling is based on using a device, from a handheld drill to a more expensive, commercial resistance-drill, to assess interior wood condition. While drilling, higher resistance indicates sound wood while lower resistance or a sudden drop in resistance indicates unsound wood. Coring involves using a specialized hollow bit to remove a small sample core from a specimen. Some information can be determined by looking at the core but, typically, the core is sent to a laboratory for further analysis to assess decay and preservative chemical assays. Both coring and drilling penetrate the treated shell on wood guardrail posts, so specimens must be re-sealed with a treated wood dowel or the application of a sealant. Both of these minimally destructive methods can also be used to locate pockets of decay near the ground line with reasonable accuracy. They are not recommended for standalone inspection use due to the time-consuming nature of drilling or coring each post to be inspected, but their occasional use, along with other inspection methods, can be quite useful. For additional information on drilling and coring, see (Anthony 2004), (Brashaw et al. 2005a), and (Seavey and Larson 2002).

2.4 Sounding

Advanced training or experience is required for sounding, but testing is rapid. This method involves impacting the specimen with a sounding hammer or other tool and listening to the resulting sound. Sound wood will have a “clear” or “ringing” sound, while decayed wood will have a “dull” or “thudding” sound. Sounding can be affected by many things besides decay, such as moisture content and surface conditions. Additionally, it is most effective on members less than 4 inches thick. For more information on sounding, see (Ross et al. 1999), and (Seavey and Larson 2002).

2.5 Stress Wave Timers

A stress wave timer measures the transit time of a stress wave (plane wave) as it travels from a transmitter to a receiver. In general, sound wood results in a faster stress wave transit speed, while decayed wood results in a slower wave speed. This method has rapid testing capabilities and utilizes low, typically audible frequencies (less than 20 KHz). These low frequencies result in lower resolution for detecting defects but less wave attenuation when compared to higher frequency systems such as ultrasound. Important considerations for stress wave include: wave travel path, imparting a repeatable stress wave, detecting the wave front for accurate start and stop timing, species-specific wood density, and other field conditions. For more information on stress wave timing, see (Ross and Pellerin 1994), (Hoyle and Rutherford 1987), (Hoyle and Pellerin 1978), (Ross et al. 1999), (Emerson et al. 2002), (Brashaw et al. 2004), (Brashaw et al. 2005b), (Seavey and Larson 2002), and (Wacker 2010).

2.6 Ultrasound

Ultrasonic testing is similar to stress wave timing but uses higher frequencies (50 KHz–500 KHz) and requires advanced training to interpret results accurately. These higher frequencies can provide higher resolution but are subject to more rapid wave attenuation.

Ultrasonic testing devices measure transit time and record the wave-form for a bulk, or dilatation, wave. Signal processing is then used to detect the presence of decay and other defects. This method requires good coupling for a strong signal, often through the use of a coupling gel. Important considerations for ultrasound include: coupling, wave attenuation in larger specimens, signal processing, and cost. For more information on ultrasound, see (Emerson et al. 2002), (Seavey and Larson 2002), (Krautkrämer and Krautkrämer 1990), and (Bray and Stanley 1997).

2.7 Near Infra-Red Spectroscopy

Near infrared (NIR) spectroscopy uses wavelengths close to the infrared spectrum to assess surface chemistry that can be correlated to various wood properties. Advanced training is required to interpret NIR spectroscopy results, and the necessary equipment is expensive and not very portable. For more information on NIR spectroscopy, see (Rammer 2005).

2.8 Radioscopy

Radioscopy uses x-ray imaging to produce highly detailed images of the interior condition of specimens, but it requires both advanced training and significant time to set up for a single specimen. The testing machines are also expensive and not very portable. This primarily limits x-ray testing to highly efficient scanning configurations, such as grading machine evaluated lumber in large lumber mills. For more information on radioscopy, see (Anthony 2004), (Wei et al. 2011), and (Poranski 1996).

Chapter 3 Selection of Stress Wave Timing

While there are many inspection techniques available with varying advantages and disadvantages, there is currently no inspection schedule for WSDOT to examine and quantify the internal condition of timber guardrail systems quickly and efficiently. Based on the review of current NDT methods, a stress wave timing system was selected as the most appropriate technology for further consideration and development for testing wood guardrail post condition. This is due to its robustness, ease of use with minimal training, low cost, portability, rapid testing potential, and history of successful use for inspection of wood components. Coupled with visual inspection and drilling to confirm readings of decay, stress wave timing can be used to reliably assess the internal conditions of wood posts within a guardrail system. Thus, a new stress wave timer that employs updated technology for data management and analysis is a promising route for NDT analysis of guardrail systems. Combining this updated technology with GPS and GIS data has the potential to provide an extremely useful system to catalogue and monitor existing guardrail assets while providing long term predictions of localized life cycles for wood posts in different regions.

3.1 Fundamentals of Stress Wave Timing

Stress wave timing is based upon measuring the transit time for the leading edge of a plane wave to travel from one location on a specimen to another location. Typically, a stress wave timer incorporates one start accelerometer and one stop accelerometer. The start accelerometer is often attached to an impact device that is used to impart the stress wave into a specimen, and the stop accelerometer is placed on the other side of the specimen. This configuration is known as a pitch-catch or time-of-flight setup, shown in figure 3.1

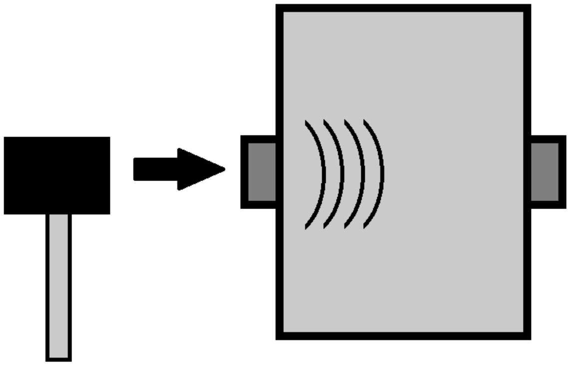


Figure 3.1 Pitch-catch testing setup

The underlying physics of stress wave timing is described by the relationship between wave speed, density, and the modulus of elasticity for a plane wave as shown in equation 1.1 or, alternatively, equation 1.2.

$$E_D = \rho c^2 \qquad (1.1)$$

$$c = \sqrt{\frac{E_D}{\rho}} \qquad (1.2)$$

where E_D = material dynamic modulus of elasticity (psi),

c = wave speed (in/s),

ρ = mass density (lb_m/in^3) = $\frac{\gamma}{g}$,

g = gravitational constant (in/s^2), and

γ = material density (lb_f/in^3).

This results in equation 1.3

$$c = \sqrt{\frac{!_!!}{!}} \qquad (1.3)$$

For a pitch-catch setup, the wave speed is simply related to the distance in the direction of wave travel and the time the wave takes to traverse that distance, as stated in equation 1.4.

$$c = \frac{!}{!} \qquad (1.4)$$

where L = travel distance (in) and

t = travel time (s).

Substituting this in to equation 1.3 yields the following

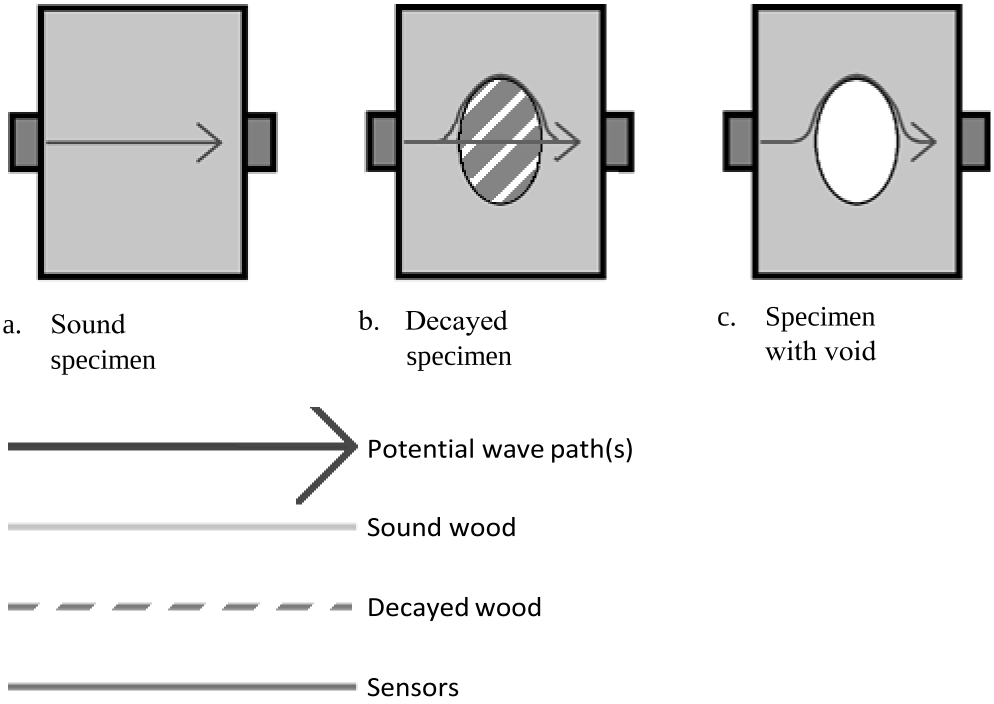
$$\frac{!}{!} = \sqrt{\frac{!_!!}{!}} \qquad (1.5)$$

By eliminating the constant variable g, the result shows

$$\frac{!^!}{!^!} \propto \frac{!_!}{!} \qquad (1.6)$$

Decay results in a decrease of both γ and the E_D for a sample; however, E_D initially declines at a much faster rate due to decay compared to density, meaning that in early stages of decay, there can be a significant loss of bending stiffness and strength with almost no change in density. As fungal deterioration advances, microscopic tendrils, or hyphae, spread through the surrounding wood. These hyphae use enzymes to break down the cellular bonds of wood during the early stages of decay, without removing significant amounts of material (Wilcox 1968; the USDA Wood Handbook 2010). This stage of decay is referred to as insipient decay. This decay progression results in the bending strength of a specimen being dominantly proportional to the inverse of the square of the travel time for a given specimen. More generally, E_D is closely proportional to the square of stress wave speed, c.

Travel distance, L, must be measured along the wave path to calculate true stress wave speed. This is simply a direct path between a transmitter and receiver in sound wood. However, if an irregularity is severe enough, the stress wave cannot travel along a direct path. Figure 3.2 shows three common scenarios that affect stress wave times. In Figure 3.2c, the measured wave speed is still based on the assumed travel distance, which is simply the length of the direct path between the transmitter and the receiver. This assumption results in an "apparent wave speed" rather than a true wave speed. This apparent wave-speed is what is actually used to estimate the interior condition of a specimen. An increase in travel time typically means the wave has traveled through either a section of material with a lower stiffness, due to decay or some other defect (shown in Figure 3.2b), or along a longer path (shown in Figure 3.2b and 3.2c).



a. Sound specimen

b. Decayed specimen

c. Specimen with void

Figure 3.2 Possible stress wave travel paths in various specimens

There are many commercially available stress wave timers; however, they tend to be somewhat cumbersome to use, or lacking in modern features. Table 3.1 is a reproduction of a table from a study comparing several available stress wave timers.

Table 3.1 Comparison of ratings for stress-wave equipment evaluated[a] (Brashaw et al. 2005)

	Metriguard 239A	Sylvatest Duo[b]	Fakopp
Accuracy	Good	Good	Good
Reliability	Good	Good	Good
Variablility	Medium	Low	Low
Ease of Use	Better	Good	Best
Size	Large	Small	Small
Display	Easy to see	Difficult to see	Easy to see
Key Consideration	Accelerometers must be orientated properly	Probes are places in pre---drilled contact holes	Spike---mounted transducers provide good contact

[a] IML Electronic Hammer not included; see comments in appendix of (Brashaw et al. 2005).

[b] Based upon placing probes in small contact holes, direct-contact method not recommended.

Many factors can affect stress wave times; however, most factors can be quantified or avoided. The most common field conditions affecting wave timers are shown in table 3.2, along with their estimated possible effects. Wood defects, such as checks, splits, and knots, can have an especially drastic effect on wave transmission times and should be carefully avoided when using a stress wave timer to detect decay.

Table 3.2 Approximate effects of various field conditions of stress wave speeds

Factor (baseline)	**Relative influence**
Species (Doug-fir)	+6% (western cedar) to -4% (southern pine)
Growth ring orientation (radial)	-20% (tangential)
	-65% (45° angle)
Checks and splits (none)	May block stress wave totally
Preservative treatment (none)	None (water-borne)
	-6% (petroleum solvent)
Temperature (70 F)	+6% (0 F) to -2% (120 F)
Decay (none)	-40% (moderate)
	-70% (advanced)

The assumed conditions for testing are listed in parentheses on the left. Percent change in wave speed is shown on the right (Hoyle and Rutherford 1987), with the condition that results in the changes listed in parentheses next to the effect.

As can be seen from table 3.2, if a mostly radial test path is used, relative to growth rings, and checks and knots are avoided, then decay can be detected. This fact is particularly true of advanced decay because other conditions will have only a minor effect on stress wave readings.

When compared to radial stress wave speeds, a tangential stress wave path, relative to growth rings, results in a drop in wave speeds of up to 25%; however, a stress wave path approximately halfway between radial and tangential (at a 45° angle to the rings) results in a drop in wave speeds of up to 65%. This large drop in wave speeds between radial and tangential paths is due to a non-linear relationship, related to stress wave path, which may not be intuitive. This effect has been observed by multiple researchers and is shown in figure 3.3 (Hoyle and Rutherford 1987).

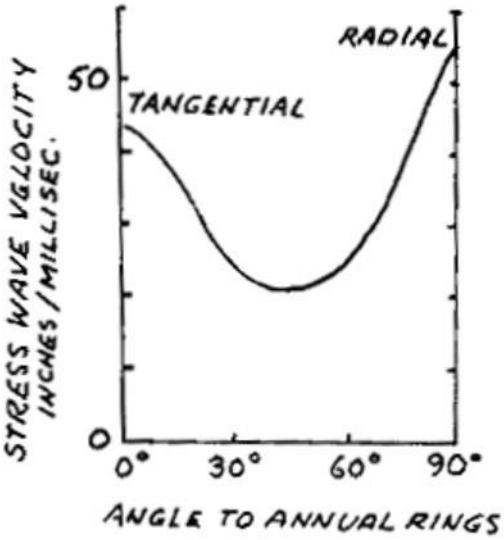


Figure 3.3 Effect of stress wave timer orientation relative to growth rings

Chapter 4 Methods

This section summarizes the materials and approaches used for laboratory nondestructive testing, as well as destructive testing and field testing. More details can be found in Appendix B.

4.1 Materials

4.1.1 Prototype

Once stress wave timing was selected as the preferred NDT technique, a new prototype stress wave device with improved ergonomics, computing software, and Bluetooth connectivity was developed. This system also utilized new technology to provide more accurate and precise results while making data recording much simpler than in older stress wave timer systems. In addition to improved signal processing, the device used a solenoid to automatically impact a sample three times and record the corresponding sample stress wave times. The software then calculated the standard deviation between the three results and, if the three samples were not within a pre-defined threshold, the device repeated the test procedure. If necessary, the prototype notifed the user to reseat the clamp. This system was validated with laboratory testing, and field testing was conducted to verify its usefulness.

4.1.2 Test Specimens

To test the new stress wave timing prototype, 205 wood guardrail posts were obtained from WSDOT. These posts were nearly all previously installed posts from various regions in Washington State. Six of the delivered posts had never been installed or used. For a complete list of post location, years in service, and years out of ground, refer to Appendix A. Many of the posts had been removed and placed in “bone yards” for years or even decades before arriving at WSU for testing. Still, these posts provided a range of internal wood conditions from no detected internal decay (114 posts) to advanced or severe decay (33 posts). Twelve posts were not tested in the lab but were instead used to help develop and modify the new stress wave prototype. In total, 193 posts were tested.

4.2 Laboratory Procedures

Before NDT, each post was identified with a number and marked every one to two inches for reference. The center of the bolt-hole pattern on each post was used as the origin. Then, length, width, depth, treatment type, and orientation of growth rings at the end were noted on a reference sheet. Visible defects were also noted on the sheet. A blank reference sheet, as well as a filled example sheet, are shown in Appendix C. Once the post details were noted, pictures were taken of the posts in two orientations: in line with the bolt holes and perpendicular to the bolt holes.

4.2.1 Nondestructive Testing

For NDT, posts were initially tested every two inches, except near the ground line and in areas of large fluctuation in wave transmission times. However, it was faster to test posts every inch, and this method was used for the majority of the posts tested. The SWT prototype was placed near the center of the post at each location and clamped firmly into place. Then the device was used to measure a transmission time and wave speed at each location. The results were recorded to a spreadsheet with the location noted. NDT was performed along the posts, both in line with the bolt holes and perpendicular to the bolt holes.

4.2.2 Destructive Testing

Posts were set up for strong axis bending in a three-point bending test, with the load centered on the ground line to simulate conditions similar to a guardrail post in a collision. Supports were placed at the center of the bolt-hole pattern and at an equidistant location, opposite the ground line (GL). Deflection was measured at the GL using a potentiometer attached at the center of the beam. This setup is shown in figure 4.1

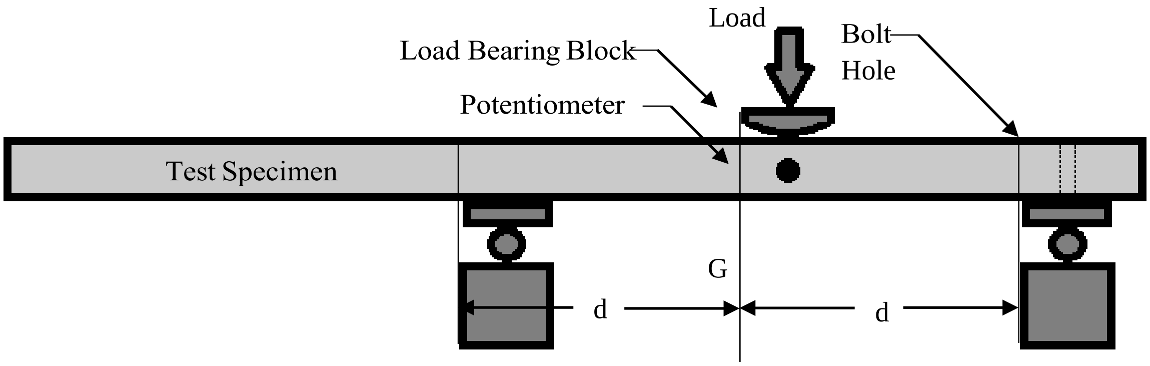


Figure 4.1 Destructive testing setup

This test closely followed ASTM D 198-09 with modifications to the test frame to more closely resemble conditions for guardrail posts in a collision. In addition, posts were loaded to failure between 30 seconds and 60 seconds. The loading at failure was compared to AASHTO M 168-07 section 5.4.1.2 with a minimum acceptable stress grade of 8.2 MPa, adjusted for load rate.

4.2.3 Moisture Content

Following destructive testing, a small slice was removed from each post, just beyond the testing area. This location was selected to be as close as possible to the test area, while keeping that tested section of post intact for later characterization of internal post condition. Once the slice was obtained, it was trimmed to remove the sections with preservative treatment. The dimensions of the remaining slice were then recorded. The sample slice was weighed, then oven-dried, and finally weighed again to estimate moisture content. Some example specimens, before oven drying but after being trimmed to remove outer, treated, areas, are shown in figure 4.2.

Figure 4.2 Example moisture content samples

4.2.4 Characterization of Internal Post Condition

Posts were rip-sawn in half, length wise, in line with the bolt holes. The internal condition was then visually characterized into three categories: no obvious decay, some decay, and advanced decay. After characterization, final pictures were taken of the posts, showing the internal view.

4.3 Field Testing Procedure

In addition to the thorough laboratory testing of the new prototype, a brief field test was conducted, under the supervision of WSDOT. A section of guardrail posts that had been scheduled for removal in western Washington State was selected and tested for possible decay. First, 15-20 suspect posts were chosen through the use of visual inspection and a sounding hammer. Then, these posts were tested with the prototype stress wave timer. After being tested with the timer, the posts were drilled to assess true interior condition at, and just below GL, where conditions are most favorable for decay.

Chapter 5 Results

5.1 Summary of Laboratory Testing Results

Initial photos were taken for each post from two orientations before NDT and DT. Figure 5.1 and figure 5.3 show photos taken in plane with the XX, or strong bending axis for post #52 and post #58 respectively. This axis was tested to bending failure during destructive tests. Figure 5.2 and figure 5.4 show photos taken in plane with the YY, or weak bending axis for post #52 and post #58 respectively.

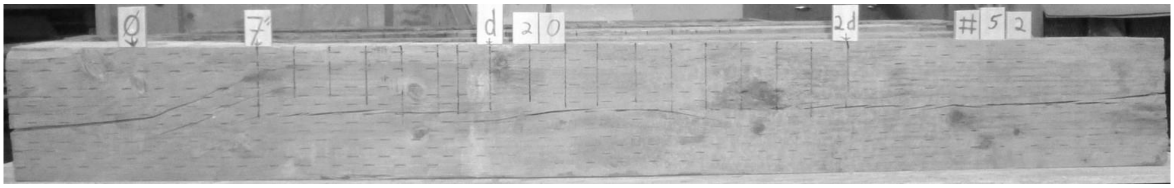


Figure 5.1 Exterior XX view of post 52 before destructive testing

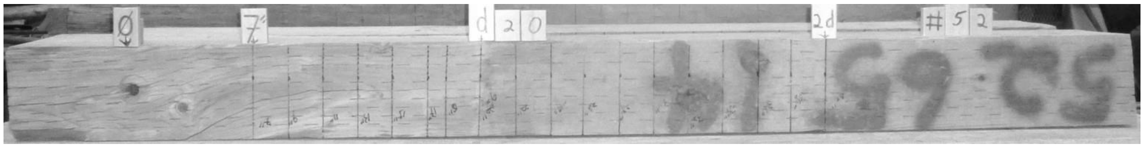


Figure 5.2 Exterior YY view of post 52 before destructive testing

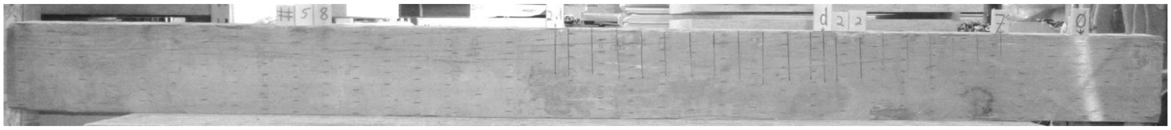


Figure 5.3 Exterior XX view of post 58 before destructive testing

Figure 5.4 Exterior YY view of post 58 before destructive testing

Following DT, each post was cut in half, length-wise, using a portable sawmill. The resulting halves were then inspected for signs of decay. The NDT plots of post #52 are aligned with the resulting halves and displayed in figure 5.5. Similarly, the NDT plots and resulting halves of post #58 are shown in figure 5.6.

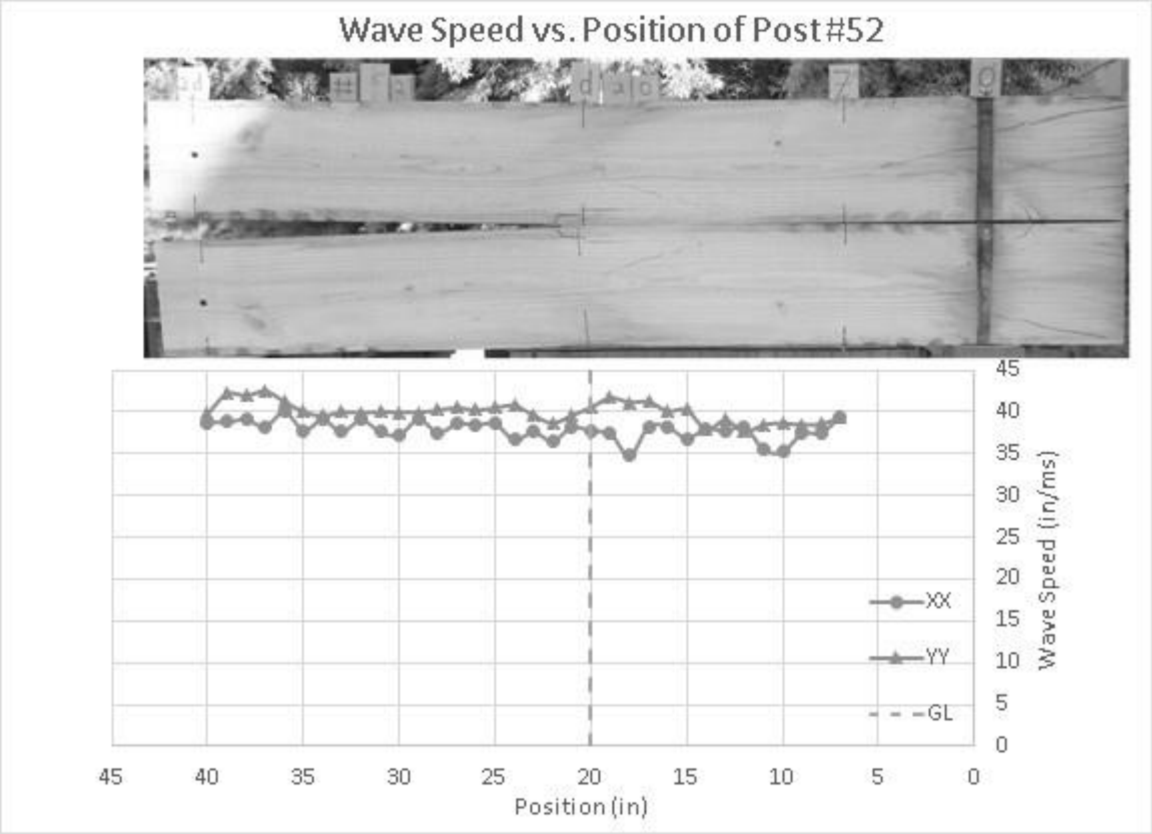


Figure 5.5 Internal view of a sound post (post #52) over wave speed vs. position

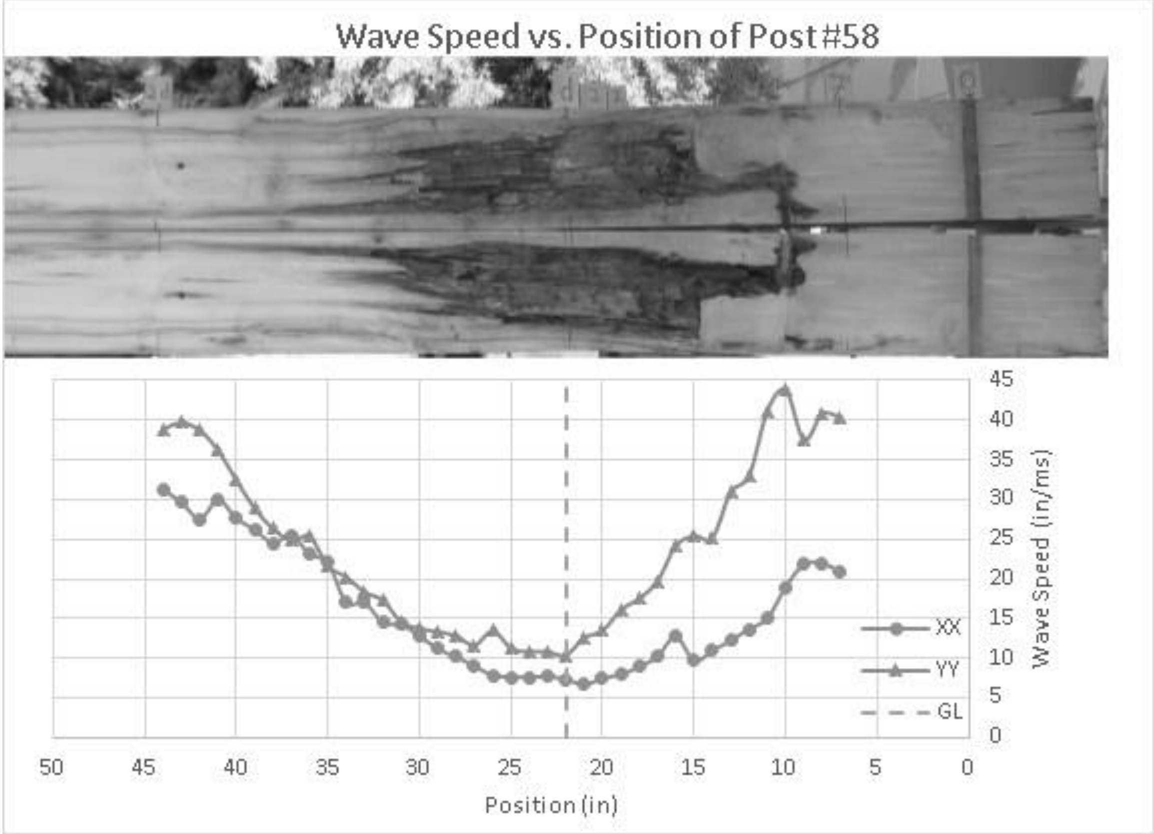


Figure 5.6 Internal view of a decayed post (post #58) over wave vs. position

Finally, the data from the internal inspection was compared to the NDT data collected with the prototype to gauge the accuracy of the device. The results of the investigation are summarized in table 5.1. The number of posts in each category are shown on the left and the corresponding percentage of tested posts is shown in parentheses on the right.

Based on the internal inspection, posts were put into three categories of “no obvious decay,” “some decay,” and “advanced decay.” Posts in which decay was not apparent were sorted into the first category, while posts which had some small pockets of decay, or decay which had not yet progressed to advanced decay, were sorted into the middle category. Advanced or severe decay was typically characterized by extremely soft and porous wood, easily crushed with a bare hand in the case of white rot. Similarly, with brown rot, advanced or severely decayed sections crumbled easily and often fell out of the post once it was cut in half. In both of these cases, the posts were placed in the “advanced decay” category.

The NDT readings for table 5.1 of “good” and “bad” were categorized based on two metrics. The first was a minimum absolute wave speed and the second is a slope based on the difference in measured wave speeds at two points on a single post. Good posts had a stress wave speed of more than 39 in/ms, and a slope greater than -1.1. If the post failed either of these metrics, it was flagged as bad.

Table 5.1 All posts rated based on decay level and prototype NDT

NDT Reading	No Obvious Decay	Some Decay	Advanced Decay
Good	121 (63%)	14 (7%)	7 (4%)
Bad	6 (3%)	19 (10%)	26 (13%)
		Total	193

Of the 193 posts tested in the lab, six posts, or 3.1%, were categorized as false positives, meaning that a good post was flagged as bad. Seven posts with advanced decay (3.6%) were categorized as false negatives. An additional 14 posts (7.3%) with some decay were categorized as good, leaving 166 posts, or 86.0% of the tested specimens, that were correctly sorted. In the field, follow-up drilling of the posts identified as "bad" by the stress wave technique would likely have correctly identified the six false positives under "No Obvious Decay," shown in table 5.1.

As expected, decay was observed to be most significant between the ground line (GL) and a few inches below GL. However, for a realistic field measurement, GL is the lowest position at which the wave speed can be easily measured. Based on measurements conducted on installed guardrail systems, the gap between GL and the bottom of the guardrail spacer block could be as little as six inches. So, although readings were taken along the post length, only the readings from the estimated ground line and six inches above were used to determine both the slope and minimum wave speed metrics. These are measurement positions that can be reasonably accessed in the field and are depicted in figure 5.7. In general, a negative slope (corresponding to a decrease in wave speed) from the higher position to the lower position on the post was indicative of possible decay near the GL.

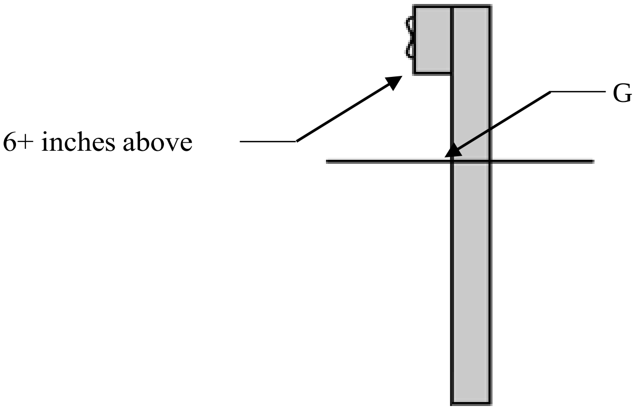


Figure 5.7 Profile view of a typical installed guardrail post

The AASHTO standards for guardrail performance recommend a failure capacity for guardrail posts of 8.2 MPa. Based on the destructive tests done in the lab, using a three point bending test, very few posts failed to meet this requirement. In fact, as can be seen in table 5.2, of the 193 posts tested to failure, only nine posts failed to meet the AASHTO minimum. The number of posts within each category is shown on the left, and the corresponding percentage of tested posts is shown in parentheses on the right.

Table 5.2 Posts sorted by performance to AASHTO minimum of 8.2 MPa.

Meets or Exceeds AASHTO	No Obvious Decay	Some Decay	Advanced Decay
Yes	127 (66%)	33 (17%)	24 (12%)
No	0 (0%)	0 (0%)	9 (5%)
		Total	193

7.2 Summary of Field Testing Results

Of the posts in the field that were identified as having decay using a sounding hammer, none were flagged as having advanced or severe decay by the stress wave timer. Drillings of the posts confirmed that the posts were sound.

Chapter 6 Discussion

6.1 Discussion of Laboratory Testing Results

Figures 5.1 to 5.6 suggest that visual inspection is not adequate for gauging internal decay. In fact, post #58, which had severe internal decay and extremely low stress wave speeds, showed little to no exterior signs of decay. This lack of external decay indicators emphasizes the need for more rigorous NDT inspection procedures to estimate the true internal condition of wood guardrail posts.

As might be expected, table 5.1 shows that the new stress wave timer is most accurate for determining when a post has no decay or when a post has advanced or severe decay. The device correctly identified 121 of 127 posts post no decay (95% accuracy) and 26 out of 33 posts with advanced decay (79%). For posts with some decay, the prototype successfully sorted 19 out of 33 posts (58% accuracy), indicating that it can also be used reasonably well to locate guardrail posts that are suspected of decay and in need of continued monitoring.

Table 5.2 shows that only posts with advanced or severe decay failed to meet the AASHTO minimum strength standard and, of those categories, about one third of the posts failed before reaching a loading consistent with the AASHTO requirement. The advanced decay condition of all of these specimens were detected by the prototype. This result indicates the potential of the prototype to effectively identifying guardrail posts that fall below or near the AASHTO minimum standard. When a wood member is loaded in bending, the outermost fibers resist most of the load. With treated wood guardrail posts, the outer treated shell is usually sound, thus explaining why so few posts failed to meet the AASHTO threshold.

6.2 Discussion of Field Testing Results

The field testing results indicated that the tested posts did not appear to be degraded by decay and, consequently, would not need to be removed due to decay. In the event that the posts were being considered for removal based upon service-life concerns these results would indicate that the posts could stay in service.

Chapter 7 Conclusions and Recommendations

SWT was the most appropriate NDT technology for rapid testing of highway guardrail systems. This technology provides a good balance for ease of use, without being cost-prohibitive. The resulting prototype from this research performed well, with an 86% success rate for identifying internal posts condition in the lab, as well as a successful field test. The device could be immediately deployed in the field with either the accompanying computer software or the freely available Android application.

It is recommended that the device undergoes further field testing and DOT use which can be used by the industrial partner, Metriguard Inc., to further improve and optimize the device. However, the prototype can already be used by WSDOT or other DOTs in a variety of ways:

(1) The device could be used to identify posts with internal decay that may be missed by conventional inspection techniques. Replacing these posts would increase highway safety, as well as reduce liability risks for WSDOT and other DOTs in the event of third party damage to a guardrail system. To accomplish this, WSDOT would need to adopt a standard inspection program for its wood guardrail post systems. Initially, this would mean a heightened awareness by WSDOT of sections of guardrail that have decay and have not yet been replaced. However, decay generally takes years to decades to develop, if at all, so a staggered inspection of guardrail systems is possible. Additionally, if a GIS database is established for guardrail posts, based on these inspections, state-specific regions could be identified in which wood posts perform better and last longer. This would give WSDOT the option of specifying more frequent inspections in areas with higher decay potential and less frequent inspections in those areas with less decay potential. Alternatively, WSDOT could specify regions where steel guardrail posts should be

used or preferred over wood posts. Eventually, WSDOT would be able to use all of this data to drastically reduce the number of in-service guardrail posts with decay, especially those posts with decay severe enough to prevent posts from performing to ASSHTO minimum standards.

(2) The prototype could also quantify the number of posts with decay, or degree of decay in guardrail sections when multiple locations are under consideration for replacement. This quantification would allow maintenance funding to be allocated more effectively to replace decaying guardrail posts and increase highway safety. This use of the prototype would not require a regular inspection procedure. Instead, users would need to conduct a field inspection only at the locations of interest. In the immediate future, these field inspections could serve as a good test for the current prototype in order to gather feedback for improvements.

(3) The device could locate decay in other timber assets, such as sign posts and bridge members. With minor modifications to the grip assembly, the prototype could be used to test a variety of components for decay; however, with little to no modification, it could be used to test sign posts for decay.

Although a policy on the collection and use of field testing data on wood posts does not currently exist at WSDOT, the availability of the method and device described in this paper provides options for those responsible for asset management policy going forward.

7.1 Field Testing Guidelines

Based on the field test, conducted to validate the prototype, and the strengths and weaknesses of each testing method used, a possible field testing procedure has been outlined in the flowchart in Figure 7.2. To determine the internal condition of a posts, in a section of guardrail, the following supplies are recommended, at a minimum: a stress wave timer and console; a sounding hammer or other sounding device; an electric hand drill, a resistance drill, or a test screw (described in Appendix D); a tape measure or a ruler; a sharp metal object for probing; treated wooden dowels, caulk, or other sealant to seal drill holes; gloves; weather-appropriate clothing; knee pads; pencils/pens; paper; boots; traffic flags and roadwork signage; and spray paint in two colors – one for questionable posts and one for bad posts.

7.2 Field Testing Flowchart

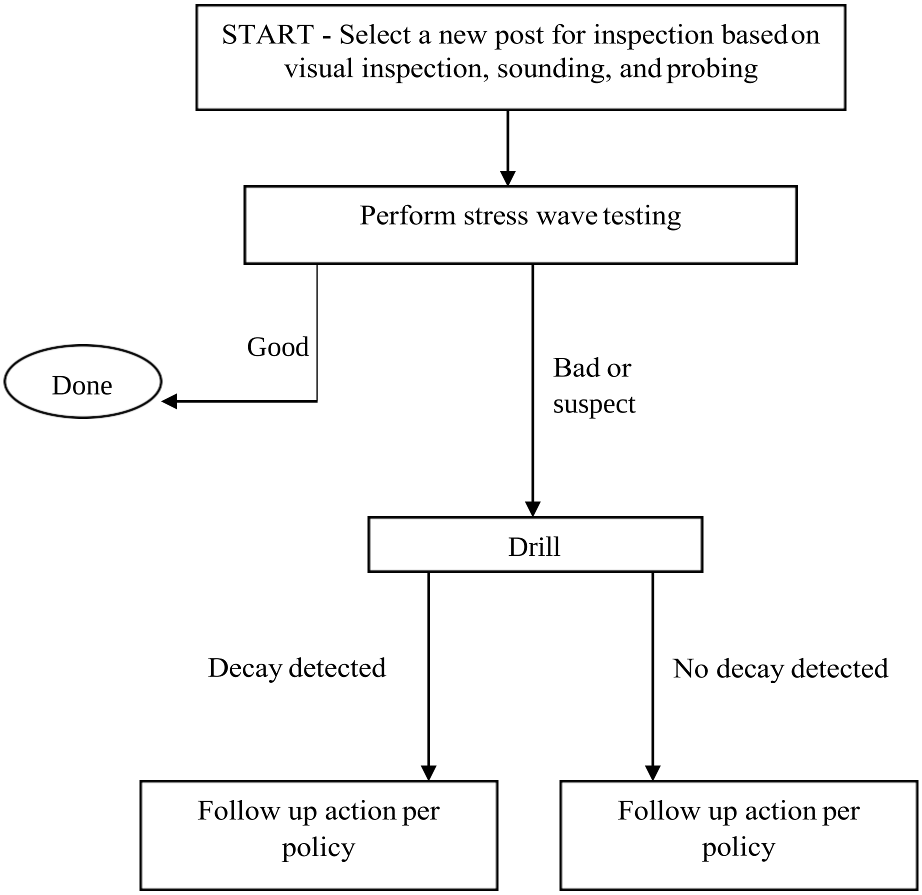


Figure 7.1 Suggested field testing procedure flowchart

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Appendix A Tabulated Post Information

. Size is given in nominal number of inches. Years in service and years out of ground are both estimated based on available data where possible. A "--" table entry indicates missing or unknown data.

Table A.1 Summary of the properties of all posts delivered by WSDOT

ID#	Total Length (in)	Marking	Size (in)	Region	Region #	Maintenance Area	Condition	Years in Service	Years out of Ground
1	108 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
2	108 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
3	71 12/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
4	71 14/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
5	72	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
6	72 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
7	57 9/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
8	71 11/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
9	72 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
10	59 13/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
11	83 13/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
12	65 13/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
13	71 15/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
14	71 15/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
15	72	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
16	72	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
17	71 15/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
18	71 12/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
19	72	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
20	96	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
21	71 14/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
22	72 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
23	65 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
24	72 3/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
25	72 1/16	Orange	6x8	Olympic	3	3 - Port Angeles	Used	20-30	1
26	71 14/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
27	71 14/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
28	71 15/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
29	72	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
30	71 15/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
31	71 15/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
32	71 15/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2

ID#	Total Length (in)	Marking	Size (in)	Region	Region #	Maintenance Area	Condition	Years in Service	Years out of Ground
33	71 14/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
34	71 14/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
35	71 13/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
36	71 14/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
37	71 14/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
38	71 13/16	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
39	72	No Mark	8x8	South Central	5	1 - Cle Elum	Used	40	2
40	65 1/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
41	71 12/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
42	65 1/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
43	67 5/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
44	66 7/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
45	64 14/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
46	71 12/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
47	66 3/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
48	62 12/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
49	65 5/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
50	61 4/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
51	60 11/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
52	65 14/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
53	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
54	94 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
55	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
56	96 1/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
57	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
58	95 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
59	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
60	95 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
61	96 2/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
62	95 14/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
63	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
64	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
65	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
66	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
67	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
68	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
69	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
70	95 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
71	95 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10

ID#	Total Length (in)	Marking	Size (in)	Region	Region #	Maintenance Area	Condition	Years in Service	Years out of Ground
72	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
73	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
74	95 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
75	95 15/16	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
76	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
77	96	White	6x8	Olympic	3	4 - Aberdeen	Used	--	10
78	72 2/16	No Mark	6x8	N/A	N/A	N/A	New	N/A	N/A
79	72 1/16	No Mark	6x8	N/A	N/A	N/A	New	N/A	N/A
80	72 2/16	No Mark	6x8	N/A	N/A	N/A	New	N/A	N/A
81	72 2/16	No Mark	6x8	N/A	N/A	N/A	New	N/A	N/A
82	72 2/16	No Mark	6x8	N/A	N/A	N/A	New	N/A	N/A
83	72 1/16	No Mark	6x8	N/A	N/A	N/A	New	N/A	N/A
84	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
85	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
86	71 14/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
87	71 14/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
88	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
89	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
90	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
91	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
92	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
93	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
94	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
95	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
96	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
97	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
98	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
99	71 12/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
100	71 14/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
101	71 13/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
102	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
103	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
104	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
105	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
106	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
107	71 13/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
108	71 15/16	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
109	72	No Mark	6x8	South Central	5	1 - Cle Elum	Used	40	2
110	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5

ID#	Total Length (in)	Marking	Size (in)	Region	Region #	Maintenance Area	Condition	Years in Service	Years out of Ground
111	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
112	64 13/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
113	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
114	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
115	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
116	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
117	67 7/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
118	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
119	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
120	72 4/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
121	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
122	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
123	63 9/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
124	62 12/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
125	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
126	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
127	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
128	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
129	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
130	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
131	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
132	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
133	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
134	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
135	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
136	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
137	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
138	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
139	72 3/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
140	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
141	63 11/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
142	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
143	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
144	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
145	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
146	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
147	66 13/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
148	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
149	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5

ID#	Total Length (in)	Marking	Size (in)	Region	Region #	Maintenance Area	Condition	Years in Service	Years out of Ground
150	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
151	71 10/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
152	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
153	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
154	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
155	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
156	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
157	72	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
158	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
159	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
160	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
161	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
162	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
163	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
164	72 4/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
165	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
166	72 2/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
167	69 7/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
168	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
169	72 1/16	No Mark	6x8	Northwest	1	4 - Kent	Used	20	0.5
170	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
171	107 14/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
172	107 15/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
173	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
174	108 2/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
175	107 15/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
176	107 15/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
177	95 12/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
178	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
179	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
180	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
181	96	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
182	107 15/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
183	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
184	108 1/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
185	108 2/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
186	83 14/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
187	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
188	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--

ID#	Total Length (in)	Marking	Size (in)	Region	Region #	Maintenance Area	Condition	Years in Service	Years out of Ground
189	107 15/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
190	83 14/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
191	96	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
192	83 9/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
193	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
194	108 3/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
195	108 1/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
196	107 14/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
197	107 15/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
198	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
199	108 1/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
200	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
201	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
202	108 3/16	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
203	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
204	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--
205	108	Green End	6x8	Southwest	4	1 - Vancouver	Used	--	--

Appendix B Detailed Testing Procedure

1. Identify specimen for testing
    a. Identify post. Note length of post and width in the direction(s) of wave travel
    b. Note end-grain orientation on provided data sheet.
2. Mark post for NDT and DT
    a. Orient post and mark apparent or approximate ground-line (GL), as well as marking every 1–2 inches.
    b. Note physical defects or inconsistencies, as well as location, on physical data sheet and take photos
3. Perform NDT
    a. Use the prototype to take NDT measurements every inch and record results for both x-x and y-y orientations, illustrated in figure B.1.

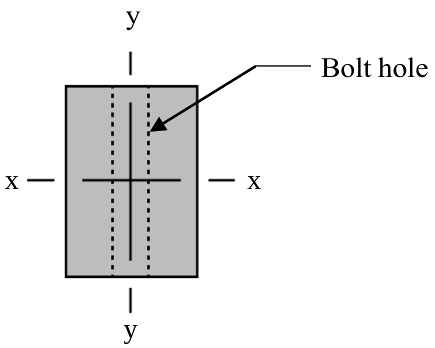


Figure B.1 Top-Down diagram of post orientation

4. Perform DT
    a. Position post on three-point center-bending apparatus, oriented so that force is applied parallel to the bolt holes.
    b. Attach a potentiometer at the neutral axis to measure deflection.
    c. Apply force incrementally at GL until failure, over 30 seconds to 60 seconds.
    d. Record force versus displacement, and note the maximum force and corresponding displacement on the data sheet.
5. Collect sample cores for decay organism and treatment analysis by OSU
    a. Collect, label, and store cores from each sample using the increment boring tools.

6. Measure moisture content (MC) and specific gravity
    a. Cut and trim a small slice from a relatively sound section of wood.
    b. Record sample weight and dimensions.
    c. Oven-dry the sample and record the weight again to estimate post MC and specific gravity.
7. Characterize internal condition and take final photos
    a. Cut pieces in half, lengthwise.
    b. Note areas of probably decay or insect damage
    c. Align pieces from each half and take pictures for comparison to NDT measurement results

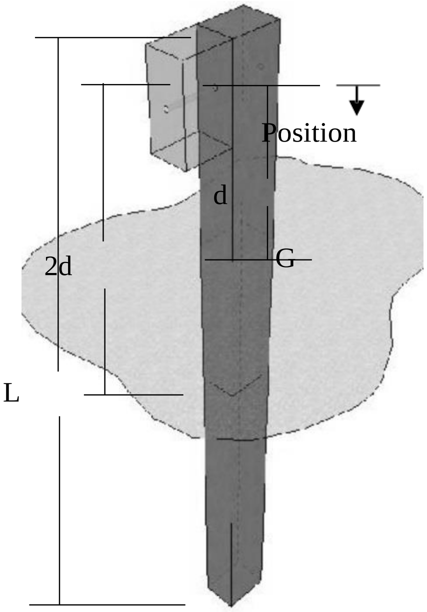
Appendix C Post Data Sheet Template and Example Sheet

Name: Project: Date:

Guardrail Post Info Sheet - #___/___

Post #	
Length (in.)	
Max Force (kips)	
Max Deflection (in.)	

	Width (in)	Height (in)
0”		
d		
2d		

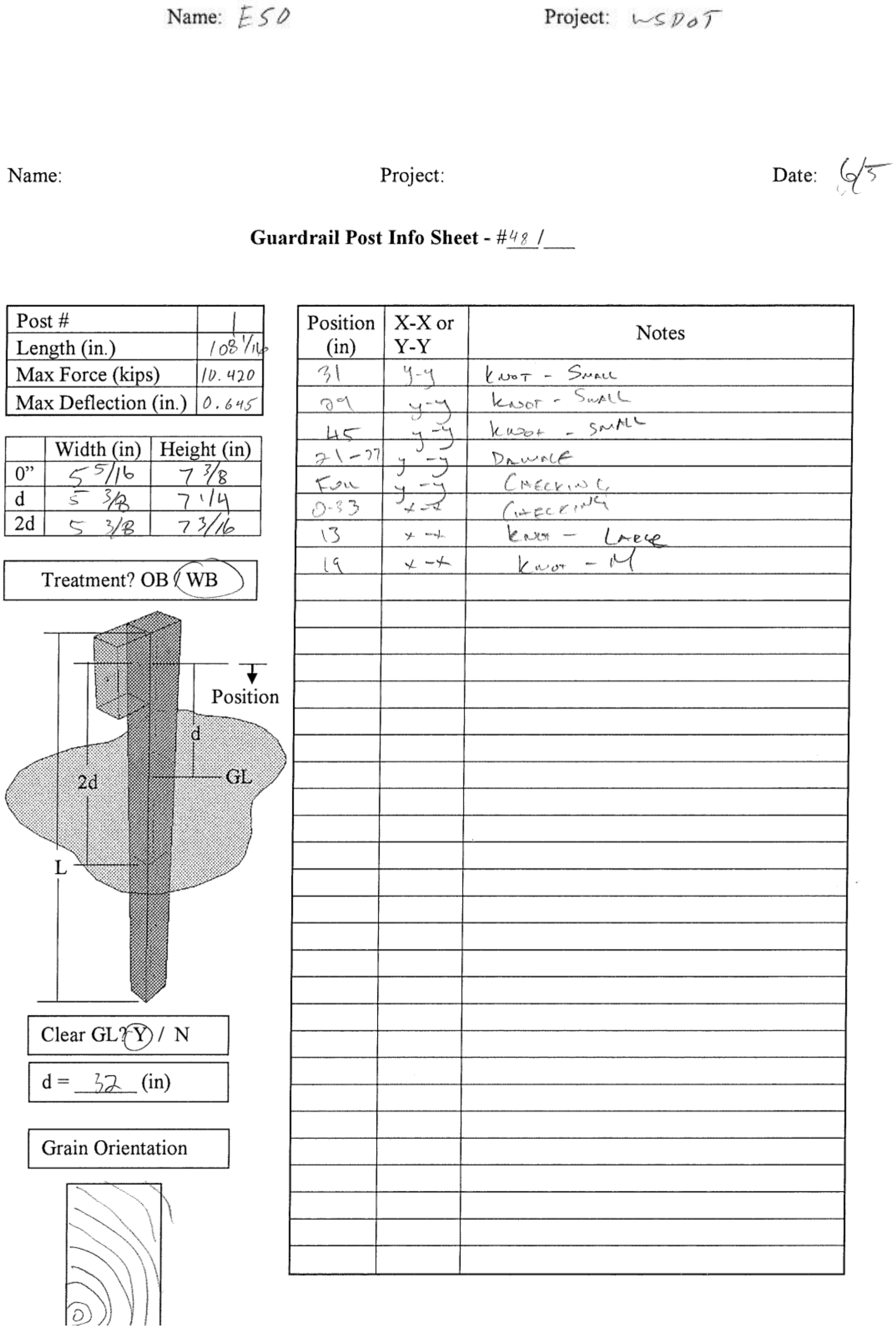


Clear GL? Y/ N

d = ______ (in)

Grain Orientation

Position (in)	X-X or Y-Y	Notes



Name: ESO

Project: WSDOT

Name:

Project:

Date: 6/5

Guardrail Post Info Sheet - #48 /___

Post #	1
Length (in.)	108 1/16
Max Force (kips)	10.420
Max Deflection (in.)	0.645

	Width (in)	Height (in)
0"	5 5/16	7 3/8
d	5 3/8	7 1/4
2d	5 3/8	7 3/16

Treatment? OB / [✓ WB]

Clear GL? [✓ Y] / N

d = 32 (in)

Grain Orientation

Position (in)	X-X or Y-Y	Notes
31	y-y	Knot - Small
29	y-y	Knot - Small
45	y-y	Knot - Small
21-27	y-y	Damage
Full	y-y	Checking
0-33	x-x	Checking
13	x-x	Knot - Large
19	x-x	Knot - M

Figure C.1 Example of filled-out guardrail post info sheet.

Appendix D Drilling Procedure and Screw Design

Recommended steps for the drilling test procedure to detect decay are listed below. The drill bit used in this research is shown in figure D.1 and specifications for the bit are described below figure D.1

1. Hold drill firmly, near the ground line, at an angle of 30-45°, and begin drilling at a uniform rate. Note any sudden drop in drilling resistance as a sign of internal decay.
2. Once the drill has penetrated halfway or more through the post, reverse drill direction and withdraw the bit. Apply as little pressure as possible to the drill during withdrawal. If no decay is present, the drill should drive the bit out of the post. If the drill gets stuck, the interior of the post may be decayed.
3. If the interior condition of the post is still unclear, a probe can be used in the drill-hole to check for soft pockets of decay or punky wood.
4. Finally, if the post is not going to be removed, seal the hole to prevent decay.

Figure D.1 Drill bit used for checking decay. The total modified bit length was 9.5 inches. The bit was created from a FastenMaster® HeadLok® HLGM010 heavy duty flathead fastener. The head was removed and the threads were machined down to four full turns, starting at the tip.