DEVELOPMENT AND CONDUCTION OF AN EXPERIMENT TO INVESTIGATE THE STATIC FRICTION INTERACTIONS BETWEEN A WOODEN CROSSTIE AND BALLAST MATERIAL

A Thesis

by

PETER HAMILL BAUER

Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	David Allen
Committee Members,	Mirjam Fürth
	Theofanis Strouboulis
Head of Department,	Sharath Girimaji

May 2022

Major Subject: Ocean Engineering

ABSTRACT

The focus of this research is on the friction interactions between railroad crossties and ballast material. These friction interactions change over time as the crossties experience continued loading due to passing trains. In order to investigate this topic, an experiment has been designed to observe the static friction coefficient, points of contact, and contact area between a crosstie and ballast material. The question arises as to whether there is a correlation between these factors and the number of loading cycles. The data collected in this experiment will be useful in ocean engineering applications such as the design of a seawall structure against a sand berm. This experiment was performed as part of a larger research effort examining railroad track buckling.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by a thesis committee consisting of committee chair Dr. Allen of the Department of Ocean Engineering and committee members Mirjam Fürth of the Department of Ocean Engineering and Theofanis Strouboulis of the Department of Aerospace Engineering.

All experimental set-up construction, experimental performance, data collection, and data analysis was completed by the student.

This work was also made possible in part by the Transportation Technology Center, Inc. (TTCI). Its contents are solely the responsibility of the author and do not represent the official views of TTCI.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

INTRODUCTION

Maritime transport is a critical to global commerce of the world today. Around 80% of global trade by volume is carried over the ocean and through ports. (United Nations, 2018). In the United States, railways play an important role in transporting goods to and from the sea ports. 35% of intermodal containers handled by the Port of Los Angeles utilize the Port's rail network. (The Port of Los Angeles, 2020). The Port of Houston, the largest port for waterborne tonnage in the United States (Port Houston, 2021), boasts 154 miles of track surrounding the Houston ship channel. (GoRail, 2016). Because rail transport is so vital to the ocean shipping industry, railroad structure stability is of significant interest to ocean engineers.

One of the most important causes of railroad structure instability is due to a loss of track lateral resistance. The track lateral resistance is any resistance which opposes the lateral movement or shifting of the crossties. (Samavedam et. al. 1995). Movements and misalignments of crossties create a weakened track structure and can lead to track buckling. Track buckling can lead to train derailments as well as lengthy and costly repairs. (Kish and Mui 2003). The majority of the track lateral resistance is the result of friction interactions between the bottom and sides of the crosstie and the ballast material. The friction on the sides of the crosstie can make up 30 to 35% of the lateral resistance while the bottom friction can make up 35 to 40%. (Zarembski 2013).

Because the friction interactions between the crosstie and ballast make up the majority of the lateral resistance, this friction is a crucial factor in track buckling. A proven way to increase lateral resistance is by increasing friction between the crosstie and the ballast material. There is evidence which suggests that ballast material will leave indentations on the bottom of wooden crossties when the crossties are subjected to vertical loadings from passing trains. These indentations result in increased ballast/crosstie friction interaction. (Zarembski 2013). Additionally, previous studies on track lateral resistance show that lateral resistance increases as the ballast consolidates. An example of one such study is shown in Figure 1 below.

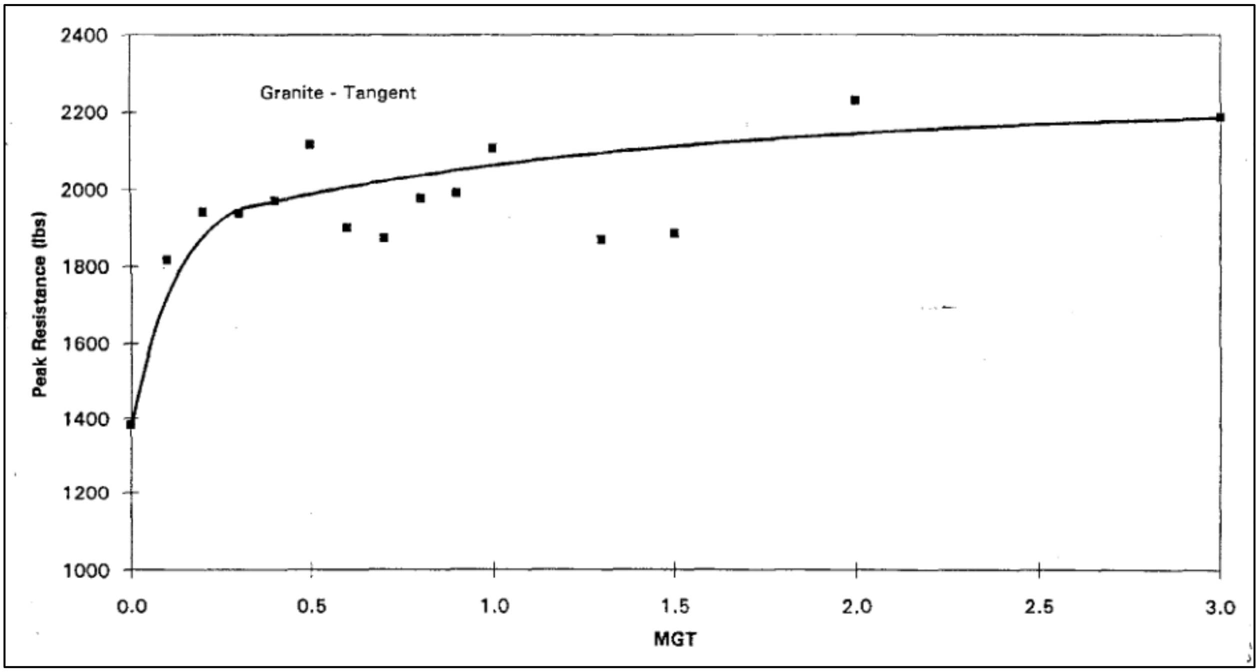

Figure 1: Ballast consolidation influence – Reprinted from Samavedam et al. 1995

Figure 1 shows the relationship between ballast consolidation, measured in million gross tons (MGT) of load passing over it, and peak lateral resistance, measured in pounds. The figure shows that as the ballast becomes more consolidated from increasing cycles of loading, the lateral resistance increases. (Samavedam et al. 1995).

This experiment observed the relation between loading cycles and the static friction coefficient between a wooden AREMA standard crosstie and ballast material. The static friction coefficient as a function of points of contact and contact area was also be explored. The results were analyzed to determine what effect increased cyclic loading and ballast consolidation had on static friction and contact interactions between the crosstie and ballast material.

RESEARCH FRAMEWORK

Problem Statement

The objective of this experiment is to investigate the friction interactions between an AREMA standard crosstie and ballast material to observe whether there is a correlation between these variables and the number of loading cycles the crosstie has experienced. The experiment is designed to collect three different data sets. The data points in each set are taken at different amounts of cyclic loading. The number of cycles being tested are 1, 2, 5, 10, 20, 50, and 100 cycles. The three data sets are listed below.

1. Static friction coefficient between the crosstie and the ballast material
2. Points of contact between the bottom of the crosstie and the ballast material
3. Contact area between the bottom of the crosstie and the ballast material

The results of the data collection will be used to determine whether a correlation exists between each of the data sets and the number of loading cycles.

Methodology

The experiment was constructed and performed in the laboratory in Room 006 of the Haynes Engineering Building (HEB) at Texas A&M University. The experiment objectives were completed using a testing apparatus that simulates a railroad crosstie embedded in ballast material. For this experiment, the crosstie is an AREMA standard wooden crosstie and the ballast material is composed of 1 inch limestone aggregate. A full description of the testing apparatus can be found in the EXPERIMENTAL SET-UP section of this document. One test outputs one data point for each of the data sets: static friction coefficient, points of contact, and contact area. Tests were run at 1, 2, 5, 10, 20, 50, and 100 loading cycles. Three tests were run for each of the aforementioned number of loading cycles for a total of twenty-one tests.

To test for the coefficient of static friction, a known weight is placed on top of the embedded crosstie. The weight is removed and reapplied to the crosstie to perform the cyclic loading. Once the desired number of loading cycles is reached, a lateral load is applied to the crosstie using a winch and chain. A spring is connected to the chain to act as a load cell. The winch slowly increases the lateral load until the crosstie begins to move. The displacement of the spring at this time is measured, and the magnitude of lateral loading is determined using Hooke's Law:

$$F = kx$$

where k is the known spring constant, x is the displacement, and F is the magnitude of the horizontal force. Once the force is determined, the static friction coefficient is determined by:

$$\frac{F}{F_N}$$

where F_N is the normal force. In this experiment, the normal force is equal to the sum of the weight of the crosstie and the know weight placed onto the crosstie. A schematic of the experiment can be seen in Figure 2 below.

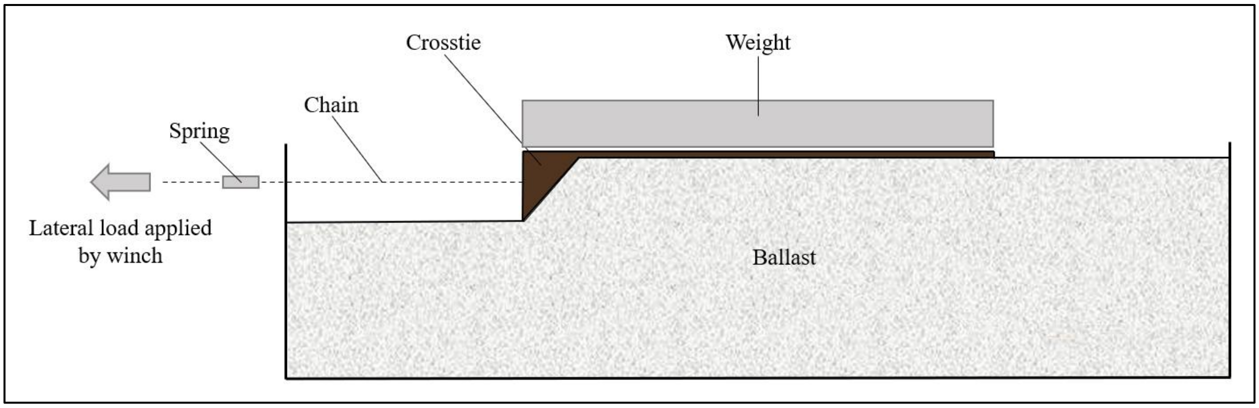

Figure 2: Experiment schematic

The points of contact and contact area are found by applying a thin layer of chalk to the bottom of the crosstie before embedding the crosstie in the ballast material. After the spring displacement is recorded, the crosstie is removed from the ballast material and turned over. Due to the movement caused by the lateral loading, the chalk on the bottom of the crosstie is disturbed at the points where the ballast material came in contact with the crosstie during the test. The number of markings is counted and measured to determine the points of contact and contact area, respectively. A full description of the experimental procedure for collecting the data for static friction coefficient, points of contact, and contact area can be found in the EXPERIMENTAL PROCEDURE section of this document.

EXPERIMENTAL SET-UP

The experimental set-up was designed and constructed as part of the overall research project. The set-up for this experiment is composed of three parts: the container which holds the crosstie and ballast, the crane and weight used to apply cyclic loading to the crosstie, and the pulling apparatus used to apply the lateral loading. Figure 3 shows the full experimental set-up.

Figure 3: Picture of full experimental set-up

Ballast Container and Crosstie

The first component of the experimental set-up is the box used to hold the crosstie and ballast. The main body was constructed using 3/4 inch plywood and 2x6 pine wood boards. The inner walls are composed of plywood, and the outer walls consist of four 2x6 boards on each side. The interior plywood forms the frame while the 2x6 boards provide support along the walls. The bottom is comprised of two layers of 3/4 inch plywood. The box sits on three legs each made of six stacked 2x6 boards. These legs lift the base of the box 10.5 inches off floor, so the crane used for the cyclic loading can be rolled underneath. The box is fastened by exterior wood screws and steel tie plates. All of the wood and fasteners used to construct the ballast container were purchased at the local hardware store and assembled using the tools provided in the laboratory. The interior of the box is measured 8x4x2 feet. Front, side, and top view drawings are shown in Figures 2, 3, and 4 below.

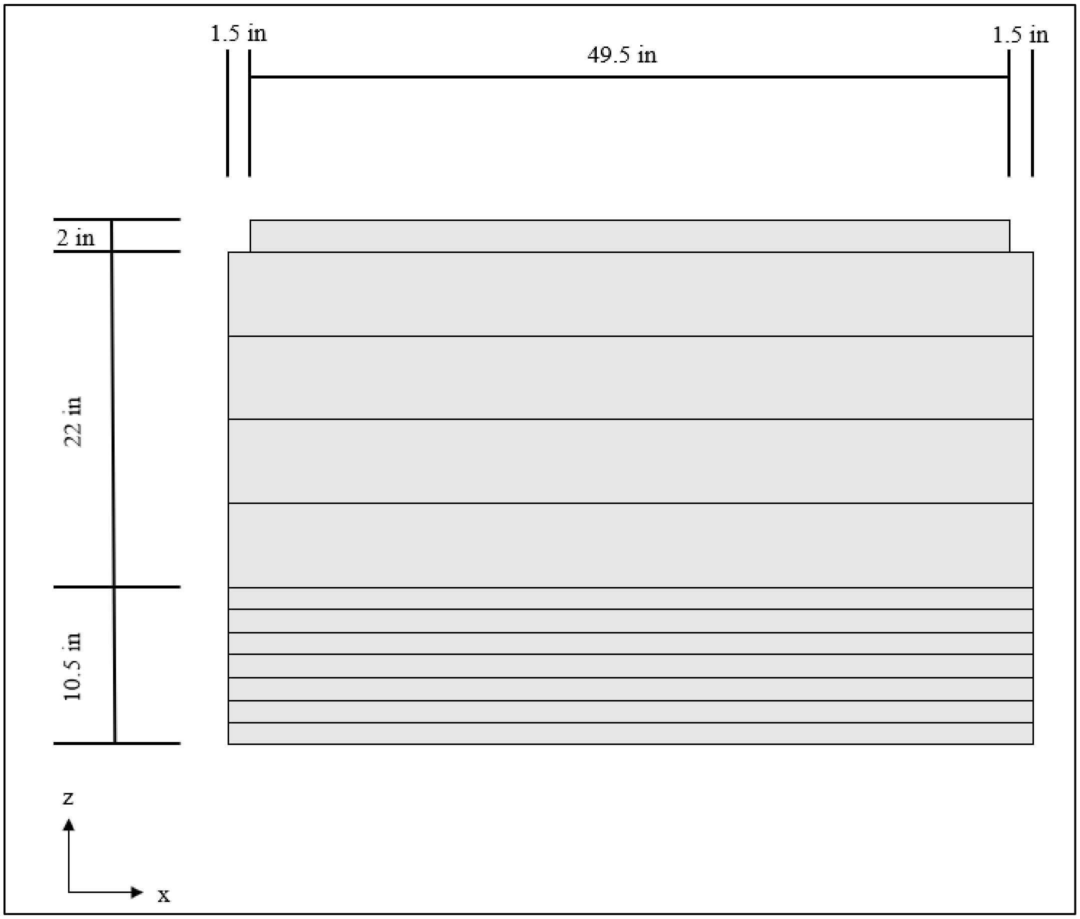

Figure 4: Front view of box

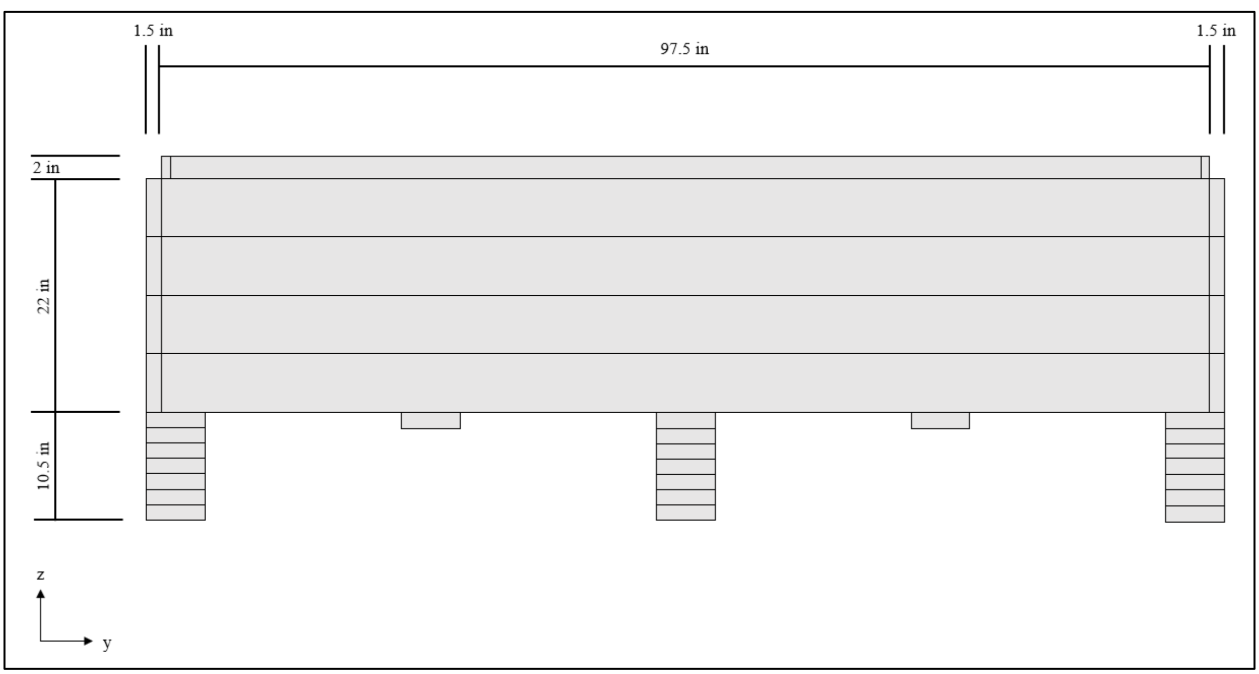

Figure 5: Side view of box

Figure 6: Top view of box

The interior is filled approximately 18 inches deep with 1 inch limestone aggregate which acts as the ballast. A hole is located on the front face of the box 16 inches above the floor. This is used to feed the chain on the lateral loading apparatus through the wall of the box to connect to the crosstie. The crosstie used is a 4 foot long section of an AREMA standard crosstie which is shown in Figure 7. A steel plate with a D-ring is attached to one end of the crosstie with 4 lag bolts. The D-ring, shown in Figure 8, is used as the anchor point between the crosstie and the lateral loading apparatus.

Figure 7: 4 ft crosstie section

Figure 8: Crosstie anchor point

Crane and Weight

The second component is the crane and weight used for cyclic loading. The crane is a 2 ton capacity engine crane with a hydraulic jack. The legs of the crane are on wheels which allows the crane to be rolled underneath the box. The weight is made up of eight pieces of steel, one of which is shown in Figure 9. Each piece weighs between 45 and 55 pounds. The steel pieces were weighed using a luggage scale accurate to 0.01 pounds. Each piece was weighed three separate times, and the three weights were averaged together to determine the weight used for calculations.

Figure 9: Example of steel pieces used

The steel pieces are held by a wooden container constructed out of 2x6 boards. The bottom of this container is of the same dimensions as the top face of the crosstie to distribute the load as evenly as possible. A chain wraps around the frame of the container and is attached to the hook of the crane to provide the connection for raising and lowering the weight. The wood and fasteners used to construct the weight container were purchased assembled using the tools provided in the laboratory. An image of the crane with the weight attached is shown in Figure 10.

Figure 10: Crane with weight container attached

Lateral Loading Apparatus

The final component of the design is the lateral loading apparatus. It consists of three parts: the frame, the winch, and the loading chain. The frame was constructed using 2x6 pine wood boards and exterior wood screws. It rests against the box on one side. On the opposite end, there is a 2x6 board which is attached to the frame at the same height as the hole cut into the front face of the ballast container.

An anchor point is attached to this board such that the ring is level with the center of the hole in the wall of the box. A 1/8 inch thick steel bar is also bolted to the board to provide additional support. This anchor point serves as the connection between the frame and the winch. The winch used is a 1200 pound capacity come-along winch.

Figure 11: Frame anchor point

The hook on the ratchet side of the winch is attached to the anchor point, and the hook on the cable side is attached to the loading chain using two 5/16 inch diameter shackles. The loading chain is a 3/8 inch chain with a grab hook pinned on one end and an extension spring hooked to the other. The other end of the spring is hooked to the shackles attached to the cable side of the winch, and the grab hook is fed through the hole in the front face of the ballast container and attached to the anchor point of the crosstie. All of the parts used to construct the loading apparatus were purchased at the local hardware store and assembled using the tools provided in the laboratory.

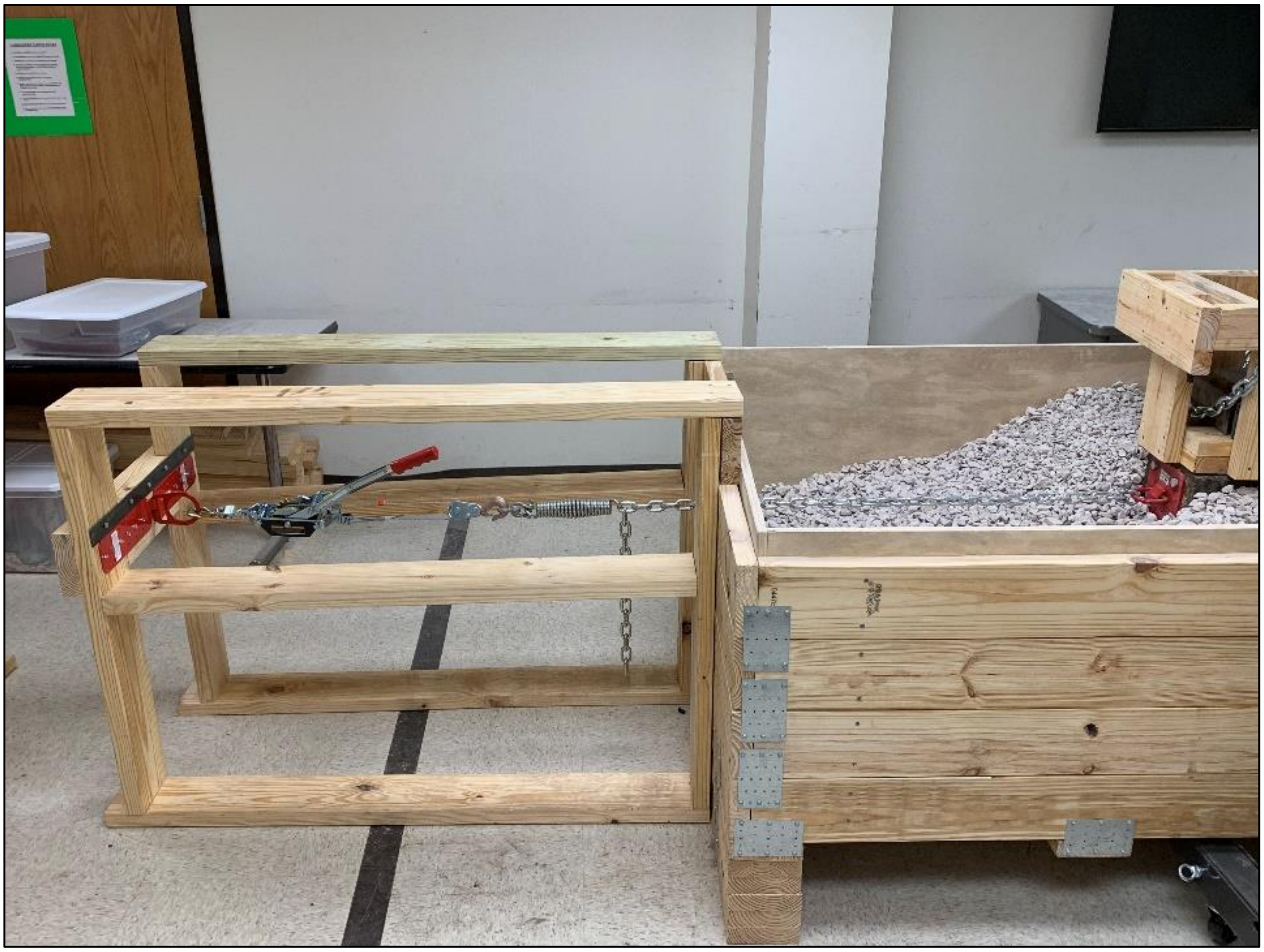

Figure 12: Fully connected load train

EXPERIMENTAL PROCEDURE

The experimental procedure was designed to collect data for lateral loading on the crosstie, points of contact between the bottom of the crosstie and the ballast, and the area of those points of contact. Multiple tests were conducted to observe how this data changes due to varying numbers of loading cycles. One test resulted in a data point for lateral loading, points of contact, contact area, and number of loading cycles. There were three tests conducted across seven different loading cycles resulting in a total of twenty-one tests. The number of cycles tested was 1, 2, 5, 10, 20, 50, and 100 cycles. The experimental procedure for an individual test can be divided in to four steps: preparing the crosstie, cyclic loading, lateral loading measurement, and contact measurements.

Preparing the Crosstie

In order to record an accurate measurement of lateral loading, the anchor point of the crosstie must be level with the chain of the lateral loading apparatus. To ensure the crosstie will sit in the proper position, it is pulled out from the center of the ballast and placed along the side wall of the box. Using a shovel, a trench in the ballast is dug out in the center of the box (Figure 13). The ballast that is shoveled out is placed along the walls of the box and will be used for embedding the crosstie later. Once the trench is formed, the crosstie is placed into the trench and connected to the loading chain to check that it is correctly aligned (Figure 14). If the crosstie is sitting too low or too high, it is removed, and more ballast is added or removed from the bottom of the trench. The crosstie is then placed back into the trench, and connected to the loading chain once more. This process is repeated until the crosstie sits at a height such that the anchor point is in line with the lateral loading apparatus. After the crosstie is in the correct position, a final check is performed to confirm that the crosstie lies flat on the ballast. If the trench is slightly sloped, the crosstie will be angled with respect to the lateral loading apparatus, and the accuracy of the measurement can be affected.

Figure 13: Trench for crosstie alignment

Figure 14: Checking for correct crosstie height and alignment

Once the crosstie is determined to be aligned with the loading chain and lying flat on the ballast, it is removed from the trench and turned upside down. A thin layer of marking chalk is applied to the bottom of the crosstie. Any excess chalk is shaken off, and a photograph of the chalked crosstie is taken. One of these photographs can be seen in Figure 15. Next, the crosstie is turned chalked-side down into the trench. This is done carefully to ensure that as little chalk is disturbed as possible. It is crucial that the crosstie is placed in line with the loading chain when it is rotated into place. Any adjustments made to the crosstie's position after it is turned over will disturb the chalk and affect the points of contact measurement. If the crosstie is not placed correctly, it will need to be turned back over, have the chalk layer removed, and have a new chalk layer applied.

Figure 15: Example of chalked crosstie

After the crosstie is chalked and rotated into the correct position, it must be embedded within the ballast. Ballast that was shoveled to the side to make the trench is repositioned around the crosstie so that the back and sides of the crosstie are covered. The front face of the crosstie, on which the anchor point is attached, is left uncovered. When the crosstie is fully embedded, the test is ready to begin applying the cyclic loading. An image of the fully embedded crosstie can be seen below in Figure 16.

Figure 16: Fully embedded crosstie

Cyclic Loading

Applying vertical, cyclic loading to the crosstie is the next step in the experimental procedure. This is achieved using the crane and weight described in the experimental set-up. To begin, the steel weight container is jacked up using the crane so that the bottom of the container clears the wall of the ballast container holding the crosstie. The crane legs are rolled underneath the ballast container until the steel weight container is positioned above the crosstie. The weight container is slowly lowered onto the crosstie, and small adjustments are made to the crane positioning to ensure the weight container is adequately aligned with the crosstie.

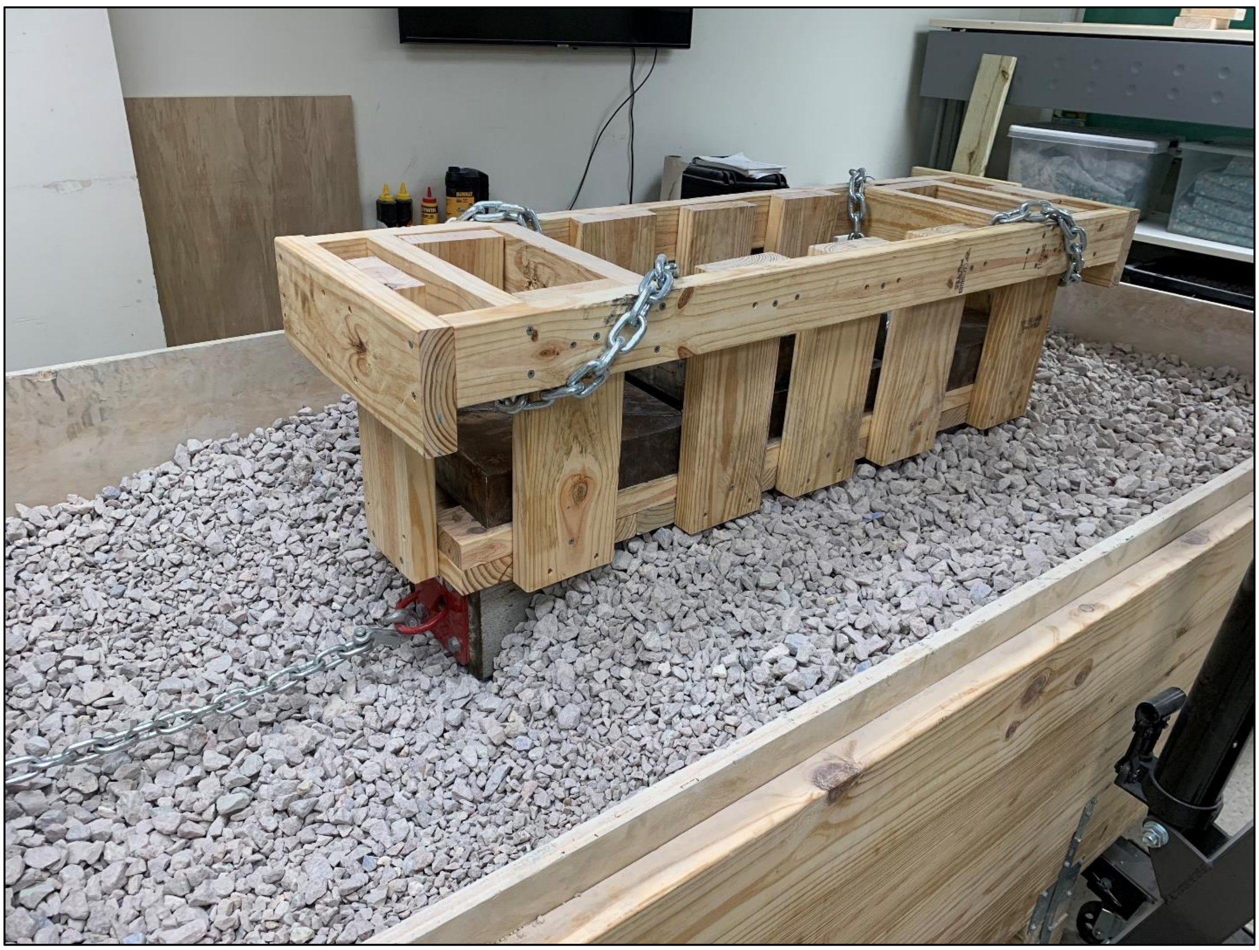

Figure 17: Crosstie with weight applied

When the alignment is complete, the weight container is raised approximately 1 inch above the crosstie (Figure 18). Once in this position, the valve on the crane jack is fully opened allowing the weight container to fall onto the crosstie. One raising and falling of the weight container equates to one cycle of loading. This is repeated until the desired number of cycles is reached. The weight container is left sitting on top of the crosstie and detached from the crane after the loading cycles are completed. When the desired number of cycles is achieved, the crosstie is ready to undergo lateral loading.

Figure 18: Weight container lifted for cyclic loading application

Lateral Loading Measurement

To apply the lateral loading to the crosstie, the anchor point of the crosstie must be attached to the grab hook on the loading chain of the lateral loading apparatus. When the hook is secured, a caliper is tightly fastened to the spring at the end of the load chain with zip-ties. This allows the jaws of the caliper to slide as the spring elongates due to the tension in the loading chain from the winch. A small loading that will cause displacement in the spring but not move the crosstie is applied to check that the caliper is securely fastened to the spring and will not slip during the measurement. The winch is released until there is slack in the loading chain and the spring has no displacement. A cell phone is placed next to the spring and caliper so that the reading on the caliper can be recorded on video as the spring elongates. A video recording is begun on the cell phone, and the caliper is zeroed out. The winch is slowly ratcheted to gradually increase lateral loading to the crosstie until the moment the crosstie is displaced forward. An audio cue from the winch operator is called out at this time to help determine when the crosstie moved on the video recording.

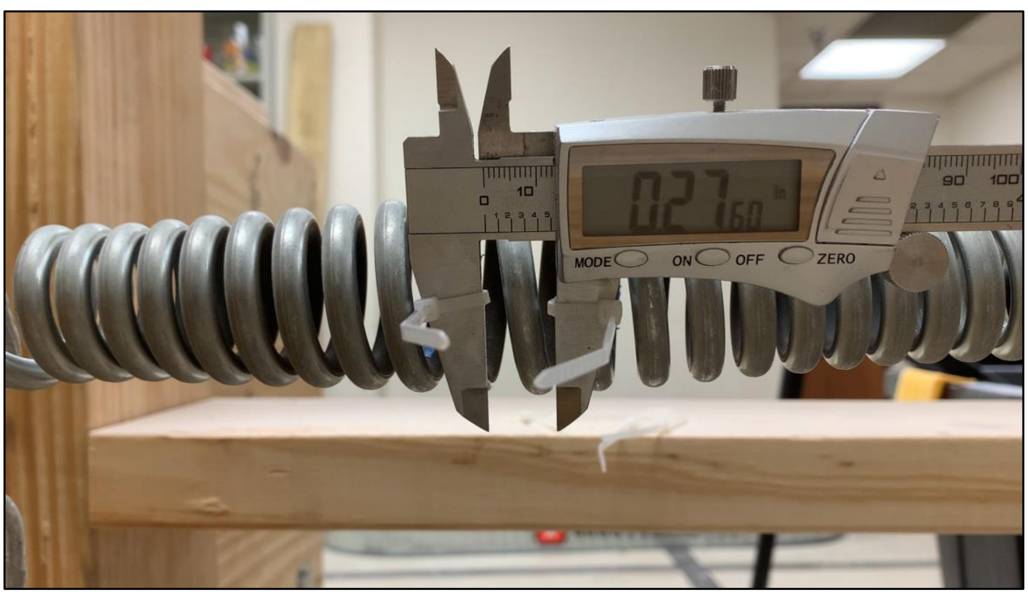

Figure 19: Caliper reading taken from video

The winch is then released to remove the lateral loading. The video recording is stopped, and the caliper is removed from the spring. Using the video recording, the reading on the caliper at the time the crosstie began to move is collected. With the collected spring displacement and the known spring constant, the magnitude of the lateral load which caused the crosstie to move can be determined using Hooke's Law.

Contact Measurement

After recording the lateral loading measurement, the points of contact and contact area must be collected. The weight container is reattached to the crane and lifted above the walls of the ballast container. The crane legs are rolled out from underneath the ballast container and the weight container is slowly lowered to the floor. The ballast along the sides of the crosstie is dug out and pushed aside, so the crosstie can be flipped over. After flipping the crosstie, a photograph of the disturbed chalk is taken. One of these photographs is shown in Figure 20. The markings made in the chalk due to the movement of the crosstie against the ballast are used to determine the number of points of contact and the contact area for the test. The points of contact and contact area are measured simultaneously. Starting at one end of the crosstie, each individual marking is counted and its area measured. To measure the area, the shape of the marking is recorded as a rectangle, circle, or triangle. Once the shape of the marking is categorized, its dimensions are measured using a caliper. These dimensions are used to approximate the marking's area. Because of the irregularity of the shape of the markings, some markings are divided into multiple shapes to better approximate their area. As the points of contact and contact area are being collected, they are entered into a spreadsheet. After the data is collected, the chalk is removed from the crosstie to prepare for the next test. Additionally, the ballast which was in contact with the bottom of the crosstie during the test is shoveled out of the box and replaced with new ballast.

Figure 20: Example of disturbed chalk after testing

RESULTS AND DISCUSSION

This section will present and discuss the data collected in this experiment. Additionally, it will investigate observations made during the conduction of the experiment and the impact these observations had on the scatter present in the data. The trendlines and correlation coefficients were calculated using both linear and power law least squares regression. (Penn State, 2021)

Discussion of Data

The data collected from the experiment was consolidated into five graphs. The graphs in Figure 21, Figure 22, and Figure 24 plot the static friction coefficient, points of contact, and contact area, respectively, as a function of loading cycles. The graphs in Figure 23 and Figure 25 plot the static friction coefficient as a function of points of contact and contact area, respectively. Each plot contains a curve fit to the data points with its the corresponding equation and correlation coefficient.

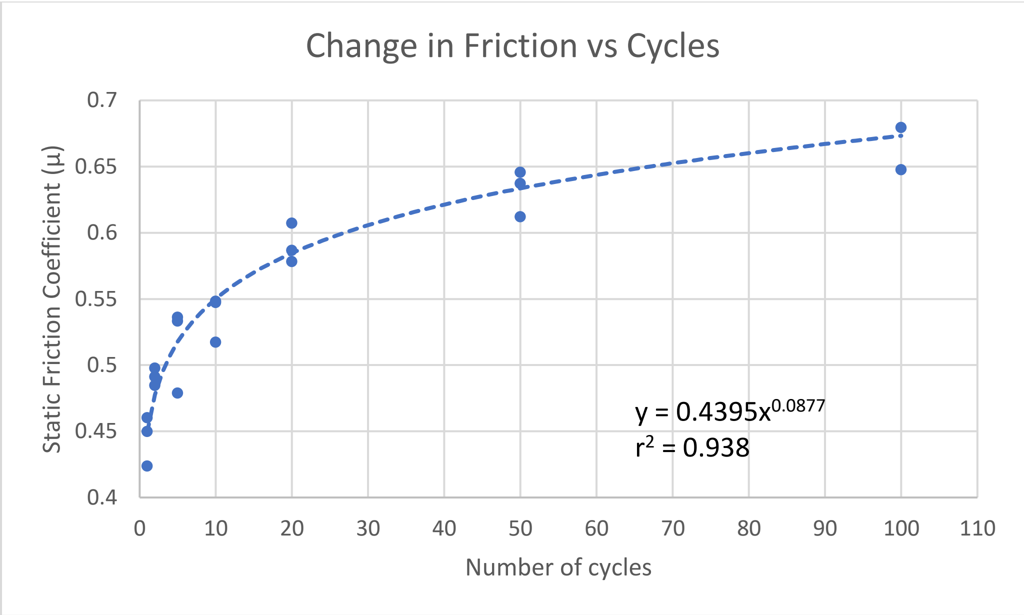

Figure 21: Static friction coefficient as a function of loading cycles

The graph in Figure 21 shows the static friction coefficient as a function of loading cycles. The plot presents a strong correlation between static friction and number of loading cycles when related using a power law curve fit. The graph shows that the static friction coefficient increases with the number of loading cycles. This suggests that more loading cycles causes the crosstie to settle into the ballast beneath it which increases the friction interactions. The relationship shown has the largest correlation coefficient of all the plots. This is most likely due to the method of data collection for both static friction coefficient and number of loading cycles. The friction was determined using spring displacement which was measured with a caliper while the number of cycles were measured by counting. Both of these methods were more precise than the methods used to measure points of contact and contact area, so it is reasonable that this plot shows the least amount of scatter in the data.

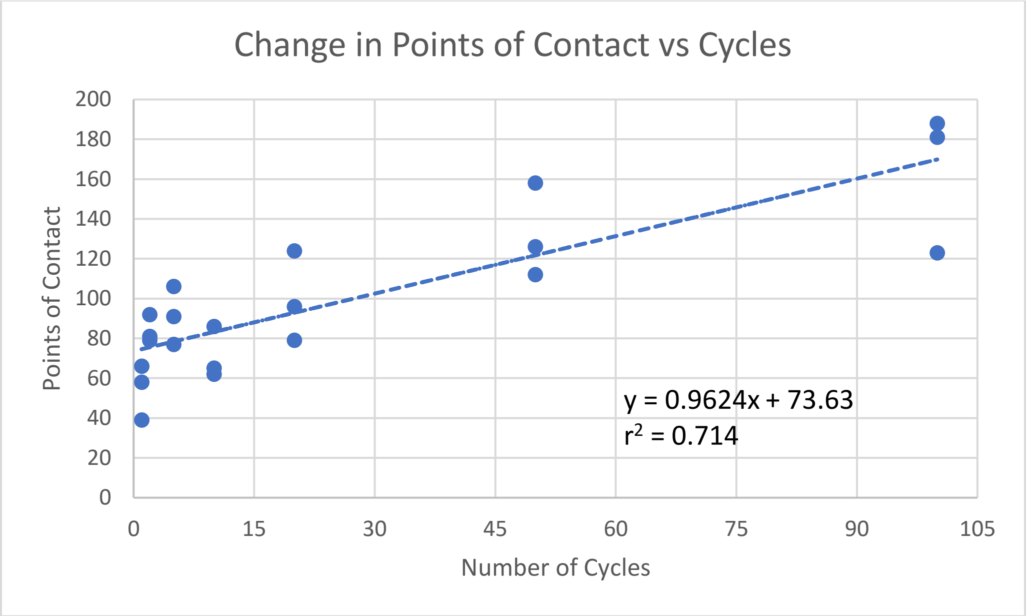

Figure 22: Points of contact as a function of loading cycles

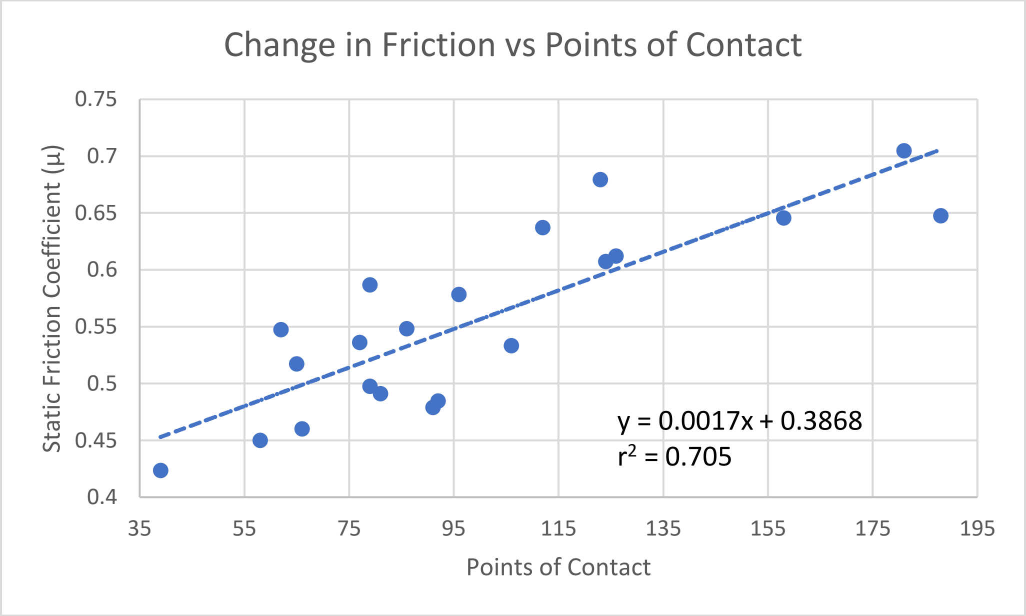

Figure 23: Static friction coefficient as a function of points of contact

Figure 22 shows the points of contact as a function of the number of loading cycles while Figure 23 shows the static friction coefficient as a function of points of contact. A linear trendline is fit to the data in both graphs. The graph in Figure 22 shows that the number of points of contact increases as the number of loading cycles increases, and the graph in Figure 23 shows that static friction coefficient increases as the number of points of contact increases. This supports the idea discussed previously. As the number of cycles increases, the crosstie settles into the ballast and more rocks come into contact with the crosstie. The extra contact with the ballast increases the friction that needs to be overcome before the crosstie can start to slide. Both relationships have a lower correlation coefficient than the relationship shown in Figure 21. The method of measuring the points of contact was to count the markings in the chalk on the bottom of the crosstie by hand. Many of the markings were quite small and some markings overlapped and intersected each other. These factors left some interpretation as to what was considered a point of contact. Because of this, the points of contact measurement was less precise than the friction and loading cycles measurements, and is likely contributes to the higher amount of scatter in Figure 22 and Figure 23 compared to Figure 21.

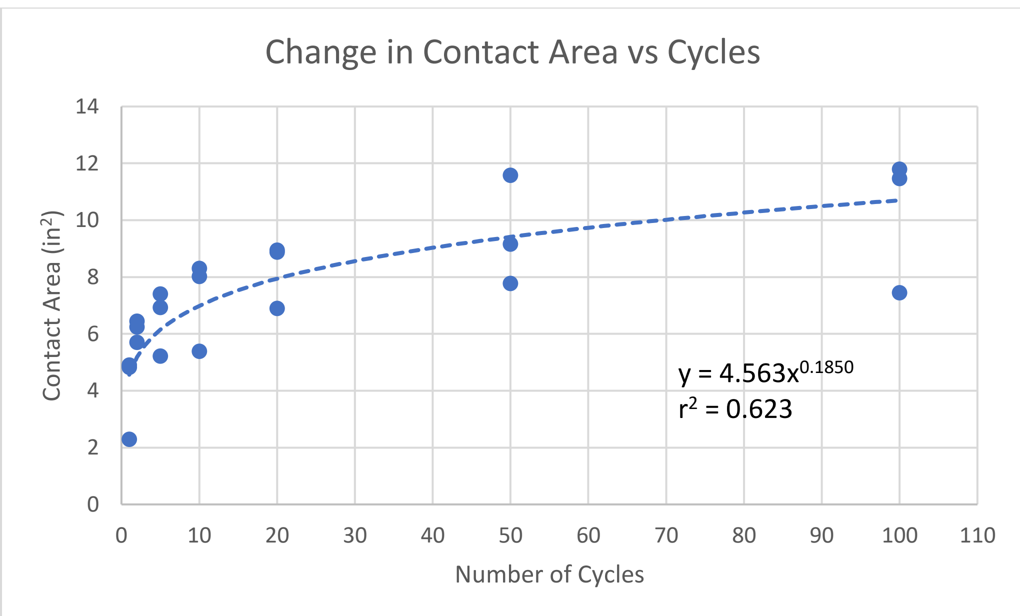

Figure 24: Contact area as a function of loading cycles

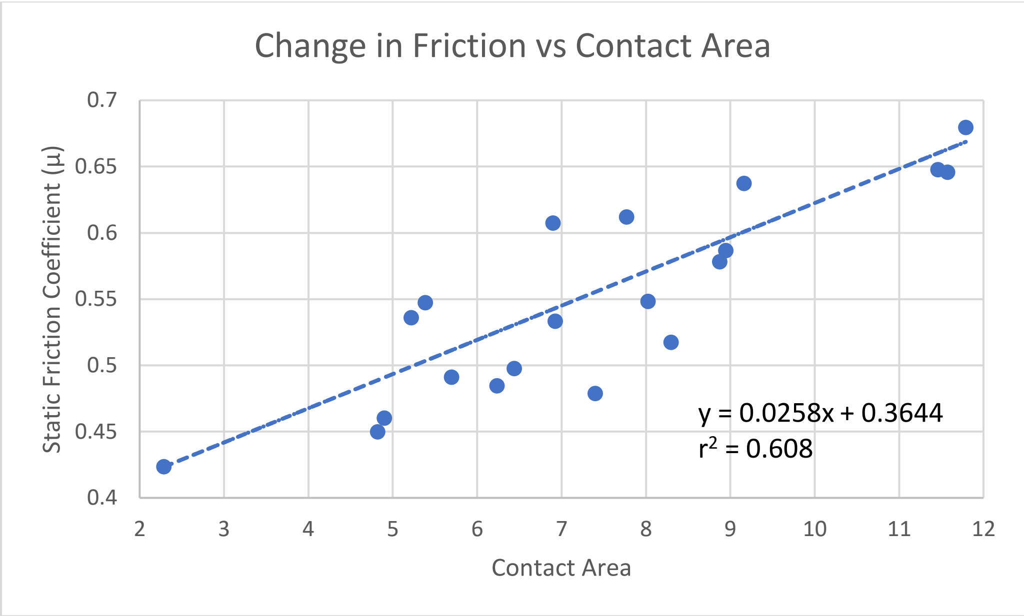

Figure 25: Static friction coefficient as a function of contact area

Figure 24 shows the contact area as a function of loading cycles while Figure 25 shows the static friction coefficient as a function of contact area. The data in Figure 24 is fit with a linear trendline, and the data in Figure 25 is fit with a power curve. Figure 24 shows that the contact area increases as the number of loading cycles increases, and Figure 25 shows that the static friction coefficient increases as the contact area increases. This suggests that increased loading cycles results in more contact area which increases the static friction. This supports the conclusions about the data presented in Figure 22 and Figure 23. If the number of points of contact increase as the crosstie settles into the ballast, it is reasonable that the contact area increases as well. The relationships shown in Figure 24 and Figure 25 have the lowest correlation of the three graphs perhaps in part because the method of measuring the contact area was the least precise. The contact area was determined by measuring the area of each point of contact and summing them together. The area of each point was measured individually with a caliper. The shapes of the points of contact were irregular and difficult to approximate which affected the precision of the measurements. As a result, there is a discrepancy between the true value and measured value of contact area for each test, and it is rational that this contributes to the scatter seen in Figure 24 and Figure 25.

Experiment Observations

While performing this experiment, several observations were made regarding the interactions between the crosstie and the ballast material. Some of the observations were of factors which could not be controlled consistently when conducting the experimental procedure and affected the data collected. These observations can be categorized into four groups: crosstie alignment, ballast arrangement, crosstie bottom degradation, and crosstie lateral displacement.

Crosstie alignment observations were made with respect to the physical orientation of the crosstie when it was embedded in the ballast. In the EXPERIMENTAL PROCEDURE section of this document, the sub-section Preparing the Crosstie notes the importance of the crosstie alignment when positioning the crosstie. To determine an accurate value for lateral force on the crosstie, it is critical that the loading on the crosstie be directed as horizontally as possible. Slight misalignments in the crosstie's position may cause the direction of the force applied to the crosstie by the winch to deviate from horizontal. If the direction of the lateral loading is not horizontal, then there will be a discrepancy between the force measured in the experiment and the true force required to move the crosstie. The downhill (sloped downwards toward the front of the box) and the uphill (sloped upwards toward the front of the box) orientations caused the largest discrepancies in the data. In the downhill orientation, the horizontal force on the crosstie was assisted by the gravitational force pulling the crosstie down the slope. This resulted in a lower magnitude of lateral load required to move the crosstie and a lower value of the static friction coefficient than expected. The uphill orientation caused the gravitational force pulling the crosstie down the slope to oppose the horizontal force on the crosstie. A higher magnitude of lateral load and higher than expected value of the static friction coefficient were observed in this scenario. To reduce the effects of crosstie alignment on the data, the crosstie was checked several times to ensure it was aligned and oriented properly before it was fully embedded.

The ballast arrangement observations were of the distribution of individual rocks that come into contact with the crosstie. The observations on the distribution of rocks considers the physical location and orientation of the individual rocks on the trench bottom. The rocks on the bottom of the trench are what determine the number and location of the points of contact along the bottom of the crosstie. Due to the number of rocks that make up the trench bottom and the rearrangement and replacement of rocks after each test, it was not possible to replicate the same distribution of rocks for every test. Each test had a different arrangement of ballast on the trench bottom which contributed to the differing value of points of contact and contact area between each of the tests. However, due to the fact that in a real track structure no two crossties experience the exact same arrangement of ballast contact, it was not controlled in this experiment.

The crosstie bottom degradation refers to the smoothing and scuffing of the bottom of the crosstie due to repeated sliding against the ballast material. The texture of the crosstie is much smoother and more rounded than when it was received as a result of continued testing. After each test, the bottom developed new gashes and cuts which caused it to degrade as testing progressed. In some cases, a small chunk of the wood would be completely fractured off. Each of these factors caused permanent changes in the texture and geometry of the bottom of the crosstie which presumably affects the friction interaction with the ballast. As there was only one crosstie available for testing, the crosstie degradation could not be controlled. This phenomenon would also be present in a real track structure and contributes to the change in friction between the crosstie and ballast, but this experiment did not focus on the investigation of this effect.

The final group of observations made was on the lateral displacement of the crosstie during the experiment. As described in the Lateral Loading Measurement sub-section of the EXPERIMENTAL PROCEDURE section of this document, the horizontal force on the crosstie was increased until the moment the crosstie began to move. For some tests, this movement was so miniscule that is was difficult to detect. For other tests, the crosstie would suddenly jerk forward and be displaced significantly. The size of the markings in the chalk on the bottom of the crosstie tended to be smaller in tests that had a small lateral displacement while tests that had a large lateral displacement had larger markings. Because the contact area measurements were determined by the size of these markings, tests with lager crosstie displacement tended to have a larger recorded value of contact area than tests that had a smaller crosstie displacement. This contributed to the scatter present in the contact area data shown in Figure 24 and Figure 25. There was no way of predicting whether the crosstie would slowly creep forward or jerk forward abruptly, so it was not possible to control this phenomenon within experiment.

CONCLUSIONS

Based on the data collected and the plots presented in the RESULTS AND DISCUSSION section, there are three main conclusions:

1. The static friction coefficient between the crosstie and track ballast increases as the number of loading cycles increases;
2. The static friction coefficient increases as the number of points of contact between the ballast and crosstie increases; and
3. The static friction coefficient increases as the contact area between the crosstie and ballast increases.

These results propose that railroad crossties experience more lateral resistance due to friction with the track ballast after they experience a few cycles of loading than when they are first embedded within the track structure. This suggests that when the track structure is first assembled, there are gaps within the ballast material and between the ballast material and the crosstie that are filled as successive trains pass over the track structure. The weight of the train cars on the tracks pushes down onto the ballast. This weight causes the individual rocks to slide past each other and fill the gaps between them, consolidating the ballast and making it more stable. This effect also pushes the crosstie into the ballast which causes it settle into the ballast as it consolidates. This increases the amount of contact between the crosstie and the ballast material which results in an increase in friction. There is a diminishing rate of increase in the coefficient of friction, however. Eventually the ballast will completely consolidate, and it will reach a configuration where the individual rocks are as tightly packed as possible. At this point, the contact area between the crosstie and ballast will be at a maximum so that increased loading cycles will no longer have the effect of increasing the static friction between the crosstie and the ballast. A curve such as the one shown in Figure 21 could be used to estimate the number of cycles required to reach this point.

It is important to note that the weight used to perform the cyclic loading in this experiment is far less than the weight of a train car. Therefore, the number of cycles required to reach the point of maximum consolidation is likely much smaller than what is suggested by the results shown on Figure 21. Additionally, this experiment is limited by the number of cycles that can be performed per test. Because the cycles were applied manually, it is not practical to apply large numbers of loading cycles such as that subjected to typical railway crossties within track structures. As such, it is still uncertain how a many of loading cycles would affect the static friction between the crosstie and the track ballast. In closing, a new experiment with a way to automate the cyclic loading application would need to be designed to investigate this problem.

FUTURE RESEARCH

Further tests of this experiment should be considered. These tests would investigate two new parameters: ballast end caps and high-density polyethylene (HDPE) crosstie material. The ballast end cap is the ballast material which covers the ends of the crosstie. In the tests discussed in this document, there was no end cap, and the end of the crosstie on which the horizontal loading was applied was left exposed. An end capped crosstie would be buried on all sides, including the end of the crosstie on which the lateral loading was applied. The tests discussed previously also used a standard wooden crosstie while the new tests would use a crosstie composed of HDPE. The HDPE crosstie would also be stamped with a dimpled texture along the sides and bottom to increase the friction. Nine new tests would be performed: three tests with the wooden crosstie with an end cap, three tests with the HDPE crosstie without an end cap, and three tests with the HDPE crosstie with an end cap. The data for these nine tests would be collected at one loading cycle. This data would be compared with the existing data for the wooden crosstie with no end cap at one loading cycle. The comparison would be used to investigate the affects that the ballast end cap and the crosstie material have on the static friction between the crosstie and the ballast material.

REFERENCES

Aira, J.R., Arriaga, F., Íñiguez-González, G., Crespo, J. "Static and Kinetic Friction Coefficients of Scots Pine (Pinus sylvestris L.), Parallel and Perpendicular to Grain Direction", Universidad Politécnica de Madrid, Universidad de Santiago de Compostela, July 2014

"Freight Rail Keeps Port of Houston Strong", GoRail, June 2016, https://gorail.org/ports/freight-rail-keeps-port-of-houston-strong

Kabo, E. "A Numerical Study of the Lateral Ballast Resistance in Railway Tracks", Chalmers University of Technology, July 2006

Kish, A. "On the Fundamentals of Track Lateral Resistance", American Railway Engineering and Maintenance of Way Association, 2011

Kish, A., Mui, W. "Track Buckling Research" *volpe.dot.*gov, U.S. Department of Transportation, Volpe Center, July 2003

"On-Dock Rail Service, the Alameda Corridor and Intermodal Yards", The Port of Los Angeles, 2020, https://www.portoflosangeles.org/business/supply-chain/rail

"Overwiew", Port Houston, October 2021, https://porthouston.com/about-us/.

"Review of Maritime Transport 2018", United Nations Conference on Trade and Development, United Nations Publications, 2018

Ruina, A., Pratap, R., "Introduction to Statics and Dynamics", Pre-print for Oxford University Press, January 2002

Samavedam, G., Kanaan, A., Pietrak, J., Kish, A., Sluz, A. "Wood Tie Track Resistance Characterization and Correlations Study", U.S. Department of Transportation, Federal Railroad Administration, January 1995

"STAT 415: Introduction to Mathematical Statistics", *online.stat.psu.edu,* Penn State Eberly College of Science, The Pennsylvania State University 2021

Zarembski, Allan M. "Survey of Techniques and Approaches for Increasing the Lateral Resistance of Wood Tie Track" *rtax.memberclicks.net,* University of Delaware, Department of Civil and Environmental Engineering, 2013