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Analysis of Selected Factors Affecting Concrete Cover Measurements on Bridge Decks

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Measurements on Bridge Decks

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ABSTRACT

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The objective of this research was to quantify the effects of selected parameters on the accuracy of concrete cover measurements on bridge decks. This research involved three full-factorial laboratory experiments each designed to investigate one of three primary variables. These primary variables included distance to a parallel adjacent bar, distance to a reinforcement intersection, and incorrect bar size input for the cover meter. Each experiment also involved four secondary variables known to affect cover readings. These secondary variables included actual cover depth, meter brand, antenna type, and bar size. Statistical analyses were performed to determine the significance of each factor. A margin of error of 0.125 in., corresponding to the increase in diameter between successive U.S. standard rebar sizes, was established as the threshold for practical importance in the data analysis. Three primary findings resulted from the three experiments performed in this research. For the meters and antennas tested, the results of the field-of-view experiment indicated that, if the spacing is greater than approximately 4.0 in., the returned readings are within the threshold for practical importance established for this research. The results of the proximity-to-an-intersection experiment indicated that, regardless of where the measurement is taking place in relation to an intersection, the operator can be confident that the errors will be less than 0.125 in. as long as the bar in question is above the intersecting bar. The results of the wrong-bar-size experiment indicated that, if the operator of the cover meter does not know the actual rebar size in question, the measured cover will be within 0.125 in. of the actual cover depth as long as the meter input is within one bar size of the correct value. Obtaining accurate cover measurements on bridge decks is important for quality assurance, service life prediction, and rehabilitation programming.

Key words: bridge deck, concrete, concrete cover, cover meter, non-destructive testing, rebar, reinforcing steel

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1 INTRODUCTION

1.1 Problem Statement

The most commonly reported mechanism of bridge deck deterioration is salt-induced corrosion of the reinforcing steel [1, 2]. Corrosion of reinforcing steel in concrete bridge decks can cause safety hazards, decrease bridge rideability, and initiate premature bridge failure [3, 4, 5, 6]. One effective way of protecting bridge deck reinforcement, commonly known as rebar, from salt-induced corrosion is to ensure consistent concrete cover depth of at least 2.5 in. [5, 7,8]. Concrete cover is the distance from the surface of the reinforcement to the nearest exposed concrete surface. As concrete cover increases, the time required for chloride ions to permeate the bridge deck and reach the rebar also increases [2, 3, 7, 8]. Concrete cover can be quickly and non-destructively measured using cover meters commonly available in the industry [7].

Cover meters can be used by department of transportation (DOT) personnel for quality assurance, bridge deck life prediction, and rehabilitation programming for bridge decks. Contractors' pay scales are frequently dependent on their ability to produce a desired product within a given set of tolerances. To ensure proper compensation, contracting agencies must have accurate cover meter readings when pay factors are attached to cover specifications. Cover meters can be used to obtain post-construction measurements, without damaging bridge decks, enabling DOTs to hold contractors accountable for achieving adequate cover depth.

Cover meters can also be used to predict bridge deck life. When accurate measurements of cover depth are achieved, chloride diffusion rates in concrete can be used to reasonably estimate when corrosion of the reinforcing steel will begin [9]. As corrosion of the reinforcing steel progresses, the byproducts of the oxidation process cause spalling and delamination of the bridge deck, precursors to deck failure [1, 2].

Another application for cover meter readings is planning rehabilitation activities. One form of deck rehabilitation involves the removal of existing deteriorated concrete, scarification of the underlying concrete, and placement of a new concrete overlay on the deck surface [9]. Accurate knowledge of the concrete cover over the top reinforcing mat of a deck allows surface milling equipment to remove the top layer of concrete without damaging the underlying reinforcement. However, if the cover depth is inaccurately estimated, costly mistakes such as mobilizing incorrect equipment or damaging the reinforcement can occur. Furthermore, incorrect estimations may cause mistiming of preventative maintenance, resulting in irreversible exposure of reinforcement to chlorides and increased maintenance costs.

In spite of the widespread use of concrete as a main component in bridge decks and the long existence of cover meter technology, few standards associated with proper cover meter usage currently exist. Designation 1881-204: 1988 in the British Standards describes an approach for using cover meters that outlines calibration techniques, method of use, expected accuracy, and possible sources of error. However, the standard does not give parameter restrictions for field use. Although using a cover meter to non-destructively determine concrete cover in the field has many advantages, meter readings can be influenced by several variables. Some variables that can increase the variation of cover measurements from actual cover depths are incorrect rebar setting for the meter, bar orientation in relation to the meter antenna, proximity of one rebar to another rebar, grade of steel, and reinforcement depth [10].

Regarding these variables, some research has been performed to investigate the effects of taking measurements in areas of high reinforcement congestion using multiple antennas at various cover depths [11]; however, the research results do not address rebar sizes commonly used in bridge decks. Furthermore, although the effect of entering the incorrect bar size when testing cover depth has been researched in Great Britain, the scope of that research does not include bar sizes common to bridge decks and does not utilize statistical analysis [11]. Better quantification of the effects of certain variables on cover measurements will facilitate the development of better protocols associated with concrete cover measurements and allow for better interpretation of obtained measurements. The objective of this research was therefore to quantify the effects of selected parameters on the accuracy of concrete cover measurements on bridge decks. Implementation of the findings and recommendations from this research will lead to higher quality bridge decks and more efficient rehabilitation efforts by increasing the accuracy of concrete cover readings.

1.2 Scope

This laboratory research expands upon the current literature by investigating factors such as rebar size, spacing, and cover depth specific to bridge deck reinforcement. Other factors that are not specific to bridge deck reinforcement, such as meter brand, rebar size input, and antenna type, were also included in the full-factorial experimental design. While the levels of each factor selected for evaluation in this research are applicable to conditions on most bridge decks, the results of this research do not extend beyond the scope of this experiment.

1.3 Outline of Report

This chapter describes the problem statement and scope of research and outlines the report. Chapter 2 provides background information on theory and standards pertaining to cover meter operation, Chapter 3 describes the experimental procedures, and Chapter 4 presents the results of the study. Chapter 5 summarizes the research, highlights important findings, and offers recommendations based on the research.

2 BACKGROUND

2.1 Overview

Cover meters are non-destructive electromagnetic devices that are used to detect rebar location and to determine the depth of concrete cover over the reinforcement. Most cover meters consist of an antenna that is used to scan the surface of the concrete, a meter that interprets the signal received from the antenna and reports the measured cover depth, and a hard-wired connection between the antenna and the meter. The following sections describe theory and standards pertaining to cover meter operation.

2.2 Theory

Most commercially available cover meters use either eddy currents or magnetic induction to measure reinforcement depth [10, 11, 12, 13, 14, 15, 16]. The conditions under which the cover measurements are taken may preclude the use of either of the meter types. Understanding the theory behind how the cover meters work will aid in selecting the best cover meter for the job.

Of the two types of cover meters, those using eddy currents are less common and are based on magnetically induced currents in conductive material. The cover meter antenna, or probe, uses a single search coil operating at frequencies above 1.0 kHz to create an alternating magnetic field. At frequencies above 1.0 kHz, when rebar is in the magnetic field, eddy currents are generated within the rebar. The eddy currents produce a magnetic field in opposition to the original magnetic field, which changes the impedance of the coil [17]. The change in impedance of the coil is then interpreted by the meter as cover depth. The strength of the magnetic field generated by the eddy currents is mainly a function of three variables. The first variable is the conductivity of the material generating the eddy currents; the more conductive the material, the stronger the eddy current. The second variable is the total volume of the material located in the generated magnetic field; larger volumes will create larger magnetic fields. The final variable is the distance of the material from the coil generating the magnetic field. As the distance of the reinforcement from the coil increases, the strength of the magnetic field decreases, causing the strength of the eddy currents to also decrease. The chief limitation of the eddy-current method in comparison to the magnetic induction method is that, since the driving current in the search coil operates at frequencies over 1.0 kHz, the probe is affected by any metal that will conduct electricity within the effective zone of interrogation of the probe [12, 18].

Cover meters using magnetic induction operate at frequencies lower than 90 Hz. Magnetic fields alternating at frequencies below 90 Hz do not induce eddy currents in conductive materials within the magnetic field [17]. Cover meters using the magnetic-induction method are therefore less susceptible to non-magnetic conductive metals than cover meters using eddy currents. These meters typically use two coils within a given probe, and the configuration of the coils is similar to that of inductors in a transformer. In this system, alternating current passes through the primary coil, which then produces an alternating magnetic field that penetrates the underlying concrete. If another magnetic object, such as rebar, is present within the zone of interrogation of the probe, magnetic flux is enhanced between the primary coil and the secondary coil. As the magnetic flux passes through the secondary coil, the magnetic flux induces a voltage difference in the secondary coil, and the cover meter interprets the magnitude of the voltage difference as the cover depth [10, 12, 14, 15].

In both the eddy-current method and the magnetic-induction method, the disturbance is positively correlated to the size of the reinforcement present and negatively correlated to the distance between the rebar and the probe. In order to obtain accurate measurements of cover depth, the size of rebar in the concrete must be entered into the cover meter. With a known size of rebar and proper calibration, the meter can determine the distance from the concrete surface to the nearest rebar surface [10, 12, 14, 17, 18].

2.3 Standards

Many types of cover meters are available, and each manufacturer has a unique standard of precision. Furthermore, most meters have both a deep-scan antenna and a shallow-scan antenna, and the calibration of these antennas and the depth of investigation can also vary between manufacturers. Currently, the only requirements for cover meter precision are found in the British Standards, and these give a relatively large interval of acceptance. Thus, even when cover meters meet the specifications given in the British Standards, experiments have shown that measured cover depths can vary greatly [7]. According to the British Standards, meters tested under laboratory conditions are allowed to produce errors equal to the greater of +/- 5 percent or +/- 2 mm (0.0787 in.), and this interval is expanded to the greater of +/- 15 percent or 5 mm (0.1969 in.) for meters tested under "ideal" field conditions. For cover depths typical of bridge decks, an error of 15 percent corresponds to approximately 0.375 in., which may be unacceptable for many applications.

2.4 Summary

Cover meters are non-destructive electromagnetic devices that are used to detect rebar location and to determine the depth of concrete cover over the reinforcement. Most commercially available cover meters use either eddy currents or magnetic induction to measure reinforcement depth. In both of these methods, the disturbance is positively correlated to the size of the reinforcement present and negatively correlated to the distance between the rebar and the probe. With a known size of rebar and proper calibration, the meter can determine the distance from the concrete surface to the nearest rebar surface. Since many brands of cover meters are available and each manufacturer has a unique level of precision, inherent variation between cover meters exists. The current standards associated with cover meters are broad and may not be suitable for some applications.

3 PROCEDURES

3.1 Overview

This research involved three full-factorial laboratory experiments each designed to investigate one of three primary variables. These primary variables included distance to a parallel adjacent bar, distance to a reinforcement intersection, and incorrect bar size input for the cover meter. Each experiment also involved four secondary variables known to affect cover readings. These secondary variables included actual cover depth, meter brand, antenna type, and bar size. After the experiments were performed, the data were organized, and statistical analyses were performed to determine the significance of each variable. The following sections provide details of the experimental design, describe the testing procedures, and explain the statistical analyses.

3.2 Experimental Design

The experimental design utilized for each of three experiments performed in this research is presented in Table 3-1. In this report, these experiments are referred to as field of view (FOV), proximity to an intersection (PTAI), and wrong bar size (WBS). A hyphen indicates that the variable was not included in the given experiment.

The first primary variable, distance from adjacent parallel bar, was tested over a range of 2 to 6 in. at 0.5-in. intervals in order to more accurately define the acceptable minimum spacing

Table 3-1: Experimental Design

Experiment	Primary variables: Distance from adjacent parallel bar	Primary variables: Distance from intersection	Primary variables: Wrong bar setting	Secondary variables: Cover depth, in.	Secondary variables: Antenna type	Secondary variables: Meter brand	Secondary variables: Bar size (#)
1	2 to 6 in. at 0.5-in. intervals	-	-	2.0, 2.5, 3.0	Deep, Shallow	Brand A, Brand B	4, 6, 8
2	-	0 to 8 in. at 2-in. intervals	-	2.0, 2.5, 3.0	Deep, Shallow	Brand A, Brand B	4, 6, 8
3	-	-	Correct size, and +/- one bar size	2.0, 2.5, 3.0	Deep, Shallow	Brand A, Brand B	4, 6, 8

for tolerable error when using a cover meter. The range of 0 to 8 in. at 2-in. intervals was used for the second primary variable, distance to a reinforcement intersection, to define the acceptable minimum spacing for tolerable error. The wrong bar setting of plus or minus one size was used because the assumption was made that the operator would know the actual bar size to at least this degree of accuracy. Levels of cover depth and bar size were chosen for the experimentation to be representative of a typical bridge deck. Antenna type and meter brand were chosen according to availability. The cover meters and antennas used are shown in Figure 3-1.

Since casting enough concrete slabs to accommodate three fully crossed experiments would be costly, time consuming, and spatially cumbersome, alternate solutions for conducting the experiments were explored. As a preferred alternative to casting concrete slabs, a single wooden box having no magnetic or conductive materials was designed to hold rebar in the various configurations required for testing. This solution was based on the established theory that the medium between the cover meter antenna and the rebar will not affect the cover measurement if the medium is not conductive or magnetic.

Figure 3-1: Cover meter 1 and 2 with deep and shallow antennas.

Before the box was constructed, however, the validity of the proposed approach was confirmed in the laboratory by comparing cover measurements taken from a concrete control slab with those taken from a sample plywood box. In both cases, a single length of #6 rebar was placed at a cover depth of 2.0 in. In the comparison, a total of 40 readings were taken. Five readings were taken with each antenna type and meter brand for a total of 20 readings for each configuration. In each case, the actual cover depth was subtracted from the measured cover depth, and the resulting errors were analyzed. To investigate the effect of configuration type, the errors associated with the use of different antennas and cover meters were pooled for a given configuration, and a two-sample *t*-test was performed. For this analysis, the null hypothesis was that no difference existed between the errors from the box and the errors from the concrete slab, and the resulting *p*-value was compared to a standard error rate of 0.05. The results of the *t*-test are presented in Table 3-2, and the raw data are provided in Appendix A. Since the *p*-value for the two-sample *t*-test is larger than 0.05, sufficient statistical evidence does not exist to reject the

Table 3-2: Statistical Analysis for Wood and Concrete Comparison

Material	Average Variance	SD	Sample size	s_p	*t*-value	d.f.	*p*-value
Wood	0.082	0.056	20	0.079	0.503	38	0.309
Concrete	0.070	0.096	20				

null hypothesis, meaning that the data do not indicate a difference between errors in cover measurements obtained through concrete and errors in cover measurements obtained through plywood.

Once the viability of using a wooden box as the testing apparatus was established through the statistical analysis, the box was designed and constructed to accommodate all three experiments: FOV, PTAI, and WBS. The apparatus was built from 7/16-in. plywood and wood glue. Special care was taken to construct the apparatus without the use of ferrous fasteners to avoid potential distortion of the experimental results. The apparatus was constructed with four sides, a top, and an open bottom. To ensure that the readings were not impacted by anything below the box, the walls of the box were designed to be taller than the maximum interrogation depth of the meter. Five excess sheets of plywood were also cut to match the dimensions of the top of the box. These excess sheets were used to simulate concrete cover by placing one sheet and thin shims, as required, on top of the box for each 0.5 in. increase in desired cover depth. To test the first primary variable, the box was constructed with three 10-in. horizontal slots that were 0.5, 0.75 and 1.0 in. deep to fit rebar sizes of #4, #6, and #8, respectively. The slots were positioned as shown in Figure 3-2, and corresponding slots, not shown in the figure, were cut in the opposite walls of the box. To test the second primary variable, six sets of holes were drilled in opposite faces of the box allowing each bar to remain at a constant cover depth of 2 in. from

Figure 3-2: Completed cover meter testing apparatus.

the top of the box. These bars were used to simulate longitudinal bars in a bridge deck. A second set of holes, following the same pattern as the first set, were drilled in faces of the box orthogonal to the first set of holes, such that a transverse bar could be passed underneath the longitudinal bar to simulate an intersection. The final parameter, wrong bar size, was examined by using the longitudinal bar holes from the second experiment.

3.3 Testing

After the experimental design was established, each parameter could be tested using the constructed apparatus. The following sections describe the procedures followed in the FOV, PTAI, and WBS experiments.

3.3.1 FOV Experiment

After construction of the testing apparatus was finished, the primary variables were tested with each appropriate combination of secondary variables. The FOV experiment investigated the effects of the first primary variable, distance to a parallel adjacent bar. The configuration for this experiment is shown in Figure 3-3. The experiment was accomplished by first placing three sheets of plywood on top of the box to simulate 2 in. of cover. Next, a #4 bar was placed in the proper slot and pushed all the way to the right side of the slot. A second #4 bar was then placed in the same slot at a distance of 2 in. on center from the first bar. Three replicate cover readings were taken over the first bar with each antenna, and the results were recorded; between replicate readings, the antenna was removed from the surface of the box. The second bar was then progressively moved 0.5 in. farther away from the first, and three replicate readings were taken at each new location until the center-to-center bar spacing was 6 in. The procedure was repeated for each combination of the secondary variables.

Figure 3-3: Rebar configuration for FOV experiment.

3.3.2 PTAI Experiment

The PTAI experiment investigated the effects of the second primary variable, distance to a reinforcement intersection. The rebar configuration for the PTAI experiment is depicted in Figure 3-4. The experiment was accomplished by first placing a #4, #6, or #8 bar in the corresponding set of longitudinal holes and a matching #4, #6, or #8 bar in the set of transverse holes. The transverse rebar was always located below the longitudinal rebar in this experiment. The antenna was placed directly over the intersection, and three replicate readings were then recorded; again, the antenna was removed from the surface of the box between readings. The antenna was progressively moved at 2-in. increments away from the intersection while still centered over the longitudinal bar, and readings were taken at each new location until the center of the cover meter was 8 in. away from the intersection. The process was repeated for each relevant combination of secondary variables.

Figure 3-4: Rebar configuration for PTAI experiment.

3.3.3 WBS Experiment

The WBS experiment investigated the effects of the last primary variable, wrong bar setting, for the meter. This variable was tested by first placing a #4, #6, or #8 bar in the corresponding set of longitudinal holes. The antenna was placed directly over the bar, the meter was set to one size below the actual bar size, and three replicate readings were recorded. The same procedure was then followed with the meter set to the correct size and then one size above the actual size. For example, the #4 bar was scanned while the meter was set to #3, #4, and #5. The process was repeated for each relevant combination of secondary variables. As in the previous experiments, the antenna was removed from the surface of the box between readings.

3.4 Data Analyses

To fulfill the research objectives, statistical analyses of the data were necessary to determine the significance of the selected factors and the impact of each factor on the measured cover readings. For these analyses, the actual cover depth was subtracted from the measured cover depth to compute the error in each case. Thus, in the results of the analyses, a negative value indicates that the cover reading was shallower than the actual cover depth, and a positive value indicates that the cover reading was deeper than the actual cover depth.

The computer program SAS, a statistics software package, was then used to perform a fixed effects analysis of variance (ANOVA). The analysis investigated the main effects of all the variables in each experiment, as well as the two- and three-way interactions between variables in each of the three experiments. The purpose of examining the main effects was to assess the overall influence of a given predictor variable on the response variable, while the purpose of examining the interactions was to assess whether the influence of one factor on the response variable depended on the level of another factor.

The null hypothesis of an ANOVA is that the population means of all the factors are equal. The alternative hypothesis is that at least one population mean is significantly different from the others. For this research, factors with *p*-values less than or equal to the standard error rate of 0.05 were considered statistically significant; in such cases, the null hypothesis was rejected, and the alternative hypothesis was accepted. The coefficient of determination, or R^2 value, was also computed for each analysis. The R^2 value is the percentage of variation in the response variable that is explained by variation in the predictor variables included in the model. An R^2 value of 1.0 represents a perfect model [19].

As part of the ANOVA, the least squares mean (LSM) for each level of each factor was calculated. The LSM is an estimate of the subpopulation mean for a given level of a given factor. Since this experiment was balanced, the LSM for each level of each factor is the same as the arithmetic mean for the level. Thus, the LSM for each level of each factor in this experiment is the average error computed for all of the measurements involving that particular level.

Depending on the power of a statistical analysis, which increases with increasing sample size, very small differences between factors can be resolved. To exclude practically unimportant differences identified in the ANOVA as statistically significant, a margin of error of 0.125 in., corresponding to the increase in diameter between successive U.S. standard rebar sizes, was established for this research. If a factor was statistically significant and the magnitude of the error was greater than 0.125 in., then the factor was said to have a significant impact on the meter reading. The margin of error specified for this experiment, being more stringent than the maximum allowable margin of error prescribed in the British Standards, is expected to be suitable for all typical aspects of bridge deck management, although some applications may not require such precision.

3.5 Summary

This research involved three full-factorial laboratory experiments each designed to investigate one of three primary variables. These primary variables included distance to a parallel adjacent bar, distance to a reinforcement intersection, and incorrect bar size input for the cover meter. Each experiment also involved four secondary variables known to affect cover readings. These secondary variables included actual cover depth, meter brand, antenna type, and bar size.

A wooden box was designed and constructed to accommodate all three experiments. The apparatus was constructed with four sides, a top, and an open bottom. Five excess sheets of plywood were used to simulate concrete cover by placing one sheet on top of the box for each 0.5 in. increase in desired cover depth. To test the first primary variable, the box was constructed with three 10-in. horizontal slots that were 0.5, 0.75 and 1.0 in. deep to fit rebar sizes #4, #6, and #8, respectively. To test the second primary variable, six sets of holes were drilled in opposite faces of the box allowing each bar to remain at a constant cover depth of 2 in. from the top of the box. These bars were used to simulate longitudinal bars in a bridge deck. A second set of holes, following the same pattern as the first set, were drilled in faces of the box orthogonal to the first set of holes, such that a transverse bar could be passed underneath the longitudinal bar to simulate an intersection. The final parameter, wrong bar size, was tested by using the longitudinal bar holes from the second experiment.

After the experiments were performed, ANOVA statistical analyses were performed on the collected data to determine the significance of each factor. The standard error rate of 0.05 was considered statistically significant, and a margin of error of 0.125 in., corresponding to the increase in diameter between successive U.S. standard rebar sizes, was established as the threshold for practical importance.

4 RESULTS

4.1 Overview

The results of the experimentation are presented in the following sections. Although the full analysis included examination of the main effects, two-way interactions, and three-way interactions for all of the primary variables, only the analyses that are both statistically significant and practically important are discussed. Throughout the chapter, an asterisk connecting two or three variables within a table indicates an interaction between those variables.

4.2 FOV Experiment Results

The results of the ANOVA for the FOV experiment are shown in Table 4-1. Since factors with *p*-values less than or equal to 0.05 are considered statistically significant, the model indicates that all of the factors are statistically significant. The R^2 value for the model is 0.97.

4.2.1 Main Effects

The LSMs for the main effects investigated in the FOV experiment are displayed in Table 4-2, which shows that the magnitude of error for 15 of the 19 analyses is greater than 0.125 in. Plots of the main effects are given in Figures 4-1 to 4-5. The dashed line on each graph indicates the threshold for practical importance.

Table 4-1: ANOVA Results for FOV Experiment

Factor	*p*-value	Factor	*p*-value
Size	<0.0001	Cover*Spacing	<0.0001
Brand	<0.0001	Antenna*Spacing	<0.0001
Cover	<0.0001	Size*Brand*Cover	<0.0001
Antenna	<0.0001	Size*Brand*Antenna	<0.0001
Spacing	<0.0001	Size*Brand*Spacing	<0.0001
Size*Brand	<0.0001	Size*Cover*Antenna	<0.0001
Size*Cover	<0.0001	Size*Cover*Spacing	<0.0001
Size*Antenna	<0.0001	Size*Antenna*Spacing	<0.0001
Size*Spacing	<0.0001	Brand*Cover*Antenna	<0.0001
Brand*Cover	<0.0001	Brand*Cover*Spacing	<0.0001
Brand*Antenna	<0.0001	Brand*Antenna*Spacing	<0.0001
Brand*Spacing	<0.0001	Cover*Antenna*Spacing	<0.0001
Cover*Antenna	<0.0001		

Table 4-2: Main Effects for FOV Experiment

Variable	Level	Error (in.)
Bar Size	4	-0.119
	6	-0.161
	8	-0.149
Meter Brand	Brand A	-0.137
	Brand B	-0.149
Antenna Type	Deep	-0.134
	Shallow	-0.152
Cover Depth (in.)	2	-0.086
	2.5	-0.147
	3	-0.196
Spacing (in.)	2	-0.273
	2.5	-0.220
	3	-0.179
	3.5	-0.138
	4	-0.117
	4.5	-0.106
	5	-0.090
	5.5	-0.085
	6	-0.079

The magnitude of error in this experiment is attributable in part to the experimental design. The purpose of the FOV experiment was to find the minimum spacing required for the meter reading to be unaffected by an adjacent bar. Since the bar configurations in this experiment included adjacent bars in very close proximity to one another, the associated cover meter readings exhibited elevated levels of error that were reflected in the LSMs computed in this experiment.

The main effect of the first secondary variable, bar size, is shown in Figure 4-1. The figure shows that, on average, errors associated with the #4 bar are within the threshold for practical importance established for this research, while errors associated with the #6 and #8 bars are beyond the threshold. A possible explanation for why the #6 bar has a higher average error than the #4 and #8 bars is that meter 2 could only be set to metric bar sizes, and the difference between the available metric input and the actual bar size for the #6 bar was greater than the difference between the available metric input and the actual bar size for the #4 and #8 bars.

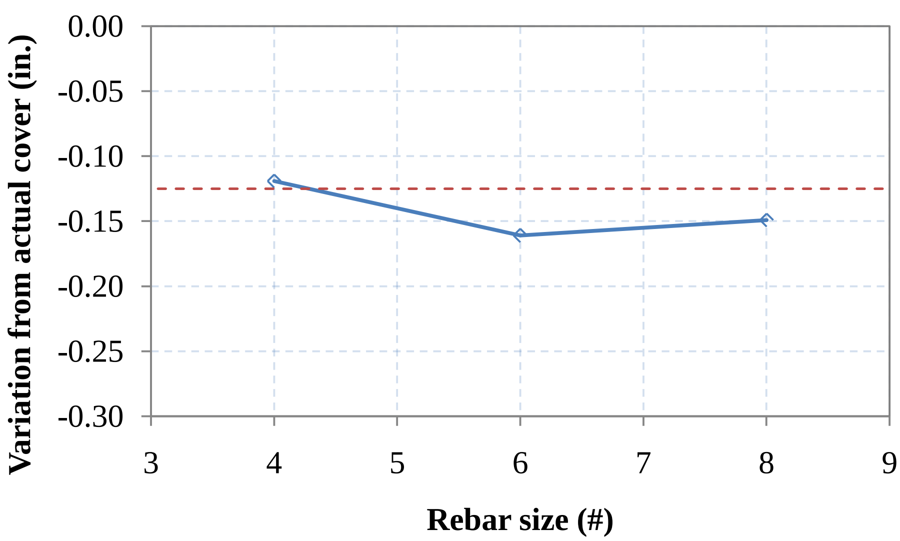

Figure 4-1: Main effects of bar size for FOV experiment.

Thus, when the antenna sensed the #6 bar, the meter returned a shallower cover reading than what actually existed.

The main effect of the second secondary variable, meter brand, is shown in Figure 4-2. Although this figure is presented as a line graph, neither interpolation nor extrapolation between or beyond the stated levels of this categorical factor is possible. While the average error for both meter brands was beyond the threshold for practical importance established for this research, one brand appeared slightly more accurate. A likely reason for this observation is that, as explained previously, the accuracy of meter 2 was affected by the requirement to use metric inputs for bar sizes.

The main effect of the third secondary variable, actual cover depth, is shown in Figure 4-3. The data points in this figure are nearly linear and indicate that, as cover increases, the error of the readings will also increase. However, this observation is likely due to the design of the experiment and not the limitations of the meters. Since the field of view of a cover meter

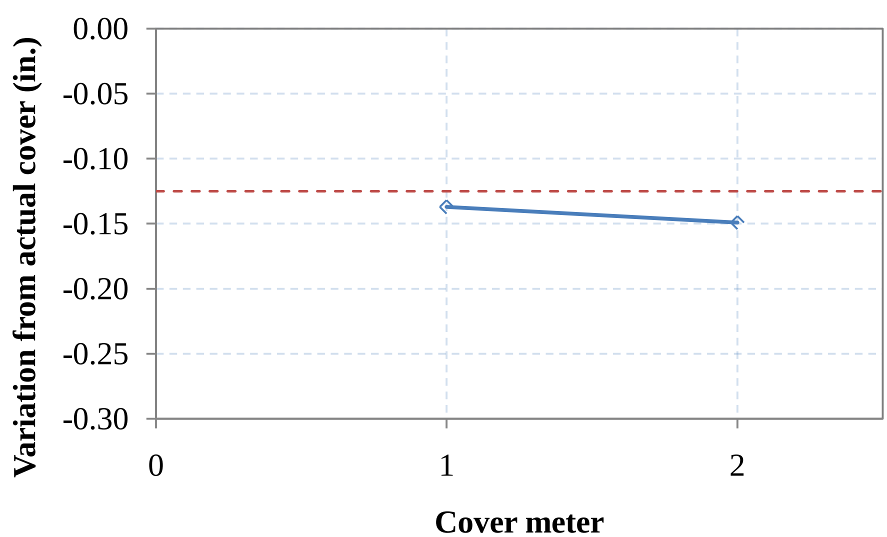

Figure 4-2: Main effects of meter brand for FOV experiment.

increases with increasing depth, the meter could detect the secondary rebar at greater spacing intervals when the actual cover was higher.

The main effect of the fourth secondary variable, antenna type, is shown in Figure 4-4. As in Figure 4-2, neither interpolation nor extrapolation between or beyond the stated levels of this categorical factor is possible. Both antenna types returned readings of practical error, but the deep antenna was slightly more accurate than the shallow antenna. One possible explanation for this observation is that the shallow antenna has a wider field of view at a given depth than the deep antenna. Thus, the offset bar was detected by the shallow antenna at greater spacing intervals than the deep antenna, which gave the appearance of less accuracy for the shallow antenna.

The main effect of the primary variable, rebar spacing, is shown in Figure 4-5. The data indicate that, as spacing increases, the error of the readings decreases. For the meters and

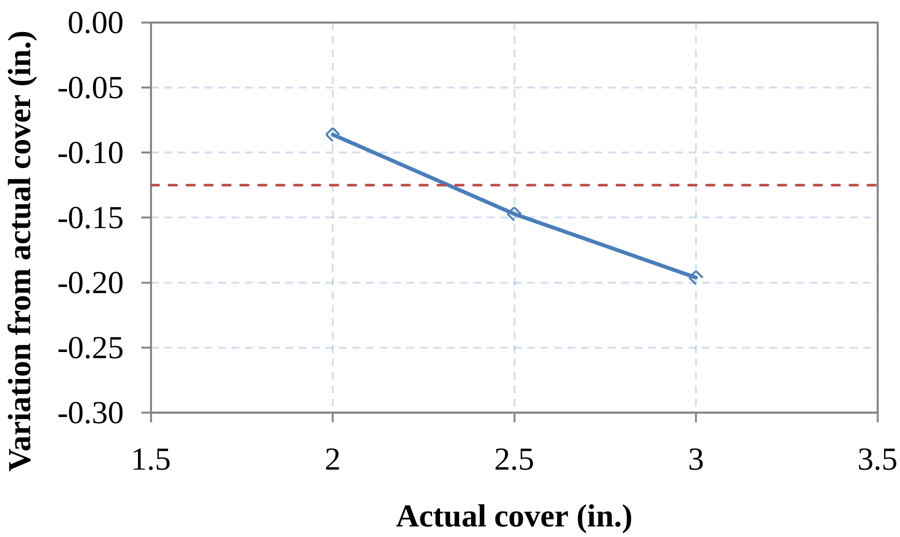

Figure 4-3: Main effects of actual cover depth for FOV experiment.

antennas tested, if the spacing is greater than approximately 4.0 in., the returned readings are within the threshold for practical importance established for this research.

4.2.2 Two-Way Interactions

Table 4-1 presents *p*-values for the two-way interactions for the FOV experiment, and Appendix B gives the LSMs for all of the two-way interactions investigated in this experiment. Because they are all less than or equal to 0.05, all 10 of the two-way interactions are statistically significant. Since all of the statistically significant two-way interactions for the FOV experiment have the same trends as the main effects, the threshold for practical importance for the two-way interactions is dependent on the difference in cover measurement error between two levels of one variable when examined in conjunction with the same level of another variable. Using this definition of practical importance, only one two-way interaction, which is shown in Figure 4-6,

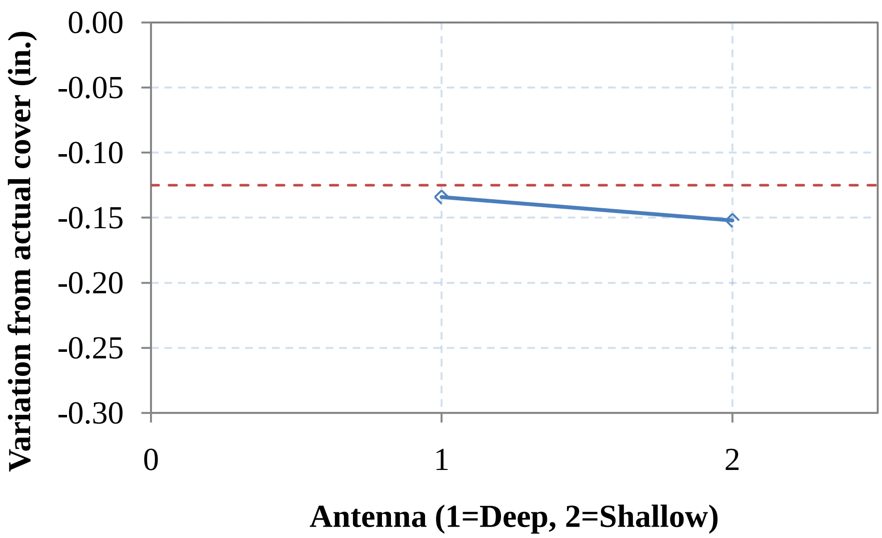

Figure 4-4: Main effects of antenna type for FOV experiment.

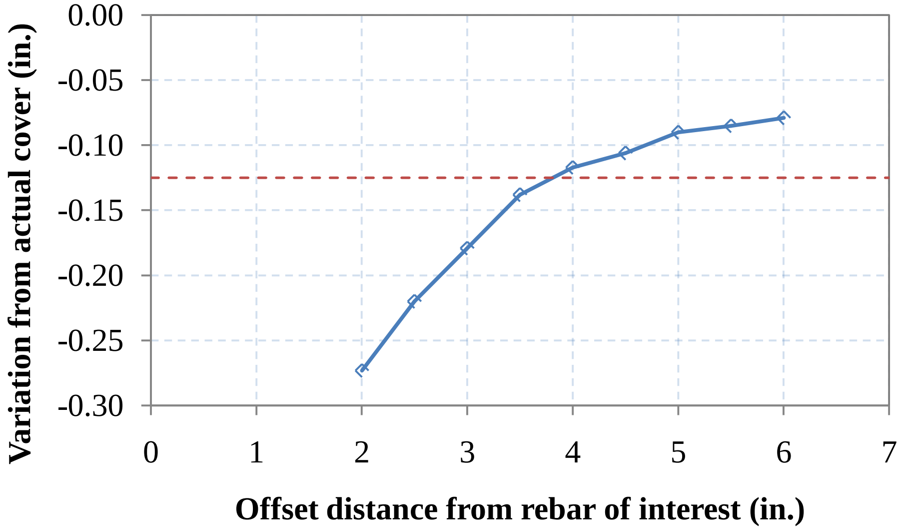

Figure 4-5: Main effects of offset distance for FOV experiment.

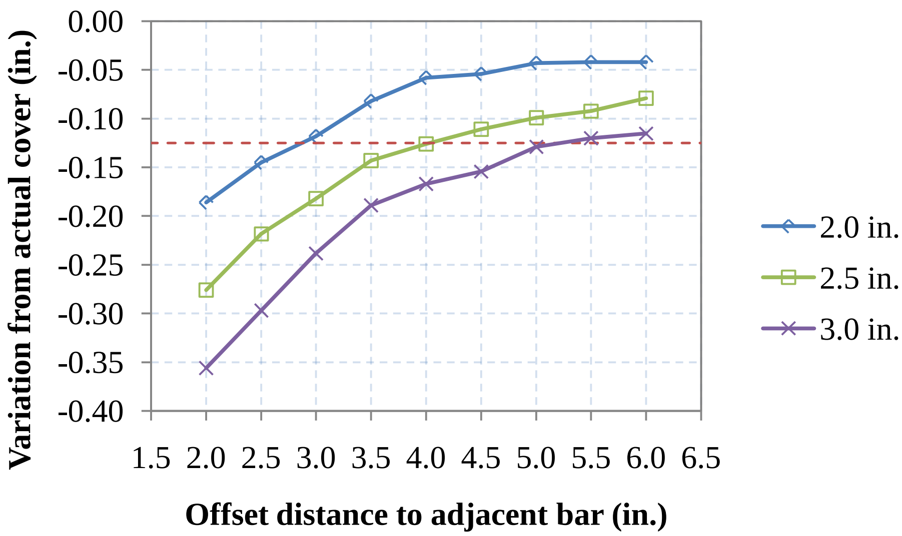

Figure 4-6: Two-way interaction between offset distance and actual cover depth for FOV experiment.

is both statistically significant and practically important. This interaction shows that the effect of rebar spacing on error depends on the actual cover depth. Graphs of the other nine two-way interactions, which were determined to be practically unimportant, are provided in Appendix B.

4.2.3 Three-Way Interactions

Table 4-1 presents *p*-values for the three-way interactions for the FOV experiment, and Appendix B gives the LSMs for all of the three-way interactions investigated in this experiment. Because they are all less than or equal to 0.05, all 10 of the three-way interactions are statistically significant. However, none of the three-way interactions are practically important. Graphs of all the three-way interactions are also given in Appendix B.

4.3 PTAI Experiment Results

The results of the ANOVA for the PTAI experiment are shown in Table 4-3. Since factors with p-values less than or equal to 0.05 are considered statistically significant, the model indicates that all of the factors except one are statistically significant. The R2 value for the model is 0.89.

4.3.1 Main Effects

The LSMs for the main effects investigated in the PTAI experiment are displayed in Table 4-4, which shows that the magnitude of error for none of the analyses is greater than 0.125 in.; therefore, none are practically important. The results of these analyses are important because they indicate that, regardless of where the measurement is taking place in relation to an intersection, the errors will be less than 0.125 in. as long as the bar in question is above the intersecting bar. Graphs of these factors are provided in Appendix C.

Table 4-3: ANOVA Results for PTAI Experiment

Factor	*p*-value	Factor	*p*-value
Size	<0.0001	Cover*Spacing	0.0204
Brand	<0.0001	Antenna*Spacing	<0.0001
Cover	<0.0001	Size*Brand*Cover	<0.0001
Antenna	<0.0001	Size*Brand*Antenna	<0.0001
Spacing	<0.0001	Size*Brand*Spacing	0.0532
Size*Brand	<0.0001	Size*Cover*Antenna	<0.0001
Size*Cover	<0.0001	Size*Cover*Spacing	<0.0001
Size*Antenna	<0.0001	Size*Antenna*Spacing	<0.0001
Size*Spacing	0.0037	Brand*Cover*Antenna	<0.0001
Brand*Cover	<0.0001	Brand*Cover*Spacing	<0.0001
Brand*Antenna	<0.0001	Brand*Antenna*Spacing	0.0138
Brand*Spacing	<0.0001	Cover*Antenna*Spacing	0.0001
Cover*Antenna	<0.0001		

Table 4-4: Main Effects for PTAI Experiment

Variable		Error (in.)
Bar Size	4	-0.049
	6	0.025
	8	0.023
Meter Brand	Brand A	0.046
	Brand B	-0.047
Antenna Type	Deep	0.027
	Shallow	-0.029
Cover Depth (in.)	2	-0.003
	2.5	0.013
	3	-0.012
Spacing (in.)	0	-0.009
	2	-0.0194
	4	-0.021
	6	0.018
	8	0.028

4.3.2 Two-Way Interactions

Table 4-3 presents *p*-values for the two-way interactions for the PTAI experiment, and Appendix C gives the LSMs for all of the two-way interactions investigated in this experiment. Because they are all less than or equal to 0.05, all 10 of the two-way interactions are statistically significant. Based on the same definition of practical importance given previously for the FOV experiment, none of the two-way interactions were practically important. Graphs of these two-way interactions are provided in Appendix C.

4.3.3 Three-Way Interactions

Table 4-3 presents *p*-values for the three-way interactions for the PTAI experiment, and Appendix C gives the LSMs for all of the three-way interactions investigated in this experiment. With *p*-values less than or equal to 0.05, nine of the 10 three-way interactions are statistically significant. However, none of the three-way interactions are practically important. Graphs of all the three-way interactions are also given in Appendix C.

4.4 WBS Experiment Results

The results of the ANOVA for the WBS experiment are shown in Table 4-5. Since factors with *p*-values less than or equal to 0.05 are considered statistically significant, the model indicates that all of the factors except four are statistically significant. The R^2 value for the model is 0.97.

Table 4-5: ANOVA Results for WBS Experiment

Factor	*p*-value	Factor	*p*-value
Size	<0.0001	Cover*Input	<0.0001
Brand	<0.0001	Antenna*Input	<0.0001
Cover	<0.0001	Size*Brand*Cover	<0.0001
Antenna	<0.0001	Size*Brand*Antenna	<0.0001
Input	<0.0001	Size*Brand*Input	<0.0001
Size*Brand	<0.0001	Size*Cover*Antenna	0.0749
Size*Cover	<0.0001	Size*Cover*Input	<0.0001
Size*Antenna	<0.0001	Size*Antenna*Input	<0.0001
Size*Input	<0.0001	Brand*Cover*Antenna	<0.0001
Brand*Cover	<0.0001	Brand*Cover*Input	0.0749
Brand*Antenna	<0.0001	Brand*Antenna*Input	0.0600
Brand*Input	<0.0001	Cover*Antenna*Input	0.1662
Cover*Antenna	0.0007		

4.4.1 Main Effects

The LSMs for the main effects investigated in the PTAI experiment are displayed in Table 4-6, which shows that the magnitude of error for none of the analyses is greater than 0.125 in.; therefore, none are practically important. The results of these analyses are important because they indicate that, if the operator of the cover meter does not know the actual rebar size in question, the measured cover will be within 0.125 in. of the actual cover depth as long as the meter input is within one bar size of the correct value. Graphs of these factors are provided in Appendix D.

4.4.2 Two-Way Interactions

Table 4-5 presents *p*-values for the two-way interactions for the WBS experiment, and Appendix D gives the LSMs for all of the two-way interactions investigated in this experiment. Because they are all less than or equal to 0.05, all 10 of the two-way interactions are statistically

Table 4-6: Main Effects for WBS Experiment

Variable		Error (in.)
Bar Size	4	-0.025
	6	0.015
	8	0.002
Meter Brand	Brand A	-0.027
	Brand B	0.021
Antenna Type	Deep	0.038
	Shallow	-0.044
Cover Depth (in.)	2	0
	2.5	0.013
	3	-0.023
Input	-1	-0.095
	0	-0.011
	1	0.097

significant. Based on the same definition of practical importance given previously for the other experiments, none of the two-way interactions were practically important. Graphs of these two-way interactions are provided in Appendix D.

4.4.3 Three-Way Interactions

Table 4-5 presents *p*-values for the three-way interactions for the WBS experiment, and Appendix D gives the LSMs for all of the three-way interactions investigated in this experiment. With *p*-values less than or equal to 0.05, six of the 10 three-way interactions are statistically significant. However, none of the three-way interactions are practically important. Graphs of all the three-way interactions are also given in Appendix D.

4.5 Summary

The results of the ANOVA for the FOV experiment indicate that all of the factors are statistically significant, and the R^2 value for the model is 0.97. The LSMs for the main effects investigated in the FOV experiment show that the magnitude of error for 15 of the 19 analyses is greater than 0.125 in. For the meters and antennas tested, the FOV experiment indicates that, if the spacing is greater than approximately 4.0 in., the returned readings are within the threshold for practical importance established for this research. All of the *p*-values for the two-way interactions are less than or equal to 0.05, indicating that all 10 of the two-way interactions are statistically significant. However, only one two-way interaction, actual cover depth and rebar spacing, is both statistically significant and practically important. The *p*-values for the three-way interactions for the FOV experiment are less than or equal to 0.05, indicating that all 10 of the three-way interactions are statistically significant. However, the LSMs show that none of the three-way interactions are practically important.

The results of the ANOVA for the PTAI experiment indicate that all of the factors except one are statistically significant, and the R^2 value for the model is 0.89. The LSMs for the main effects investigated in the PTAI experiment show that the magnitude of error for none of the analyses is greater than 0.125 in.; therefore, none are practically important, which indicates that, regardless of where the measurement is taking place in relation to an intersection, the operator can be confident that the errors will be less than 0.125 in. as long as the bar in question is above the intersecting bar. All of the *p*-values for the two-way interactions are less than or equal to 0.05, indicating that all 10 of the two-way interactions are statistically significant. However, none of the two-way interactions were practically important. Likewise, although nine of the 10 *p*-values for the three-way interactions for the PTAI experiment were less than or equal to 0.05, none of the three-way interactions are practically important.

The results of the ANOVA for the WBS experiment indicate that all of the factors except four are statistically significant, and the R^2 value for the model is 0.97. The LSMs for the main effects investigated in the PTAI experiment show that the magnitude of error for none of the analyses is greater than 0.125 in.; therefore, none are practically important, which indicates that, if the operator of the cover meter does not know the actual rebar size in question, the measured cover will be within 0.125 in. of the actual cover depth as long as the meter input is within one bar size of the correct value. All of the *p*-values for the two-way interactions are less than or equal to 0.05, indicating that all 10 of the two-way interactions are statistically significant. However, none of the two-way interactions are practically important. Likewise, although six of the 10 *p*-values for the three-way interactions for the WBS experiment were less than or equal to 0.05, none of the three-way interactions were practically important.

5 CONCLUSION

5.1 Summary

The objective of this research was to quantify the effects of selected parameters on the accuracy of concrete cover measurements on bridge decks. This research involved three full-factorial laboratory experiments each designed to investigate one of three primary variables. These primary variables included distance to a parallel adjacent bar, distance to a reinforcement intersection, and incorrect bar size input for the cover meter. Each experiment also involved four secondary variables known to affect cover readings. These secondary variables included actual cover depth, meter brand, antenna type, and bar size. A single wooden apparatus was designed and constructed to accommodate all three experiments. ANOVA statistical analyses were performed to determine the significance of each factor. The standard error rate of 0.05 was considered statistically significant, and a margin of error of 0.125 in., corresponding to the increase in diameter between successive U.S. standard rebar sizes, was established as the threshold for practical importance.

5.2 Findings

Three primary findings resulted from the three experiments performed in this research. For the meters and antennas tested, the results of the FOV experiment indicated that, if the spacing is greater than approximately 4.0 in., the returned readings are within the threshold for practical importance established for this research. The results of the PTAI experiment indicated that, regardless of where the measurement is taking place in relation to an intersection, the operator can be confident that the errors will be less than 0.125 in. as long as the bar in question is above the intersecting bar. The results of the WBS experiment indicated that, if the operator of the cover meter does not know the actual rebar size in question, the measured cover will be within 0.125 in. of the actual cover depth as long as the meter input is within one bar size of the correct value.

5.3 Recommendations

Since rebar congestion greatly influences cover meter readings, special protocols should be followed when rebar spacing is smaller than 4.0 in. for conditions similar to those investigated in this research. When rebar is spaced closer than 4.0 in., the operator should use an antenna with a narrow field of view to minimize error in readings. However, the operator need not apply special procedures for measurement of cover depth in the vicinity of rebar intersections as long as the bar in question is above the intersecting bar. Finally, the operator should ensure that bar size inputs are accurate to within one bar size so that errors in cover meter readings are within the threshold for practical importance established for this research. The margin of error specified for this experiment is expected to be suitable for all typical aspects of bridge deck management, although some applications may not require such precision. Obtaining accurate cover measurements on bridge decks is important for quality assurance, service life prediction, and rehabilitation programming.

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APPENDIX A: DATA FOR PRELIMINARY EXPERIMENT

Table A-1: Cover Measurements for Meter 1 through Wood

Deep meter			Shallow meter		
Actual cover	Meter reading	Variation	Actual cover	Meter reading	Variation
1.83	1.9	0.07	1.83	1.85	0.02
1.83	1.9	0.07	1.83	1.85	0.02
1.83	1.9	0.07	1.83	1.85	0.02
1.83	1.9	0.07	1.83	1.85	0.02
1.83	1.9	0.07	1.83	1.85	0.02

Table A-2: Cover Measurements for Meter 2 through Wood

Deep meter			Shallow meter		
Actual cover	Meter reading	Variation	Actual cover	Meter reading	Variation
1.83	2	0.17	1.83	1.9	0.07
1.83	2	0.17	1.83	1.9	0.07
1.83	2	0.17	1.83	1.9	0.07
1.83	2	0.17	1.83	1.9	0.07
1.83	2	0.17	1.83	1.9	0.07

Table A-3: Cover Measurements for Meter 1 through Concrete

Deep meter			Shallow meter		
Actual cover	Meter reading	Variation	Actual cover	Meter reading	Variation
2.03	2.2	0.17	2.03	2.1	0.07
2.03	2.2	0.17	2.03	2.1	0.07
2.03	2.2	0.17	2.03	2.1	0.07
2.03	2.2	0.17	2.03	2.1	0.07
2.03	2.2	0.17	2.03	2.1	0.07

Table A-4: Cover Measurements for Meter 2 through Concrete

Deep meter			Shallow meter		
Actual cover	Meter reading	Variation	Actual cover	Meter reading	Variation
2.03	1.95	-0.08	2.03	2.15	0.12
2.03	1.95	-0.08	2.03	2.15	0.12
2.03	1.95	-0.08	2.03	2.15	0.12
2.03	1.95	-0.08	2.03	2.15	0.12
2.03	1.95	-0.08	2.03	2.15	0.12

APPENDIX B: DATA FOR FOV EXPERIMENT

B.1 FOV Two-Way Interaction Tabulated Results

Table B-1: Two-Way Interaction between Bar Size and Meter Brand for FOV Experiment

Size	Brand	Error
4	1	-0.118
6	1	-0.149
8	1	-0.144
4	2	-0.12
6	2	-0.173
8	2	-0.155

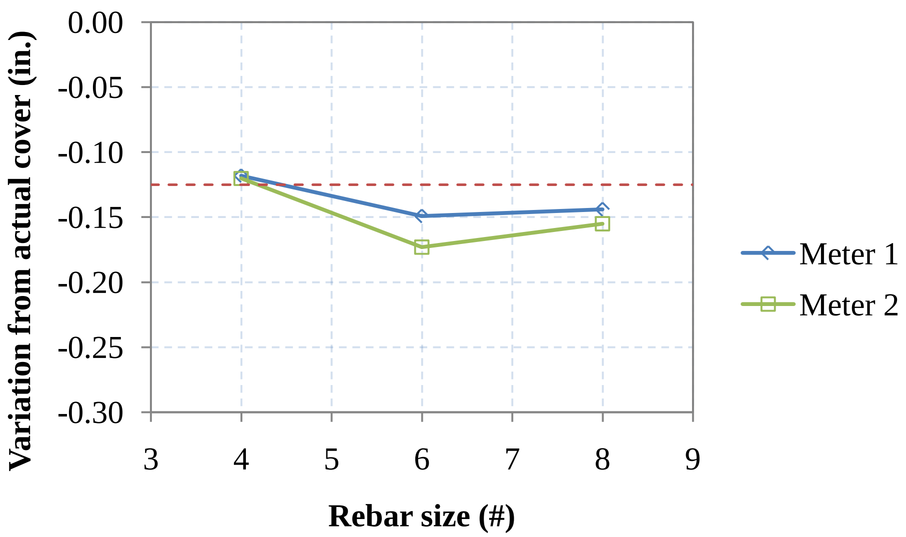


Figure B-1: Two-way interaction between bar size and meter brand for FOV experiment.

Table B-2: Two-Way Interaction between Bar Size and Actual Cover Depth for FOV Experiment

Size	Cover	Error
4	2	-0.063
6	2	-0.097
8	2	-0.097
4	2.5	-0.125
6	2.5	-0.173
8	2.5	-0.144
4	3	-0.169
6	3	-0.213
8	3	-0.206

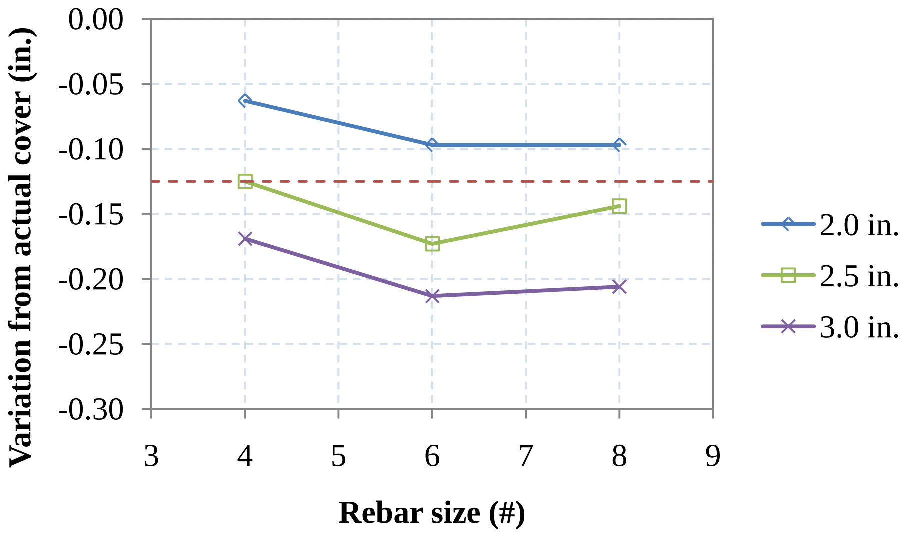


Figure B-2: Two-way interaction between bar size and actual cover depth for FOV experiment.

Table B-3: Two-Way Interaction between Bar Size and Antenna Type for FOV Experiment

Size	Antenna	Error
4	D	-0.106
6	D	-0.161
8	D	-0.136
4	S	-0.131
6	S	-0.161
8	S	-0.162

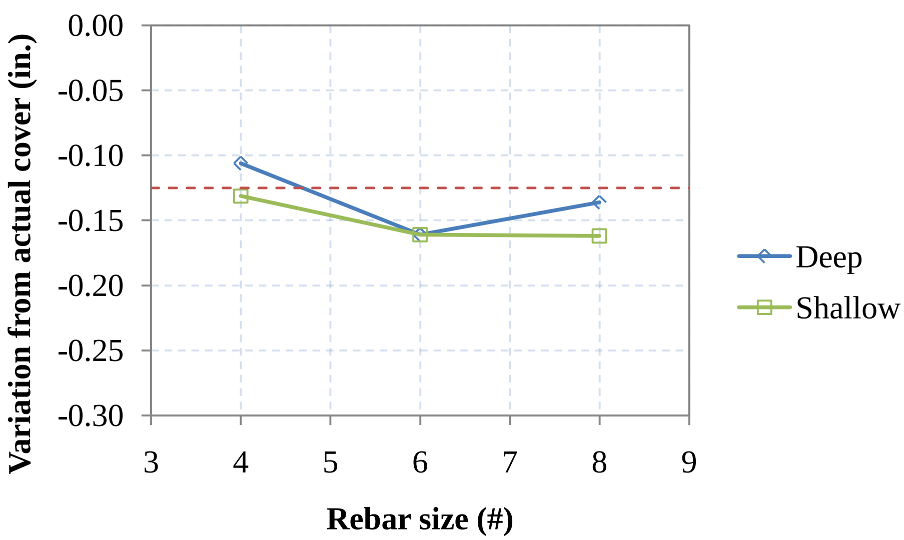


Figure B-3: Two-way interaction between bar size and antenna type for FOV experiment.

Table B-4: Two-Way Interaction betweez Bar Size and Offset Distance for FOV Experiment

Size	Spacing	Error
4	2	-0.258
4	2.5	-0.197
4	3	-0.156
4	3.5	-0.114
4	4	-0.092
4	4.5	-0.079
4	5	-0.061
4	5.5	-0.058
4	6	-0.054
6	2	-0.265
6	2.5	-0.225
6	3	-0.191
6	3.5	-0.149
6	4	-0.135
6	4.5	-0.132
6	5	-0.121
6	5.5	-0.117
6	6	-0.115
8	2	-0.296
8	2.5	-0.239
8	3	-0.19
8	3.5	-0.151
8	4	-0.125
8	4.5	-0.108
8	5	-0.089
8	5.5	-0.079
8	6	-0.067

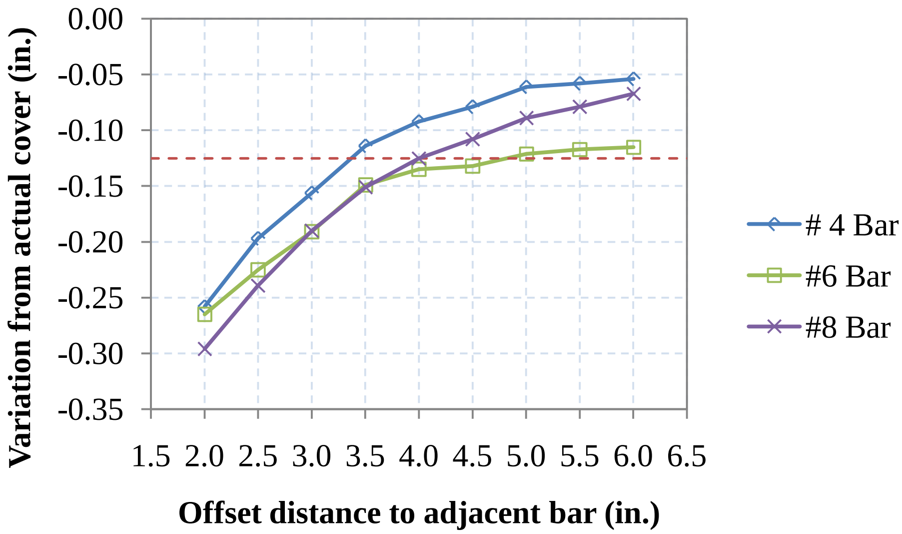


Figure B-4: Two-way interaction between bar size and offset distance for FOV experiment.

Table B-5: Two-Way Interaction between Meter Brand and Actual Cover Depth for FOV Experiment

Brand	Cover	Error
1	2	-0.077
2	2	-0.094
1	2.5	-0.144
2	2.5	-0.15
1	3	-0.19
2	3	-0.203

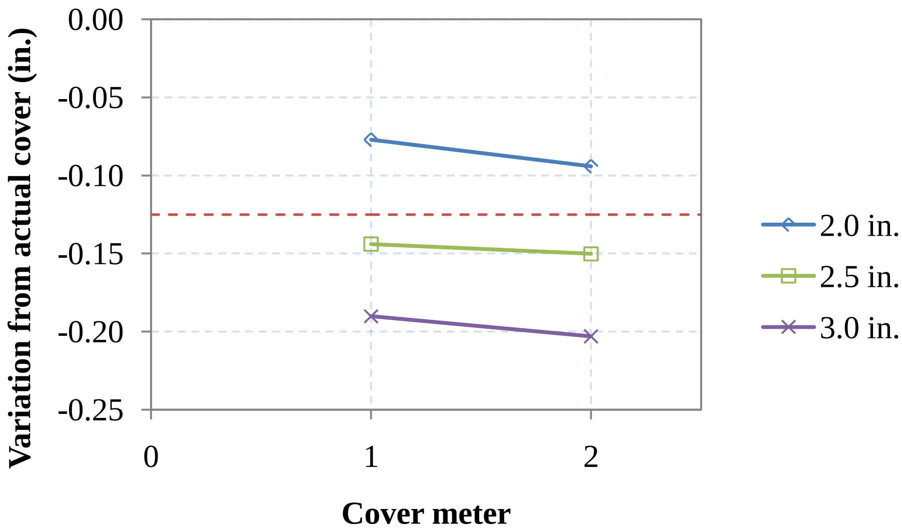


Figure B-5: Two-way interaction between meter brand and actual cover depth for FOV experiment.

Table B-6: Two-Way Interaction between Meter Brand and Antenna Type for FOV Experiment

Brand	Antenna	Error
1	D	-0.134
2	D	-0.135
1	S	-0.14
2	S	-0.163

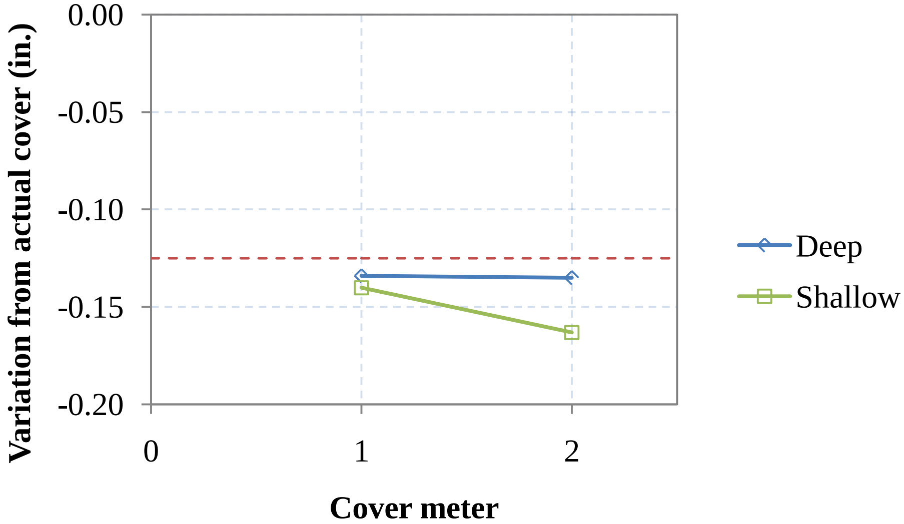


Figure B-6: Two-way interaction between meter brand and antenna type for FOV experiment.

Table B-7: Two-Way Interaction between Meter Brand and Offset Distance for FOV Experiment

Brand	Spacing	Error
1	2	-0.248
1	2.5	-0.193
1	3	-0.157
1	3.5	-0.119
1	4	-0.112
1	4.5	-0.11
1	5	-0.102
1	5.5	-0.094
1	6	-0.096
2	2	-0.298
2	2.5	-0.248
2	3	-0.201
2	3.5	-0.156
2	4	-0.122
2	4.5	-0.103
2	5	-0.078
2	5.5	-0.075
2	6	-0.061

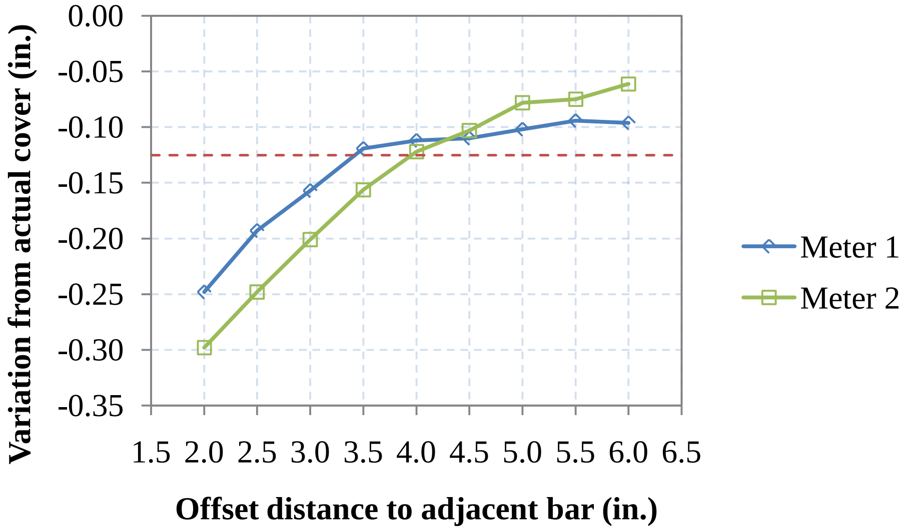


Figure B-7: Two-way interaction between meter brand and offset distance for FOV experiment.

Table B-8: Two-Way Interaction between Actual Cover Depth and Antenna Type for FOV Experiment

Cover	Antenna	Error
2	D	-0.06
2.5	D	-0.137
3	D	-0.207
2	S	-0.112
2.5	S	-0.158
3	S	-0.185

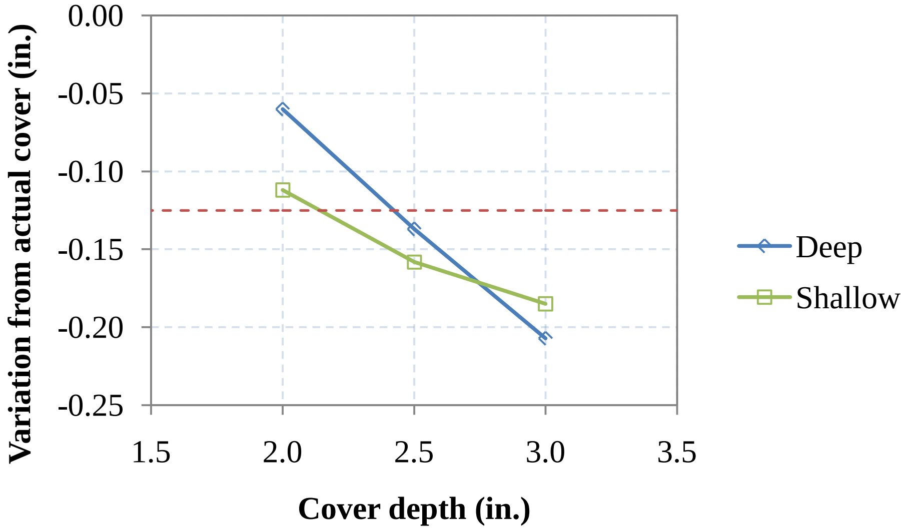


Figure B-8: Two-way interaction between antenna type and actual cover depth for FOV experiment.

Table B-9: Two-Way Interaction between Actual Cover Depth and Offset Distance for FOV Experiment

Cover	Spacing	Error
2	2	-0.186
2	2.5	-0.145
2	3	-0.118
2	3.5	-0.082
2	4	-0.058
2	4.5	-0.054
2	5	-0.043
2	5.5	-0.042
2	6	-0.042
2.5	2	-0.276
2.5	2.5	-0.218
2.5	3	-0.182
2.5	3.5	-0.143
2.5	4	-0.126
2.5	4.5	-0.111
2.5	5	-0.099
2.5	5.5	-0.092
2.5	6	-0.079
3	2	-0.356
3	2.5	-0.297
3	3	-0.238
3	3.5	-0.189
3	4	-0.167
3	4.5	-0.154
3	5	-0.129
3	5.5	-0.12
3	6	-0.115

Table B-10: Two-Way Interaction between Antenna Type and Offset Distance for FOV Experiment

Antenna	Spacing	Error
D	2	-0.283
D	2.5	-0.227
D	3	-0.176
D	3.5	-0.134
D	4	-0.11
D	4.5	-0.094
D	5	-0.069
D	5.5	-0.064
D	6	-0.053
S	2	-0.263
S	2.5	-0.214
S	3	-0.182
S	3.5	-0.142
S	4	-0.124
S	4.5	-0.119
S	5	-0.112
S	5.5	-0.106
S	6	-0.105

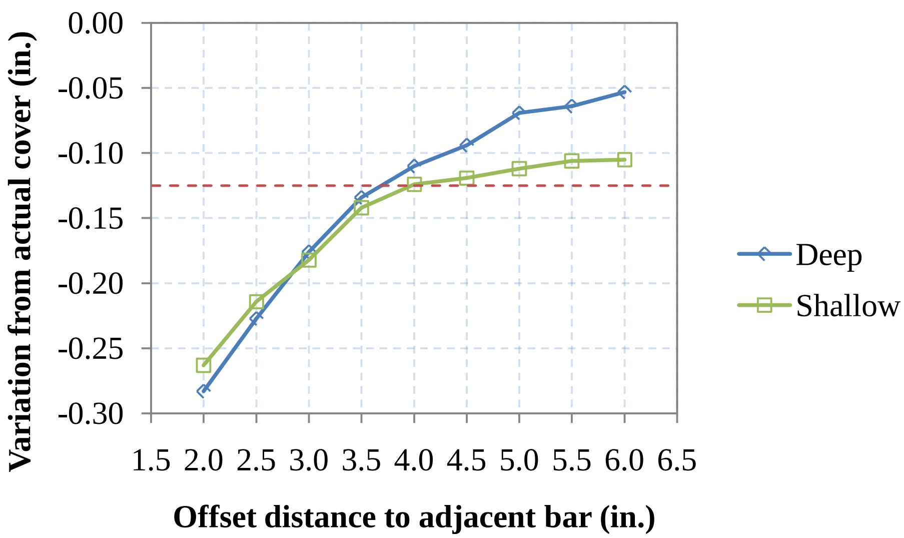
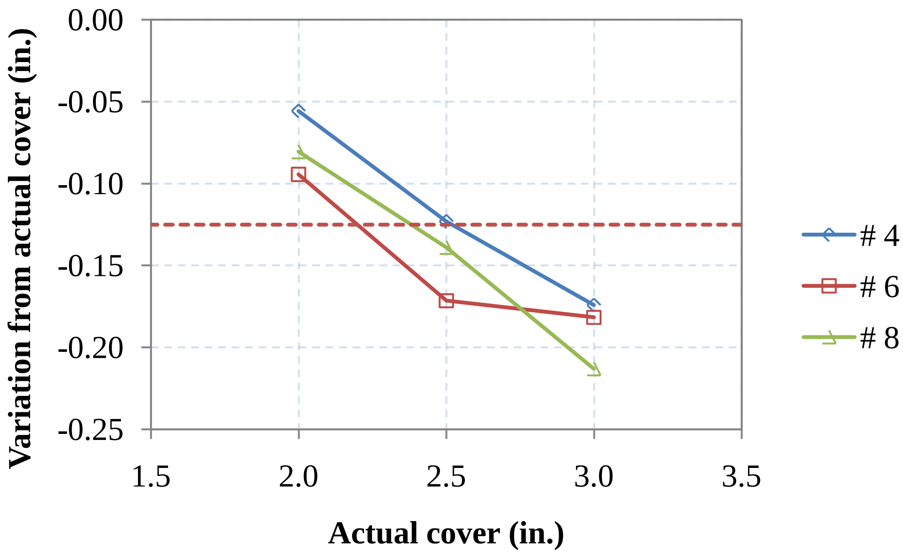


Figure B-9: Two-way interaction between offset distance and antenna type for FOV experiment.

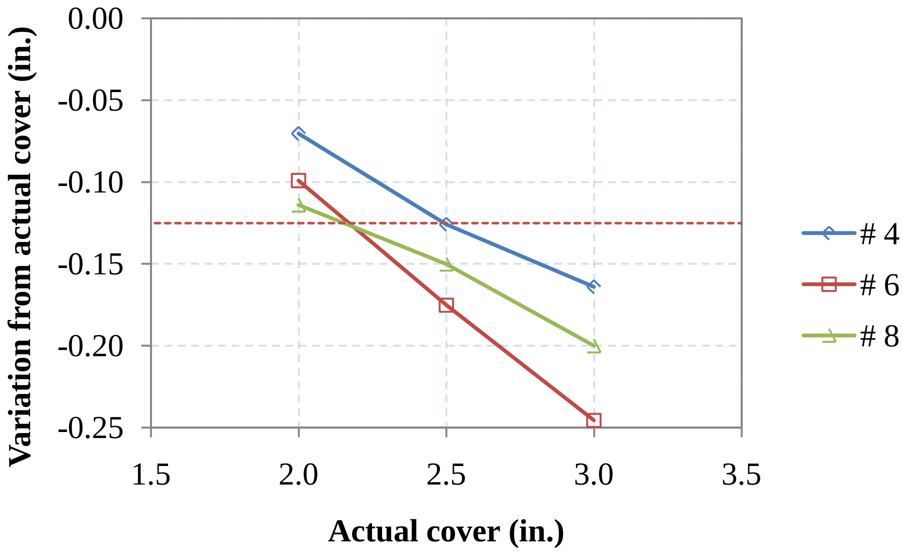
B.2 FOV Three-Way Interaction Tabulated Results and Figures

Table B-11: Three-Way Interaction between Bar Size, Actual Cover Depth, and Meter Brand for FOV Experiment

Size	Brand	Cover	Error
4	1	2.0	-0.056
4	1	2.5	-0.123
4	1	3.0	-0.174
4	2	2.0	-0.070
4	2	2.5	-0.126
4	2	3.0	-0.164
6	1	2.0	-0.094
6	1	2.5	-0.171
6	1	3.0	-0.181
6	2	2.0	-0.099
6	2	2.5	-0.175
6	2	3.0	-0.245
8	1	2.0	-0.081
8	1	2.5	-0.139
8	1	3.0	-0.213
8	2	2.0	-0.114
8	2	2.5	-0.150
8	2	3.0	-0.200



(a) Meter 1.

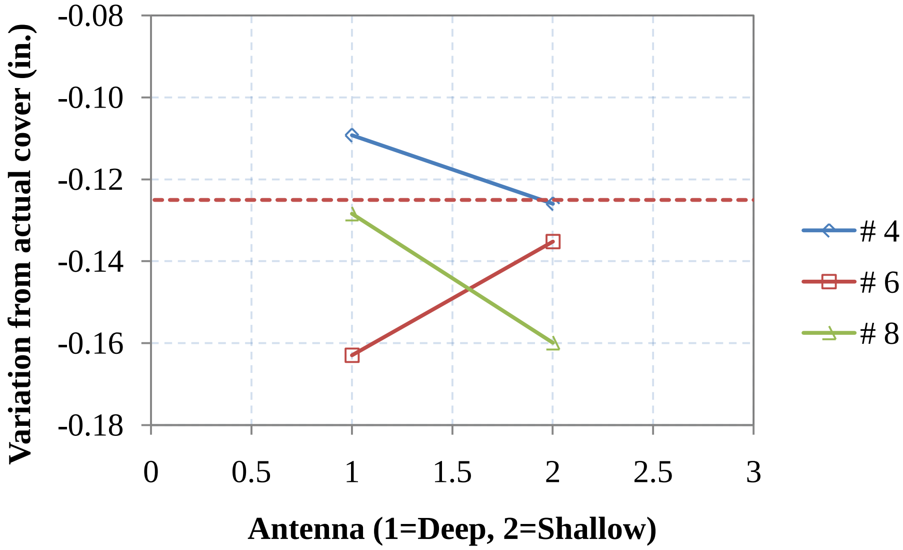


(b) Meter 2.

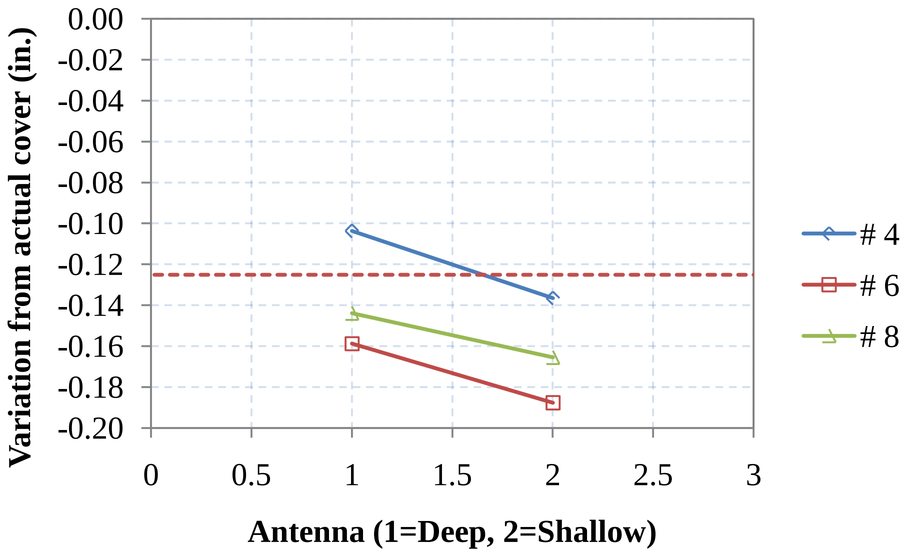
Figure B-10: Three-way interaction between bar size, actual cover depth, and meter brand for FOV experiment.

Table B-12: Three-Way Interaction between Bar Size, Antenna Type, and Meter Brand for FOV Experiment

Size	Brand	Antenna	Error
4	1	D	-0.109
4	1	S	-0.126
4	2	D	-0.104
4	2	S	-0.136
6	1	D	-0.163
6	1	S	-0.135
6	2	D	-0.159
6	2	S	-0.188
8	1	D	-0.128
8	1	S	-0.160
8	2	D	-0.144
8	2	S	-0.165



(a) Meter 1.

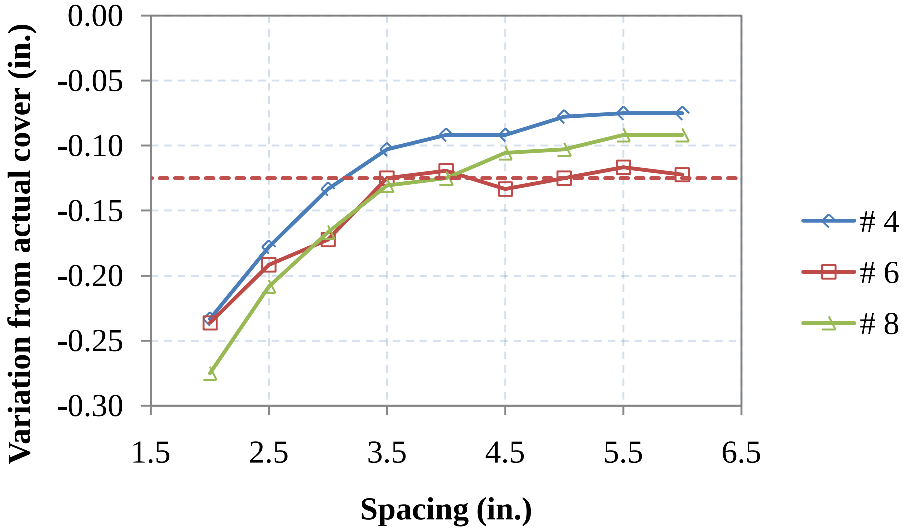


(b) Meter 2.

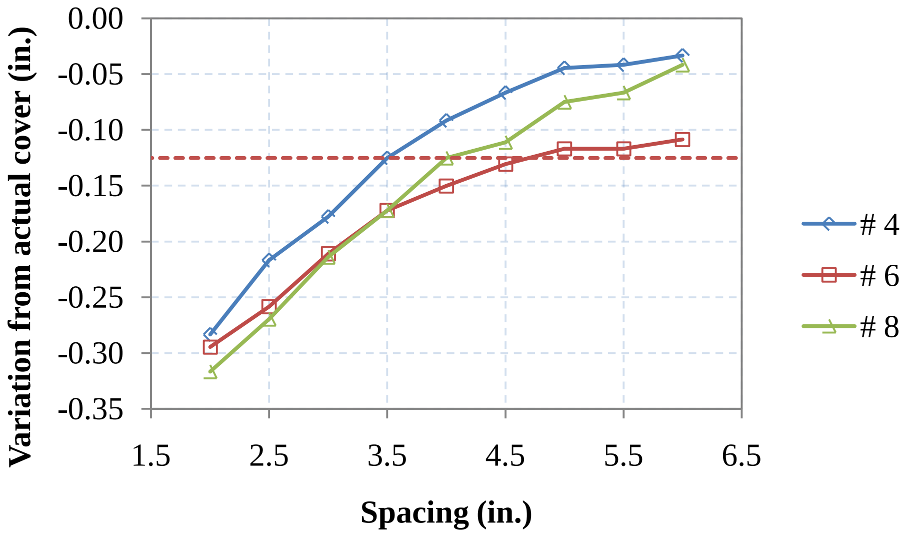
Figure B-11: Three-way interaction between bar size, antenna type, and meter brand for FOV experiment.

Table B-13: Three-Way Interaction between Bar Size, Offset Distance, and Meter Brand for FOV Experiment

Size	Brand	Spacing	Error	Size	Brand	Spacing	Error
4	1	2.0	-0.233	6	2	2.0	-0.294
4	1	2.5	-0.178	6	2	2.5	-0.258
4	1	3.0	-0.133	6	2	3.0	-0.211
4	1	3.5	-0.103	6	2	3.5	-0.172
4	1	4.0	-0.092	6	2	4.0	-0.150
4	1	4.5	-0.092	6	2	4.5	-0.131
4	1	5.0	-0.078	6	2	5.0	-0.117
4	1	5.5	-0.075	6	2	5.5	-0.117
4	1	6.0	-0.075	6	2	6.0	-0.108
4	2	2.0	-0.283	8	1	2.0	-0.275
4	2	2.5	-0.217	8	1	2.5	-0.208
4	2	3.0	-0.178	8	1	3.0	-0.167
4	2	3.5	-0.125	8	1	3.5	-0.131
4	2	4.0	-0.092	8	1	4.0	-0.125
4	2	4.5	-0.067	8	1	4.5	-0.106
4	2	5.0	-0.044	8	1	5.0	-0.103
4	2	5.5	-0.042	8	1	5.5	-0.092
4	2	6.0	-0.033	8	1	6.0	-0.092
6	1	2.0	-0.236	8	2	2.0	-0.317
6	1	2.5	-0.192	8	2	2.5	-0.269
6	1	3.0	-0.172	8	2	3.0	-0.214
6	1	3.5	-0.125	8	2	3.5	-0.172
6	1	4.0	-0.119	8	2	4.0	-0.125
6	1	4.5	-0.133	8	2	4.5	-0.111
6	1	5.0	-0.125	8	2	5.0	-0.075
6	1	5.5	-0.117	8	2	5.5	-0.067
6	1	6.0	-0.122	8	2	6.0	-0.042



(a) Meter 1.

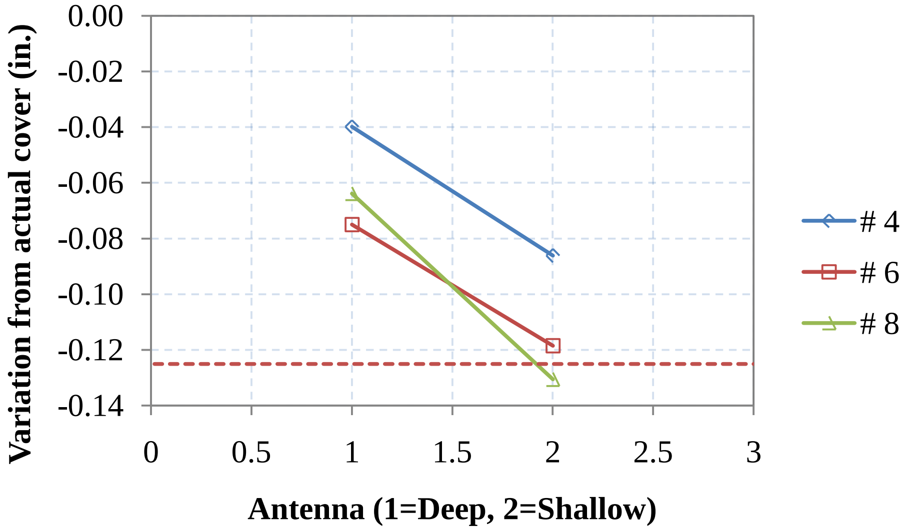


(b) Meter 2.

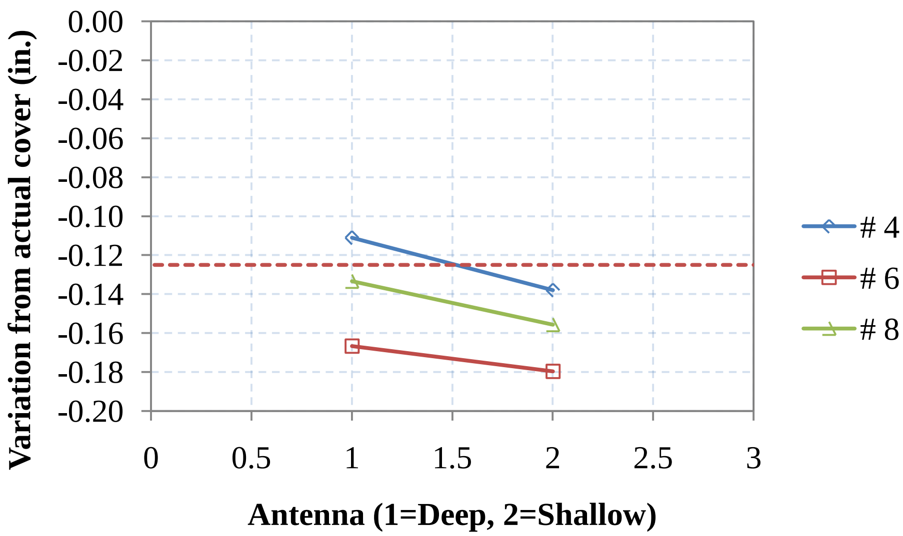
Figure B-12: Three-way interaction between bar size, offset distance, and meter brand for FOV experiment.

Table B-14: Three-Way Interaction between Bar Size, Antenna Type, and Actual Cover Depth for FOV Experiment

Size	Cover	Antenna	Error
4	2.0	D	-0.040
4	2.0	S	-0.086
4	2.5	D	-0.111
4	2.5	S	-0.138
4	3.0	D	-0.169
4	3.0	S	-0.169
6	2.0	D	-0.075
6	2.0	S	-0.119
6	2.5	D	-0.167
6	2.5	S	-0.180
6	3.0	D	-0.241
6	3.0	S	-0.186
8	2.0	D	-0.064
8	2.0	S	-0.131
8	2.5	D	-0.133
8	2.5	S	-0.156
8	3.0	D	-0.211
8	3.0	S	-0.202

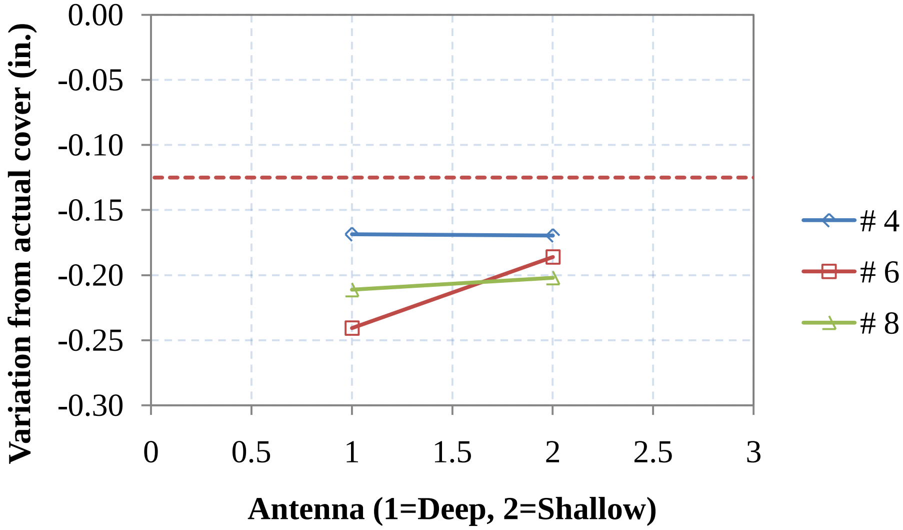


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure B-13: Three-way interaction between bar size, antenna type, and actual cover depth for FOV experiment.



(c) 3.0 in. actual cover depth.

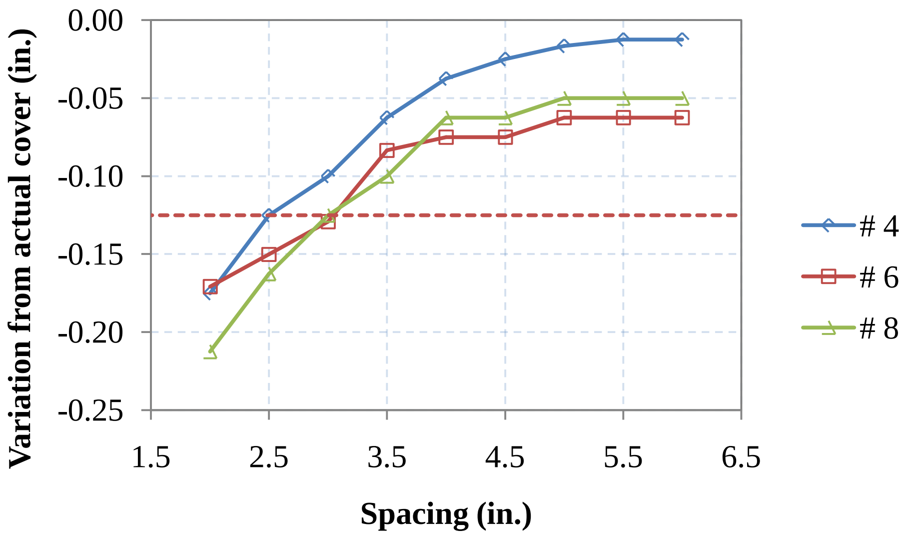
Figure B-13: Three-way interaction between bar size, antenna type, and actual cover depth for FOV experiment. (Continued)

Table B-15: Three-Way Interaction between Bar Size, Offset Distance, and Actual Cover Depth for FOV Experiment

Size	Cover	Spacing	Error	Size	Cover	Spacing	Error
4	2.0	2.0	-0.175	6	2.5	4.5	-0.138
4	2.0	2.5	-0.125	6	2.5	5.0	-0.138
4	2.0	3.0	-0.100	6	2.5	5.5	-0.138
4	2.0	3.5	-0.063	6	2.5	6.0	-0.133
4	2.0	4.0	-0.038	6	3.0	2.0	-0.350
4	2.0	4.5	-0.025	6	3.0	2.5	-0.300
4	2.0	5.0	-0.017	6	3.0	3.0	-0.246
4	2.0	5.5	-0.013	6	3.0	3.5	-0.200
4	2.0	6.0	-0.013	6	3.0	4.0	-0.179
4	2.5	2.0	-0.267	6	3.0	4.5	-0.183
4	2.5	2.5	-0.200	6	3.0	5.0	-0.163
4	2.5	3.0	-0.167	6	3.0	5.5	-0.150
4	2.5	3.5	-0.117	6	3.0	6.0	-0.150
4	2.5	4.0	-0.100	8	2.0	2.0	-0.213
4	2.5	4.5	-0.088	8	2.0	2.5	-0.163
4	2.5	5.0	-0.067	8	2.0	3.0	-0.125
4	2.5	5.5	-0.063	8	2.0	3.5	-0.100
4	2.5	6.0	-0.054	8	2.0	4.0	-0.063
4	3.0	2.0	-0.333	8	2.0	4.5	-0.063
4	3.0	2.5	-0.267	8	2.0	5.0	-0.050
4	3.0	3.0	-0.200	8	2.0	5.5	-0.050
4	3.0	3.5	-0.163	8	2.0	6.0	-0.050
4	3.0	4.0	-0.138	8	2.5	2.0	-0.288
4	3.0	4.5	-0.125	8	2.5	2.5	-0.229
4	3.0	5.0	-0.100	8	2.5	3.0	-0.179
4	3.0	5.5	-0.100	8	2.5	3.5	-0.150
4	3.0	6.0	-0.096	8	2.5	4.0	-0.129
6	2.0	2.0	-0.171	8	2.5	4.5	-0.108

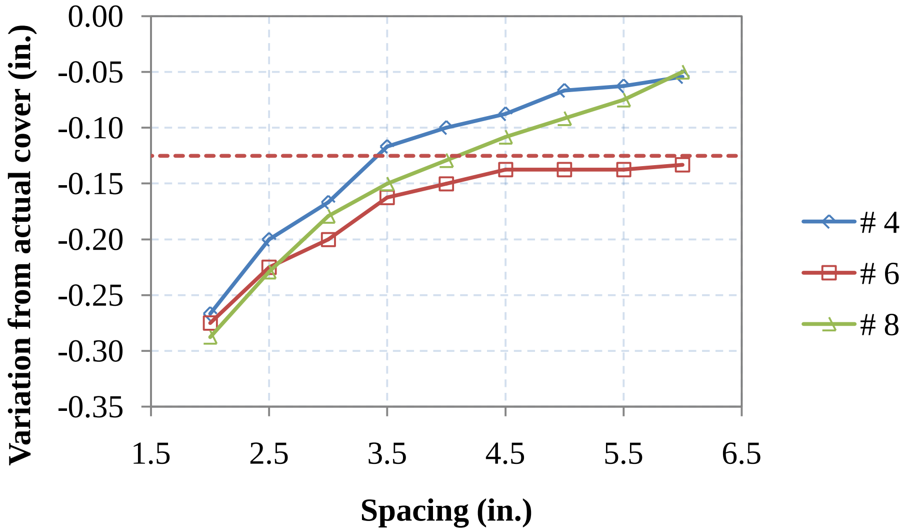
Table B-15: Three-Way Interaction between Bar Size, Offset Distance, and Actual Cover Depth for FOV Experiment (Continued)

Size	Cover	Spacing	Error	Size	Cover	Spacing	Error
6	2.0	2.5	-0.150	8	2.5	5.0	-0.092
6	2.0	3.0	-0.129	8	2.5	5.5	-0.075
6	2.0	3.5	-0.083	8	2.5	6.0	-0.050
6	2.0	4.0	-0.075	8	3.0	2.0	-0.388
6	2.0	4.5	-0.075	8	3.0	2.5	-0.325
6	2.0	5.0	-0.063	8	3.0	3.0	-0.267
6	2.0	5.5	-0.063	8	3.0	3.5	-0.204
6	2.0	6.0	-0.063	8	3.0	4.0	-0.183
6	2.5	2.0	-0.275	8	3.0	4.5	-0.154
6	2.5	2.5	-0.225	8	3.0	5.0	-0.125
6	2.5	3.0	-0.200	8	3.0	5.5	-0.113
6	2.5	3.5	-0.163	8	3.0	6.0	-0.100
6	2.5	4.0	-0.150				

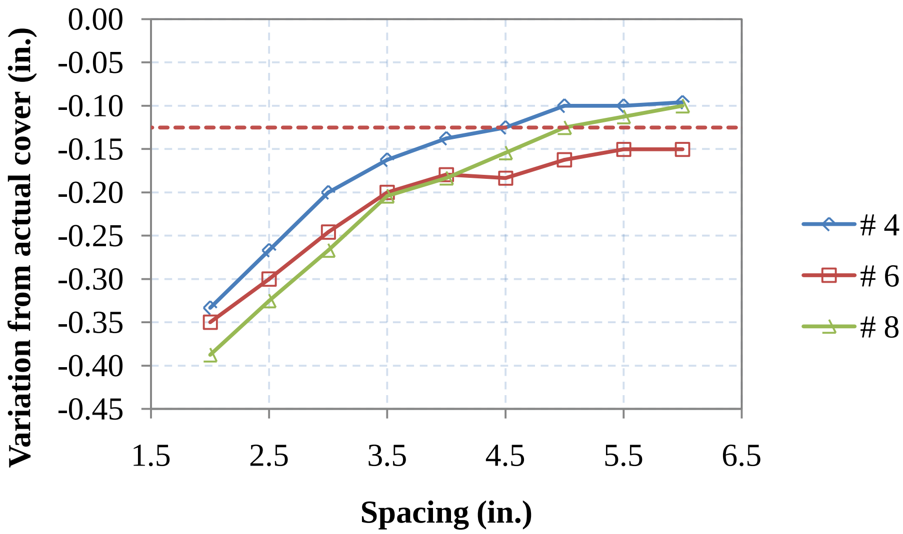


(a) 2.0 in. actual cover depth.

Figure B-14: Three-way interaction between bar size, offset distance, and actual cover depth for FOV experiment.



(b) 2.5 in. actual cover depth.

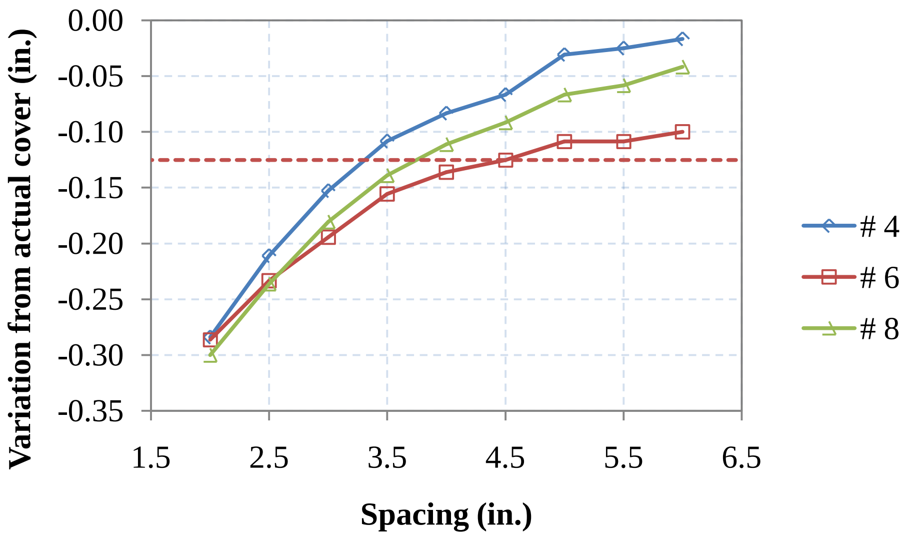


(c) 3.0 in. actual cover depth.

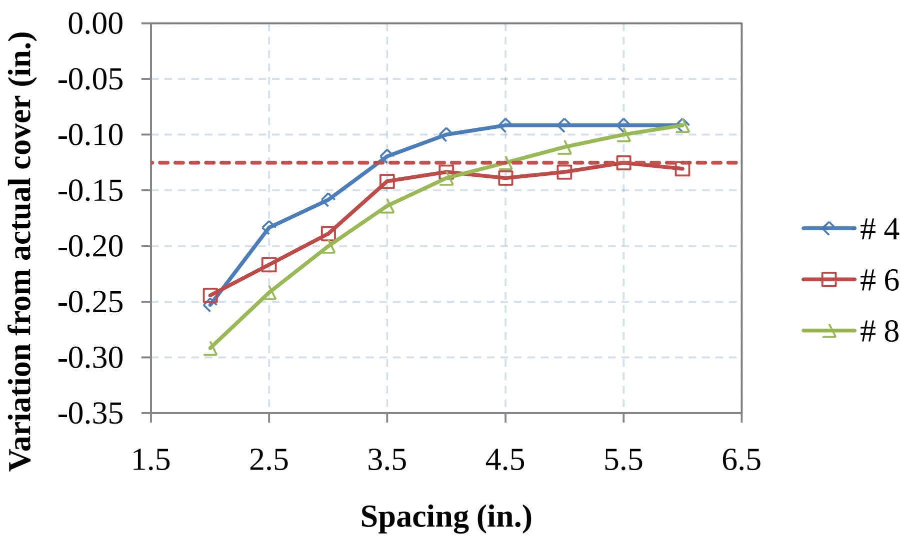
Figure B-14: Three-way interaction between bar size, offset distance, and actual cover depth for FOV experiment. (Continued)

Table B-16: Three-Way Interaction between Bar Size, Offset Distance, and Antenna Type for FOV Experiment

Size	Antenna	Spacing	Error	Size	Antenna	Spacing	Error
4	D	2.0	-0.284	6	S	2.0	-0.244
4	D	2.5	-0.211	6	S	2.5	-0.217
4	D	3.0	-0.153	6	S	3.0	-0.189
4	D	3.5	-0.108	6	S	3.5	-0.142
4	D	4.0	-0.083	6	S	4.0	-0.133
4	D	4.5	-0.067	6	S	4.5	-0.139
4	D	5.0	-0.031	6	S	5.0	-0.133
4	D	5.5	-0.025	6	S	5.5	-0.125
4	D	6.0	-0.017	6	S	6.0	-0.131
4	S	2.0	-0.253	8	D	2.0	-0.300
4	S	2.5	-0.183	8	D	2.5	-0.236
4	S	3.0	-0.158	8	D	3.0	-0.181
4	S	3.5	-0.119	8	D	3.5	-0.139
4	S	4.0	-0.100	8	D	4.0	-0.111
4	S	4.5	-0.092	8	D	4.5	-0.092
4	S	5.0	-0.092	8	D	5.0	-0.067
4	S	5.5	-0.092	8	D	5.5	-0.058
4	S	6.0	-0.092	8	D	6.0	-0.042
6	D	2.0	-0.286	8	S	2.0	-0.292
6	D	2.5	-0.233	8	S	2.5	-0.242
6	D	3.0	-0.194	8	S	3.0	-0.200
6	D	3.5	-0.156	8	S	3.5	-0.164
6	D	4.0	-0.136	8	S	4.0	-0.139
6	D	4.5	-0.125	8	S	4.5	-0.125
6	D	5.0	-0.108	8	S	5.0	-0.111
6	D	5.5	-0.108	8	S	5.5	-0.100
6	D	6.0	-0.100	8	S	6.0	-0.092



(a) Deep antenna.

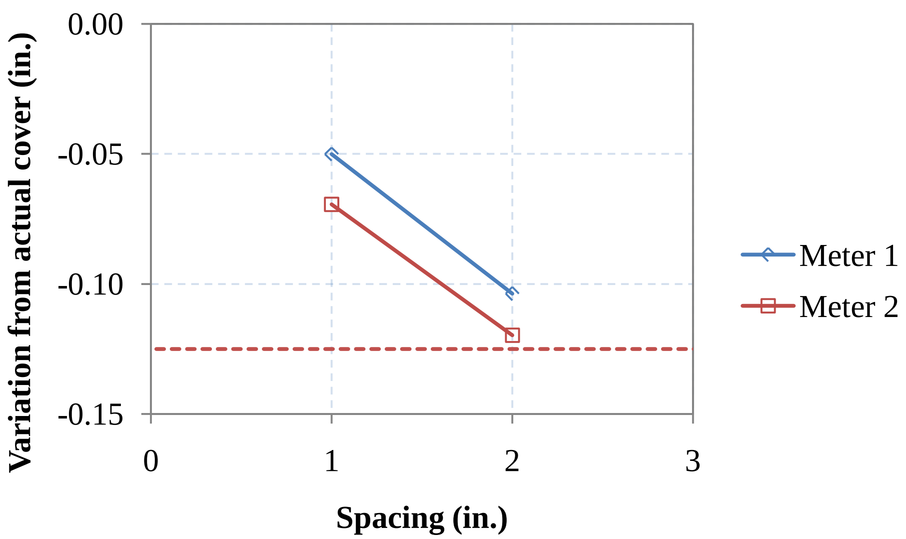


(b) Shallow antenna.

Figure B-15: Three-way interaction between bar size, offset distance, and antenna type for FOV experiment.

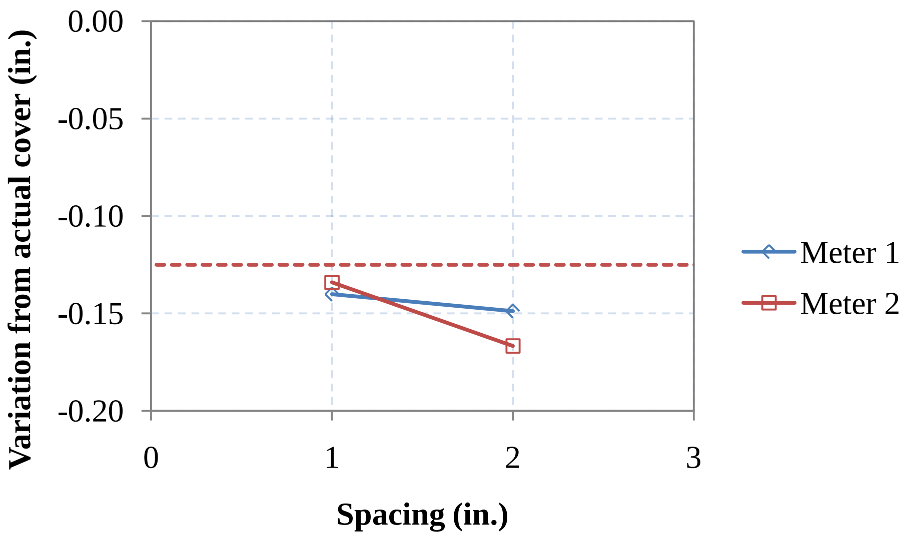
Table B-17: Three-way Interaction between Meter Brand, Antenna Type, and Actual Cover Depth for FOV Experiment

Brand	Cover	Antenna	Error
1	2.0	D	-0.050
1	2.0	S	-0.104
1	2.5	D	-0.140
1	2.5	S	-0.149
1	3.0	D	-0.210
1	3.0	S	-0.169
2	2.0	D	-0.069
2	2.0	S	-0.120
2	2.5	D	-0.134
2	2.5	S	-0.167
2	3.0	D	-0.203
2	3.0	S	-0.203

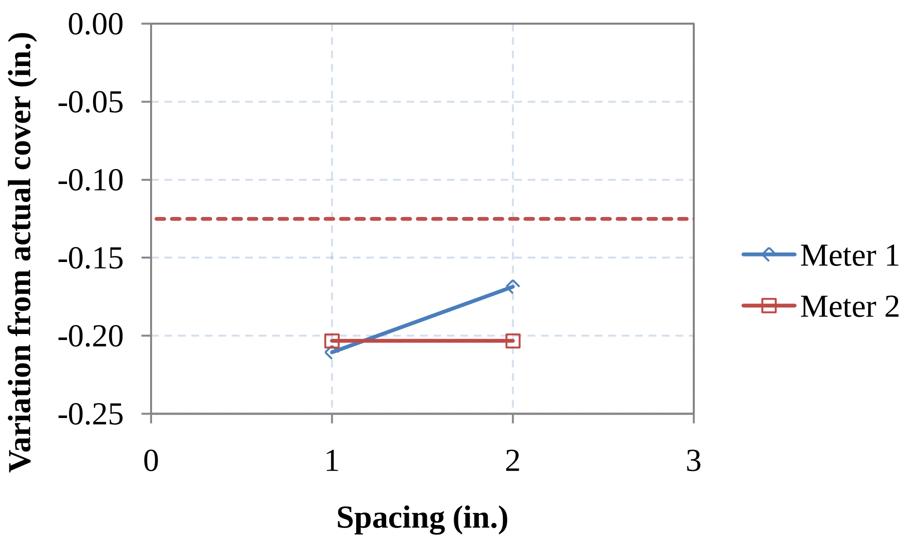


(a) 2.0 in. actual cover depth.

Figure B-16: Three-way interaction between meter brand, antenna type, and actual cover depth for FOV experiment.



(b) 2.5 in. actual cover depth.

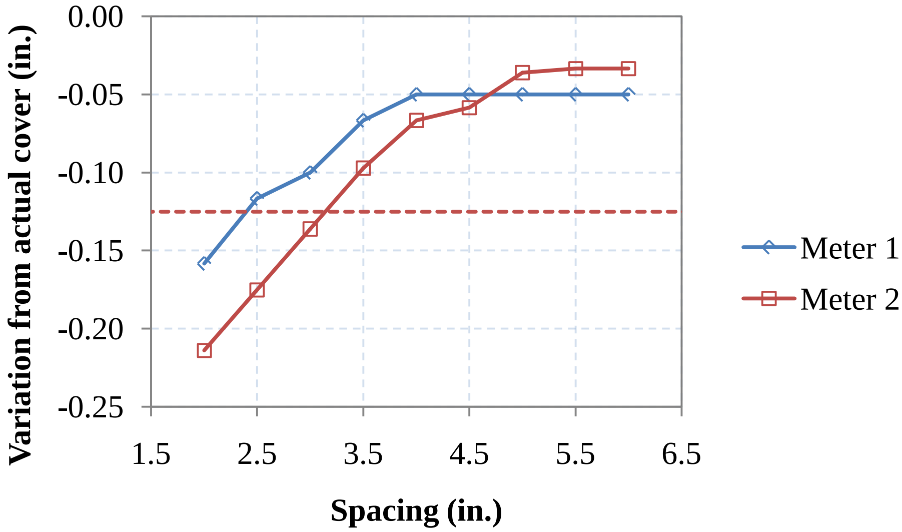


(c) 3.0 in. actual cover depth.

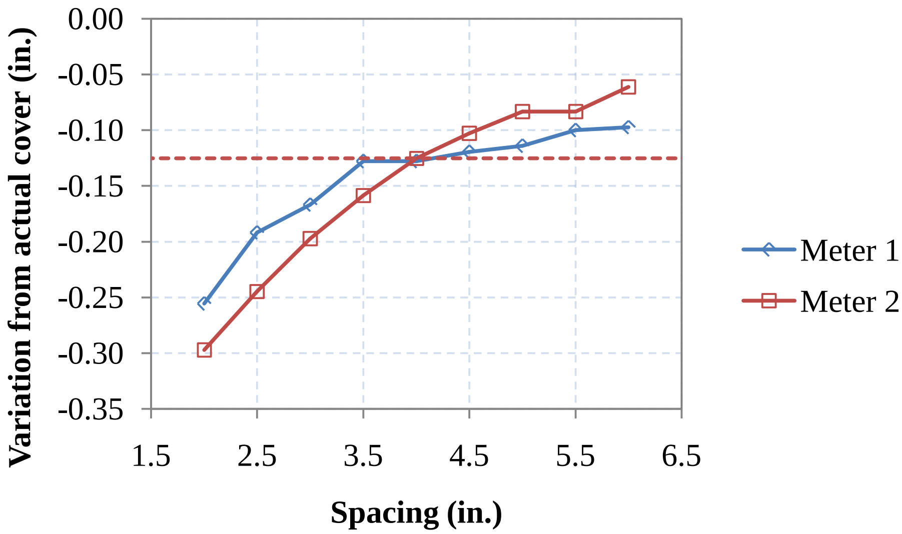
Figure B-16: Three-way interaction between meter brand, antenna type, and actual cover depth for FOV experiment. (Continued)

Table B-18: Three-Way Interaction between Meter Brand, Offset Distance, and Actual Cover Depth for FOV Experiment

Brand	Cover	Spacing	Error	Brand	Cover	Spacing	Error
1	2.0	2.0	-0.158	2	2.0	2.0	-0.214
1	2.0	2.5	-0.117	2	2.0	2.5	-0.175
1	2.0	3.0	-0.100	2	2.0	3.0	-0.136
1	2.0	3.5	-0.067	2	2.0	3.5	-0.097
1	2.0	4.0	-0.050	2	2.0	4.0	-0.067
1	2.0	4.5	-0.050	2	2.0	4.5	-0.058
1	2.0	5.0	-0.050	2	2.0	5.0	-0.036
1	2.0	5.5	-0.050	2	2.0	5.5	-0.033
1	2.0	6.0	-0.050	2	2.0	6.0	-0.033
1	2.5	2.0	-0.256	2	2.5	2.0	-0.297
1	2.5	2.5	-0.192	2	2.5	2.5	-0.244
1	2.5	3.0	-0.167	2	2.5	3.0	-0.197
1	2.5	3.5	-0.128	2	2.5	3.5	-0.158
1	2.5	4.0	-0.128	2	2.5	4.0	-0.125
1	2.5	4.5	-0.119	2	2.5	4.5	-0.103
1	2.5	5.0	-0.114	2	2.5	5.0	-0.083
1	2.5	5.5	-0.100	2	2.5	5.5	-0.083
1	2.5	6.0	-0.097	2	2.5	6.0	-0.061
1	3.0	2.0	-0.331	2	3.0	2.0	-0.383
1	3.0	2.5	-0.269	2	3.0	2.5	-0.325
1	3.0	3.0	-0.206	2	3.0	3.0	-0.269
1	3.0	3.5	-0.164	2	3.0	3.5	-0.214
1	3.0	4.0	-0.158	2	3.0	4.0	-0.175
1	3.0	4.5	-0.161	2	3.0	4.5	-0.147
1	3.0	5.0	-0.142	2	3.0	5.0	-0.117
1	3.0	5.5	-0.133	2	3.0	5.5	-0.108
1	3.0	6.0	-0.142	2	3.0	6.0	-0.089

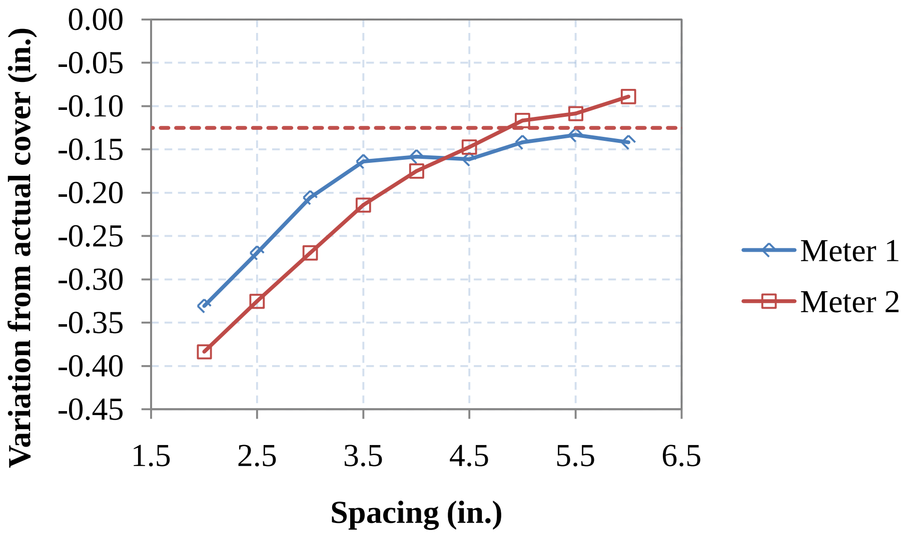


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure B-17: Three-way interaction between meter brand, offset distance, and actual cover depth for FOV experiment.

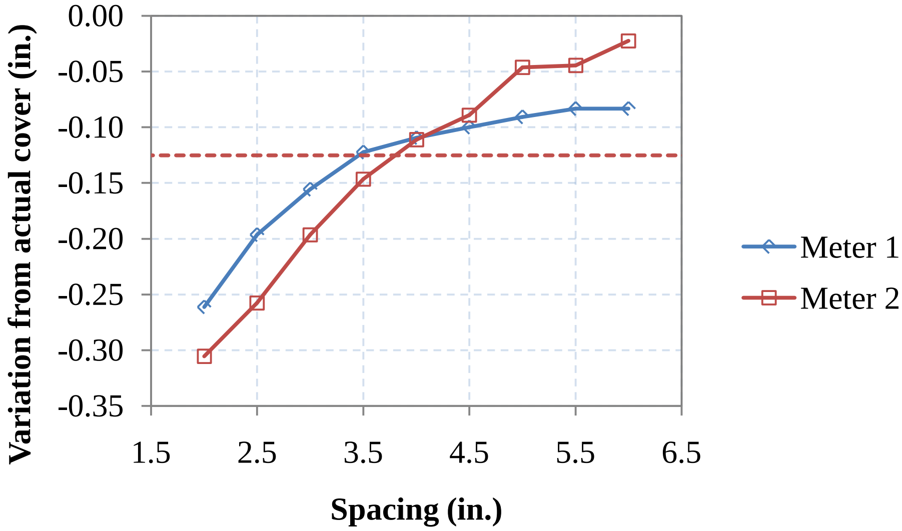


(c) 3.0 in. actual cover depth.

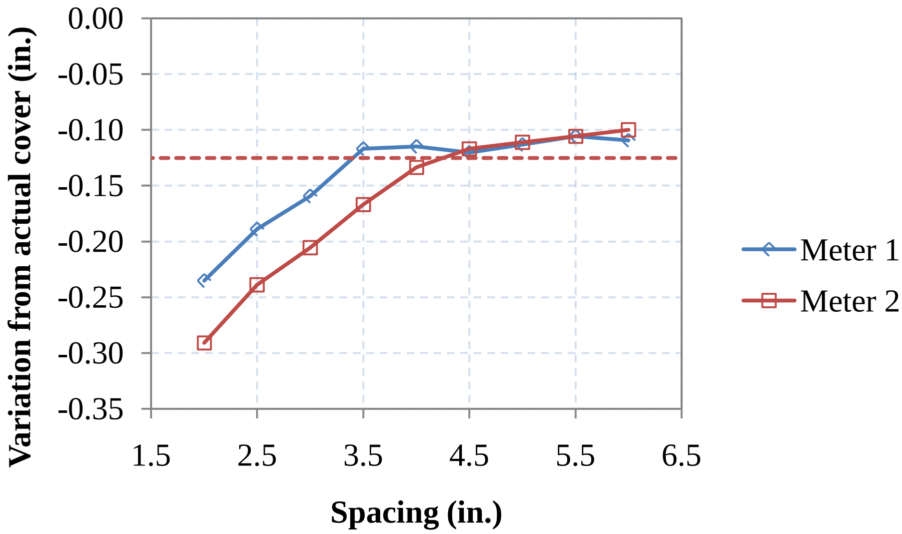
Figure B-17: Three-way interaction between meter brand, offset distance, and actual cover depth for FOV experiment. (Continued)

Table B-19: Three-Way Interaction between Meter Brand, Offset Distance, and Antenna Type for FOV Experiment

Brand	Antenna	Spacing	Error
1	D	2.0	-0.261
1	D	2.5	-0.196
1	D	3.0	-0.156
1	D	3.5	-0.122
1	D	4.0	-0.109
1	D	4.5	-0.100
1	D	5.0	-0.091
1	D	5.5	-0.083
1	D	6.0	-0.083
1	S	2.0	-0.235
1	S	2.5	-0.189
1	S	3.0	-0.159
1	S	3.5	-0.117
1	S	4.0	-0.115
1	S	4.5	-0.120
1	S	5.0	-0.113
1	S	5.5	-0.106
1	S	6.0	-0.109
2	D	2.0	-0.306
2	D	2.5	-0.257
2	D	3.0	-0.196
2	D	3.5	-0.146
2	D	4.0	-0.111
2	D	4.5	-0.089
2	D	5.0	-0.046
2	D	5.5	-0.044
2	D	6.0	-0.022
2	S	2.0	-0.291
2	S	2.5	-0.239
2	S	3.0	-0.206
2	S	3.5	-0.167
2	S	4.0	-0.133
2	S	4.5	-0.117
2	S	5.0	-0.111
2	S	5.5	-0.106
2	S	6.0	-0.100



(a) Deep antenna.

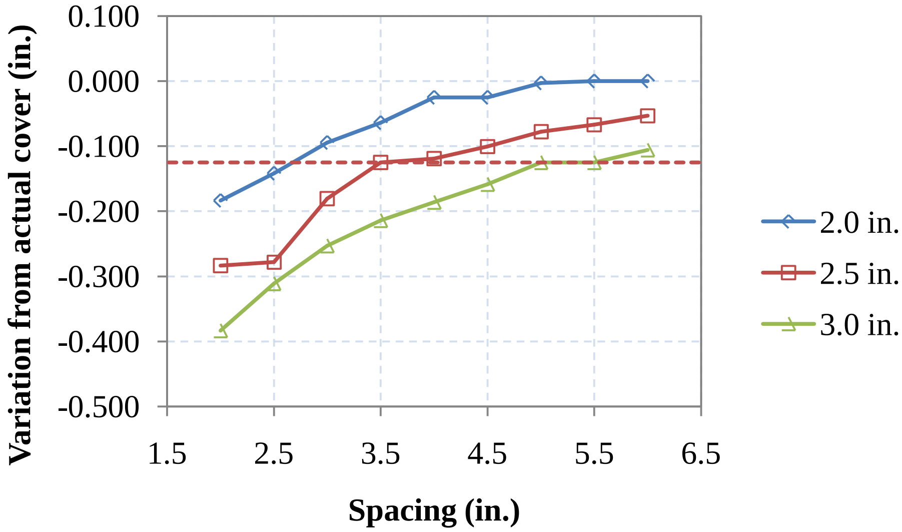


(b) Shallow antenna.

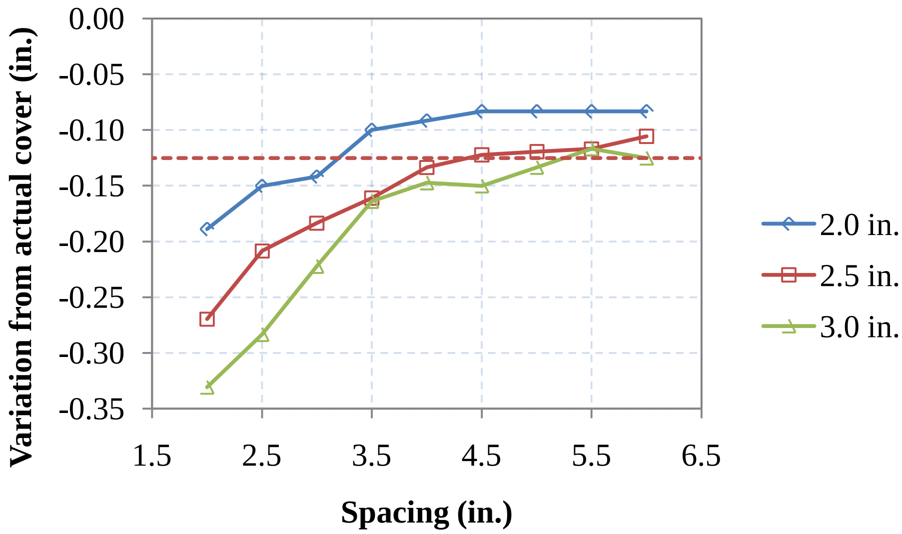
Figure B-18: Three-way interaction between meter brand, offset distance, and antenna type for FOV experiment.

Table B-20: Three-Way Interaction between Actual Cover Depth, Offset Distance, and Antenna Type for FOV Experiment

Cover	Antenna	Spacing	Error	Cover	Antenna	Spacing	Error
2.0	D	2.0	-0.183	2.5	S	2.0	-0.269
2.0	D	2.5	-0.142	2.5	S	2.5	-0.208
2.0	D	3.0	-0.094	2.5	S	3.0	-0.183
2.0	D	3.5	-0.064	2.5	S	3.5	-0.161
2.0	D	4.0	-0.025	2.5	S	4.0	-0.133
2.0	D	4.5	-0.025	2.5	S	4.5	-0.122
2.0	D	5.0	-0.003	2.5	S	5.0	-0.119
2.0	D	5.5	0.000	2.5	S	5.5	-0.117
2.0	D	6.0	0.000	2.5	S	6.0	-0.106
2.0	S	2.0	-0.189	3.0	D	2.0	-0.383
2.0	S	2.5	-0.150	3.0	D	2.5	-0.311
2.0	S	3.0	-0.142	3.0	D	3.0	-0.253
2.0	S	3.5	-0.100	3.0	D	3.5	-0.214
2.0	S	4.0	-0.092	3.0	D	4.0	-0.186
2.0	S	4.5	-0.083	3.0	D	4.5	-0.158
2.0	S	5.0	-0.083	3.0	D	5.0	-0.125
2.0	S	5.5	-0.083	3.0	D	5.5	-0.125
2.0	S	6.0	-0.083	3.0	D	6.0	-0.106
2.5	D	2.0	-0.283	3.0	S	2.0	-0.331
2.5	D	2.5	-0.278	3.0	S	2.5	-0.283
2.5	D	3.0	-0.181	3.0	S	3.0	-0.222
2.5	D	3.5	-0.125	3.0	S	3.5	-0.164
2.5	D	4.0	-0.119	3.0	S	4.0	-0.147
2.5	D	4.5	-0.100	3.0	S	4.5	-0.150
2.5	D	5.0	-0.078	3.0	S	5.0	-0.133
2.5	D	5.5	-0.067	3.0	S	5.5	-0.117
2.5	D	6.0	-0.053	3.0	S	6.0	-0.125



(a) Deep antenna.



(b) Shallow antenna.

Figure B-19: Three-way interaction between actual cover depth, offset distance, and antenna type for FOV experiment.

APPENDIX C: DATA FOR PTAI EXPERIMENT

C.1 PTAI Main Effects Graphs

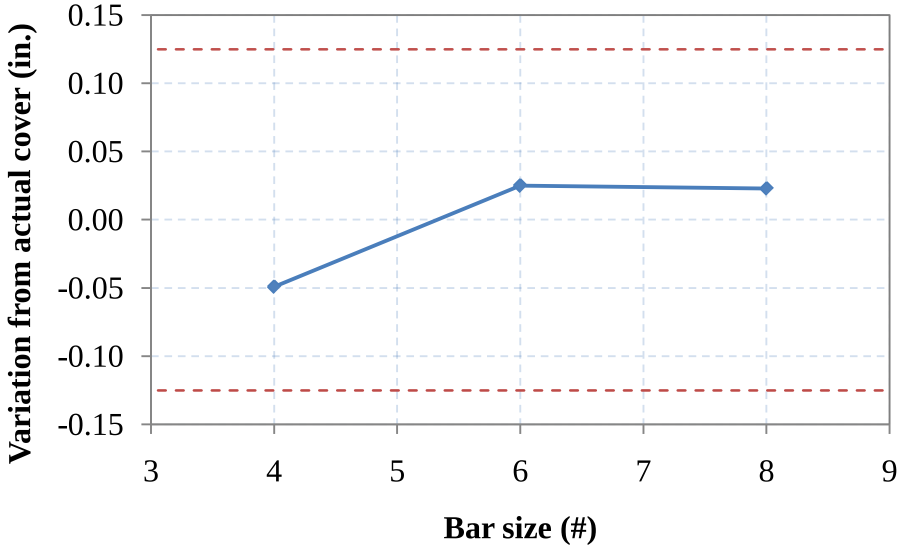


Figure C-1: Main effects of bar size for PTAI experiment.

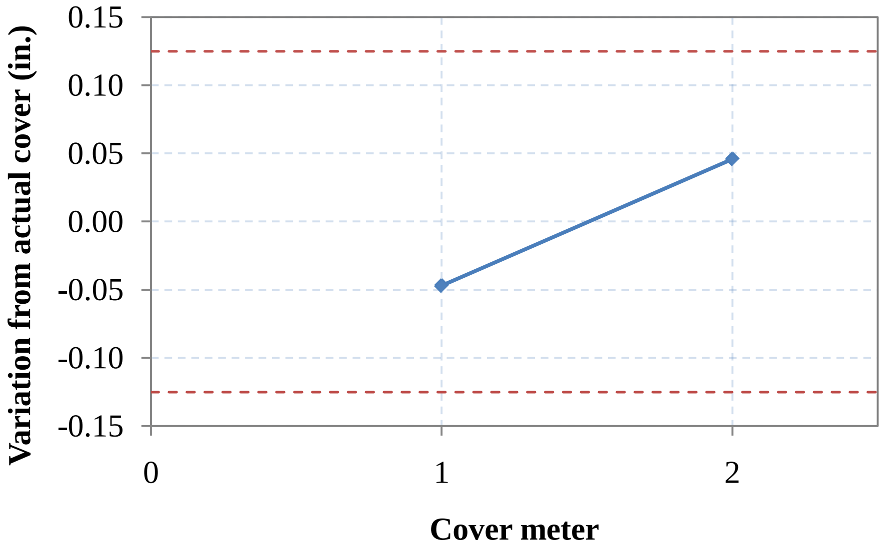


Figure C-2: Main effects of meter brand for PTAI experiment.

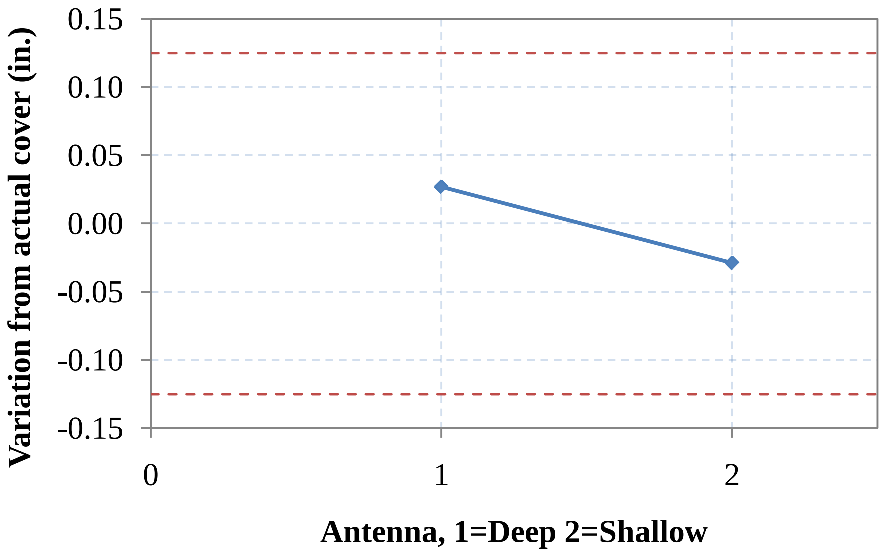


Figure C-3: Main effects of antenna type for PTAI experiment.

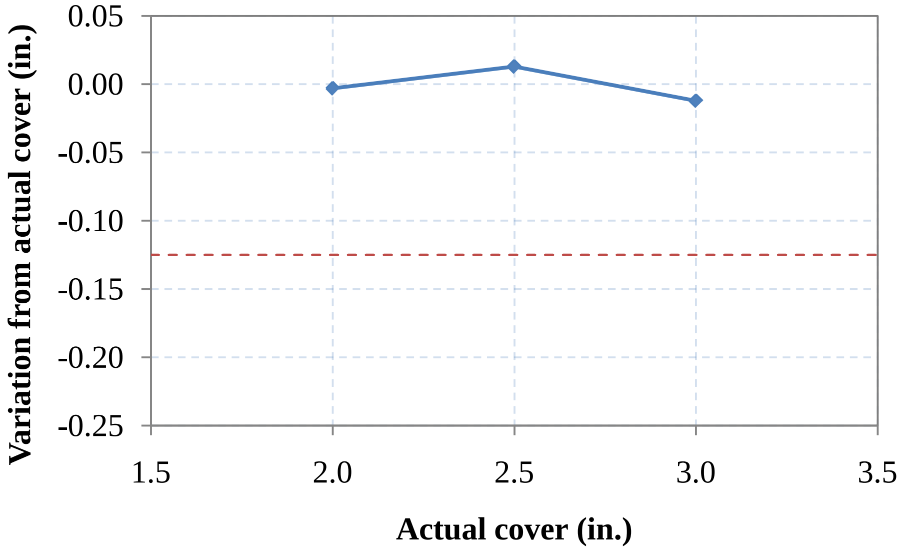


Figure C-4: Main effects of actual cover depth for PTAI experiment.

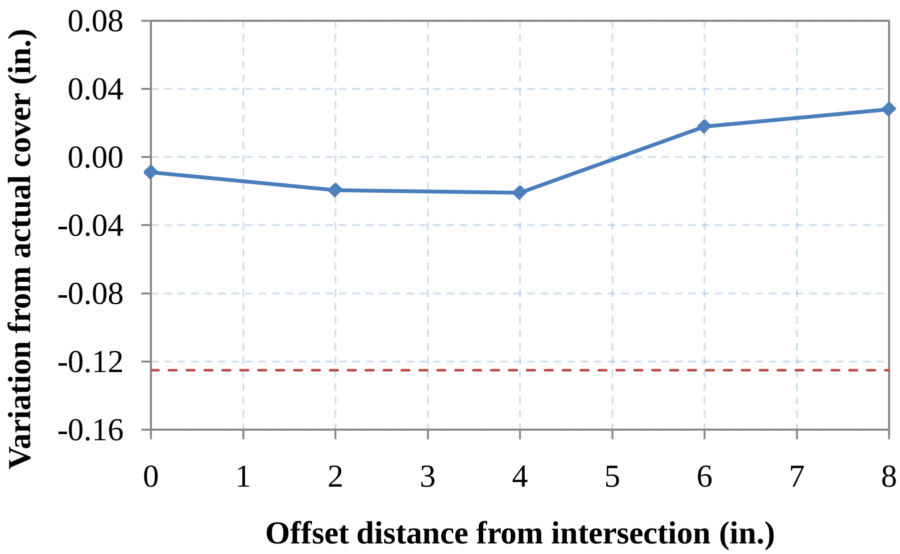


Figure C-5: Main effects of offset distance for PTAI experiment.

C.2 PTAI Two-way Interaction Tabulated Results and Figures.

Table C-1: Two-Way Interaction between Bar Size and Meter Brand for PTAI Experiment

Size	Brand	Error
4	1	-0.107
6	1	-0.033
8	1	-0.001
4	2	0.007
6	2	0.083
8	2	0.046

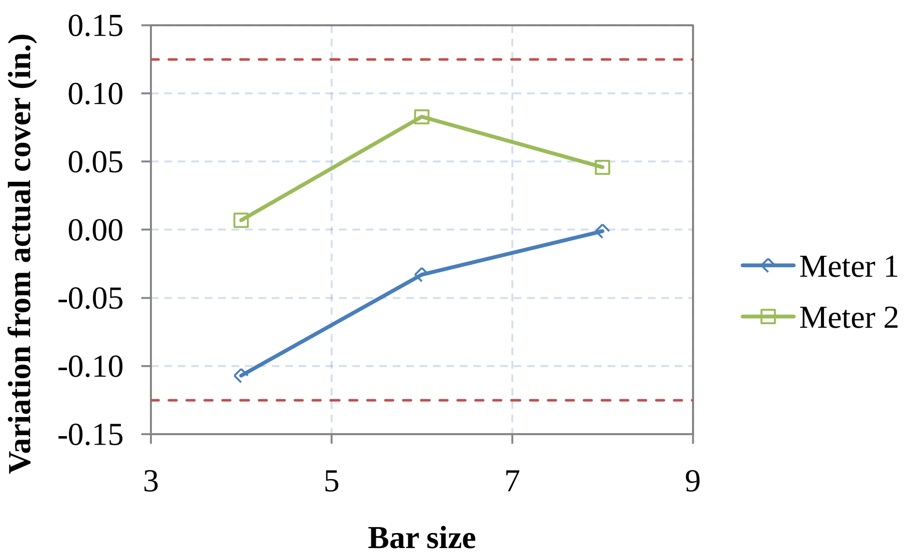


Figure C-6: Two-way interaction between bar size and meter brand for PTAI experiment.

Table C-2: Two-Way Interaction between Bar Size and Actual Cover Depth for PTAI Experiment

Size	Cover	Error
4	2	-0.001
4	2.5	-0.028
4	3	-0.121
6	2	0.031
6	2.5	0.033
6	3	0.011
8	2	-0.038
8	2.5	0.033
8	3	0.073

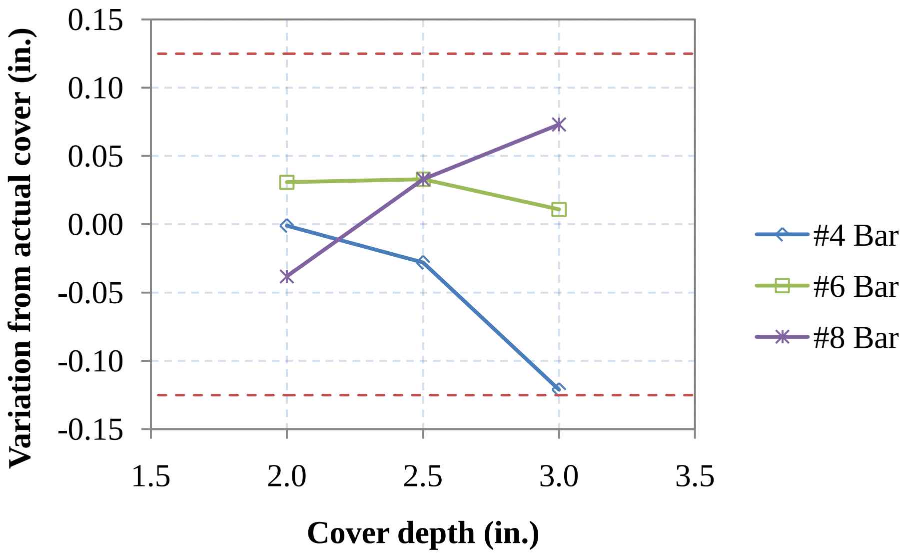


Figure C-7: Two-way interaction between bar size and cover depth for PTAI experiment.

Table C-3: Two-Way Interaction between Bar Size and Antenna Type for PTAI Experiment

Size	Antenna	Error
4	D	-0.013
6	D	0.06
8	D	0.035
4	S	-0.087
6	S	-0.01
8	S	0.011

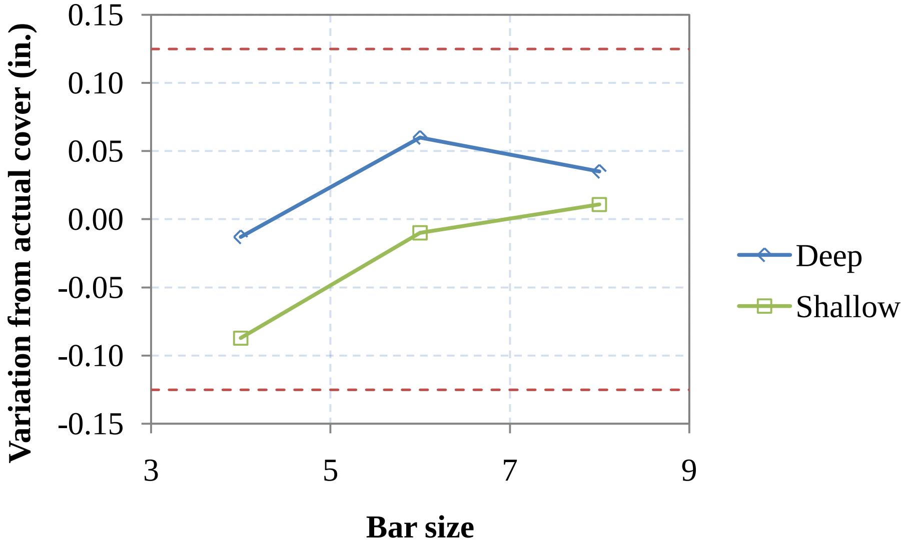


Figure C-8: Two-way interaction between bar size and antenna type for PTAI experiment.

Table C-4: Two-Way Interaction between Bar Size and Offset Distance for PTAI Experiment

Size	Spacing	Error
4	0	-0.049
4	2	-0.082
4	4	-0.065
4	6	-0.032
4	8	-0.021
6	0	0.017
6	2	0.022
6	4	-0.011
6	6	0.046
6	8	0.051
8	0	0.004
8	2	0.001
8	4	0.013
8	6	0.04
8	8	0.056

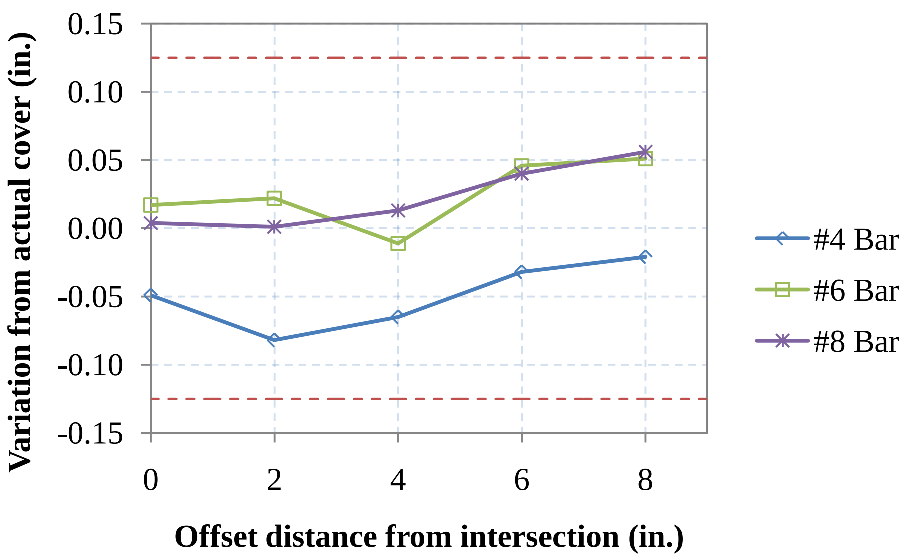


Figure C-9: Two-way interaction between bar size and offset distance for PTAI experiment.

Table C-5: Two-Way Interaction between Meter Brand and Actual Cover Depth for PTAI Experiment

Brand	Cover	Error
1	2	-0.059
1	2.5	-0.037
1	3	-0.044
2	2	0.054
2	2.5	0.062
2	3	0.02

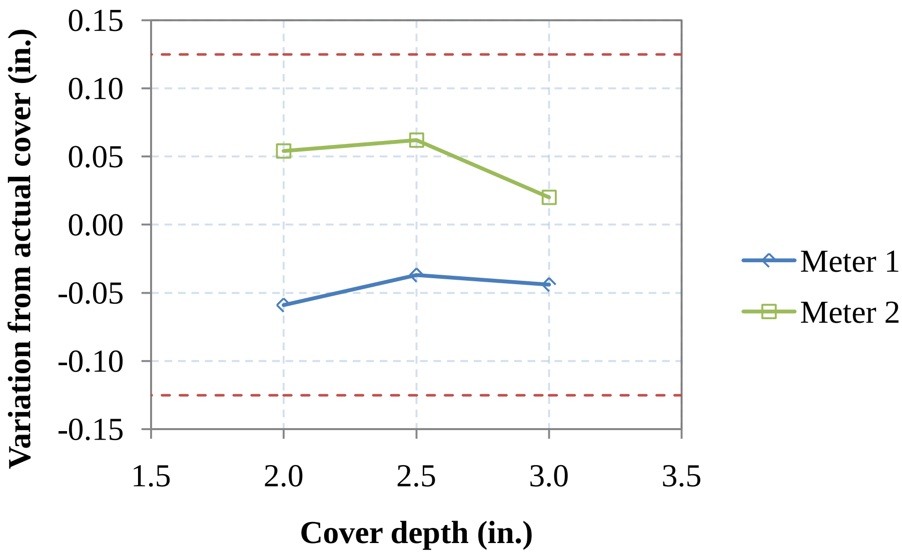


Figure C-10: Two-way interaction between meter brand and actual cover depth for PTAI experiment.

Table C-6: Two-Way Interaction between Meter Brand and Antenna Type for PTAI Experiment

Brand	Antenna	Error
1	D	-0.051
2	D	0.106
1	S	-0.043
2	S	-0.015

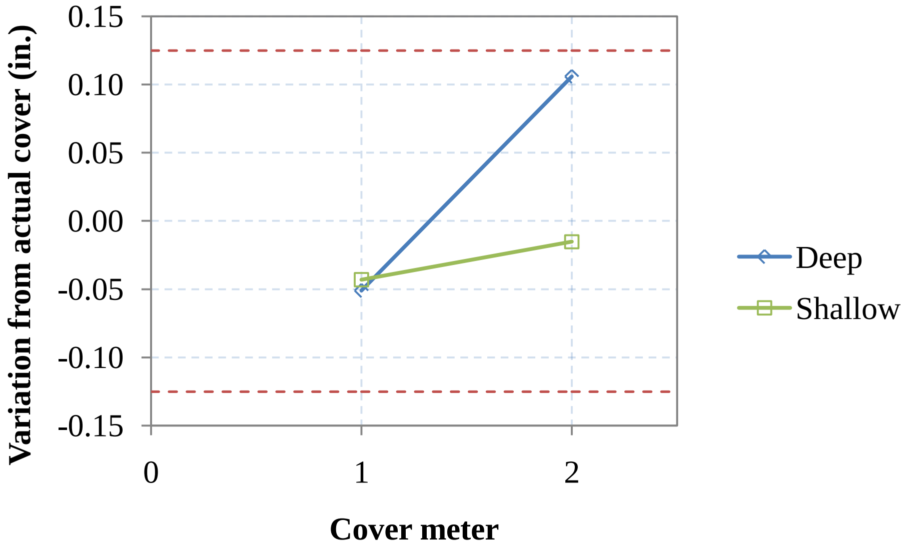


Figure C-11: Two-way interaction between meter brand and antenna type for PTAI experiment.

Table C-7: Two-Way Interaction between Meter Brand and Offset Distance for PTAI Experiment

Brand	Spacing	Error
1	0	-0.073
1	2	-0.079
1	4	-0.045
1	6	-0.019
1	8	-0.019
2	0	0.055
2	2	0.04
2	4	0.003
2	6	0.055
2	8	0.076

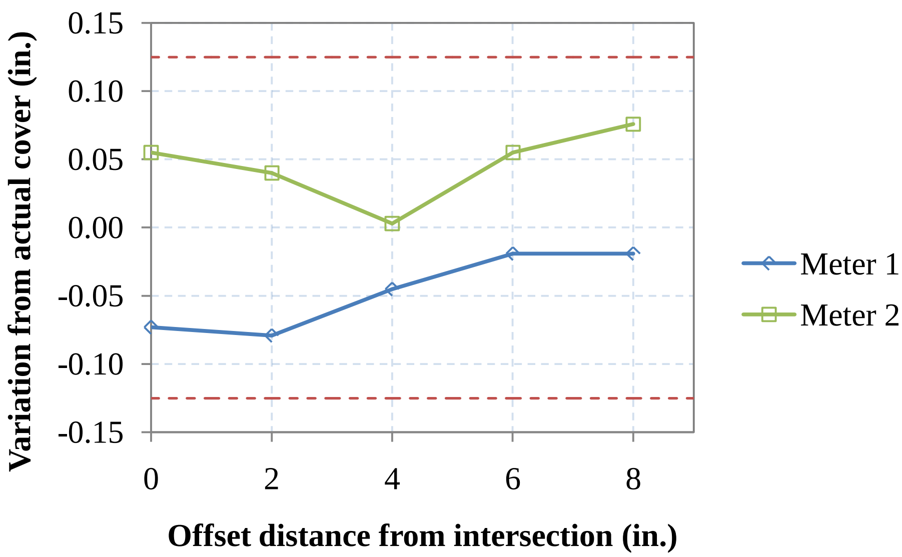


Figure C-12: Two-way interaction between offset distance and meter brand for PTAI experiment.

Table C-8: Two-Way Interaction between Actual Cover Depth and Antenna Type for PTAI Experiment

Cover	Antenna	Error
2	D	0.061
2.5	D	0.037
3	D	-0.015
2	S	-0.066
2.5	S	-0.011
3	S	-0.009

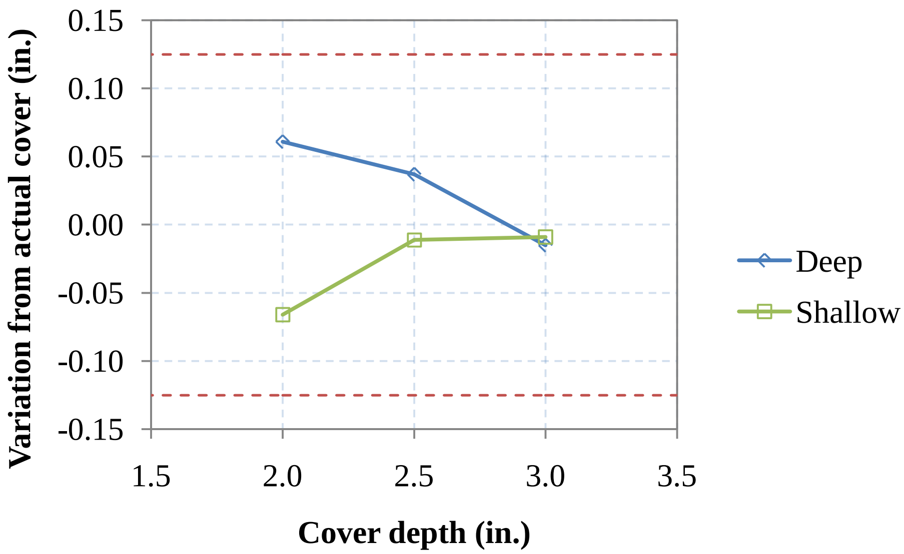


Figure C-13: Two-way interaction between actual cover depth and antenna type for PTAI experiment.

Table C-9: Two-Way Interaction between Actual Cover Depth and Offset Distance for PTAI Experiment

Cover	Spacing	Error
2	0	-0.017
2	2	-0.008
2	4	-0.036
2	6	0.018
2	8	0.031
2.5	0	0.017
2.5	2	-0.014
2.5	4	-0.003
2.5	6	0.028
2.5	8	0.036
3	0	-0.028
3	2	-0.036
3	4	-0.025
3	6	0.008
3	8	0.019

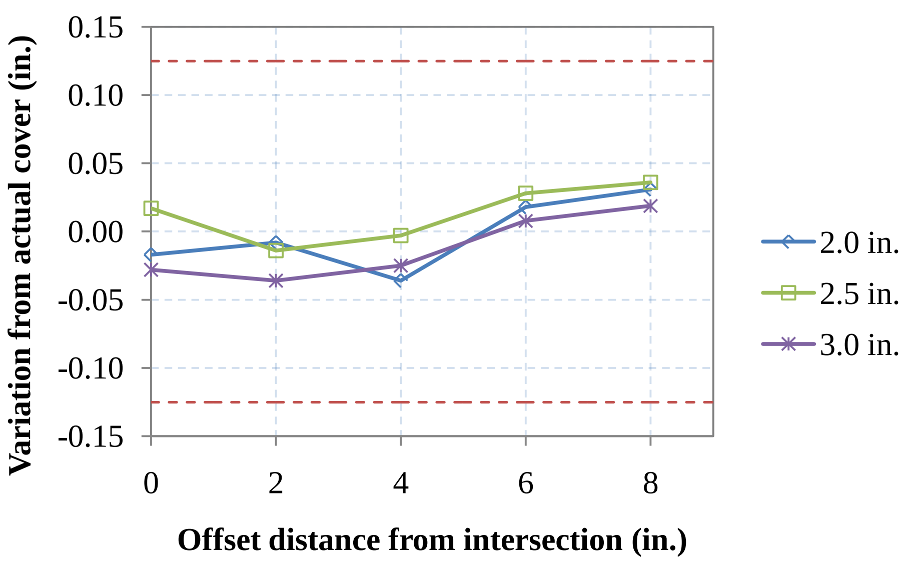


Figure C-14: Two-way interaction between offset distance and actual cover depth for PTAI experiment.

Table C-10: Two-Way Interaction between Antenna Type and Offset Distance for PTAI Experiment

Antenna	Spacing	Error
D	0	0.025
D	2	0.019
D	4	-0.011
D	6	0.045
D	8	0.058
S	0	-0.044
S	2	-0.058
S	4	-0.031
S	6	-0.009
S	8	0.001

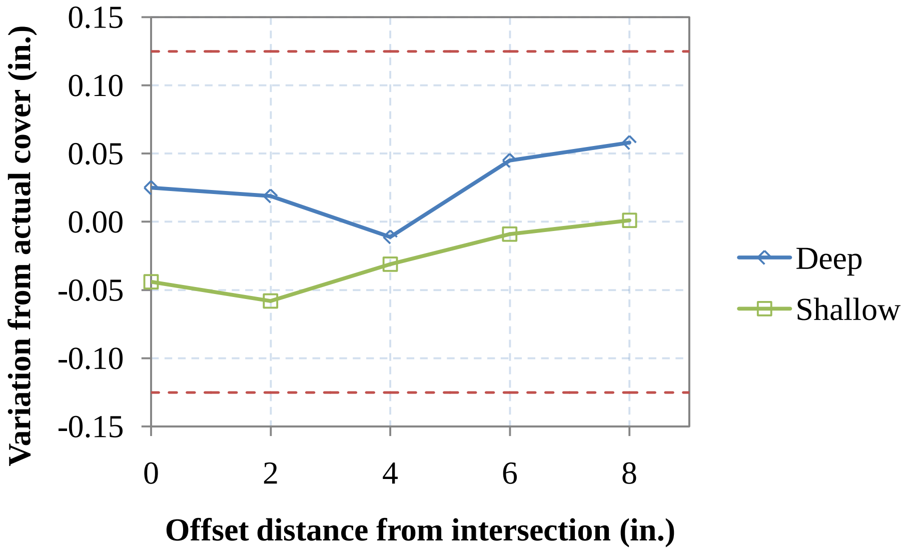
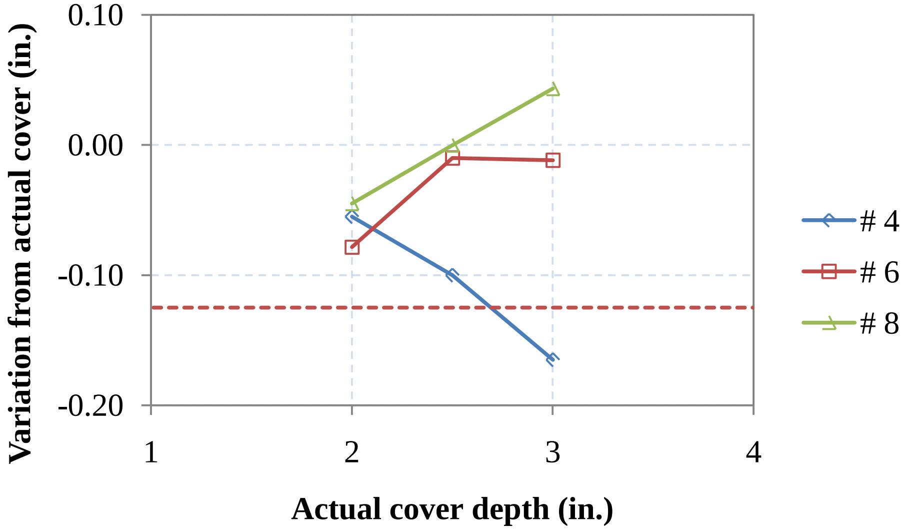


Figure C-15: Two-way interaction between offset distance and antenna type for PTAI experiment.

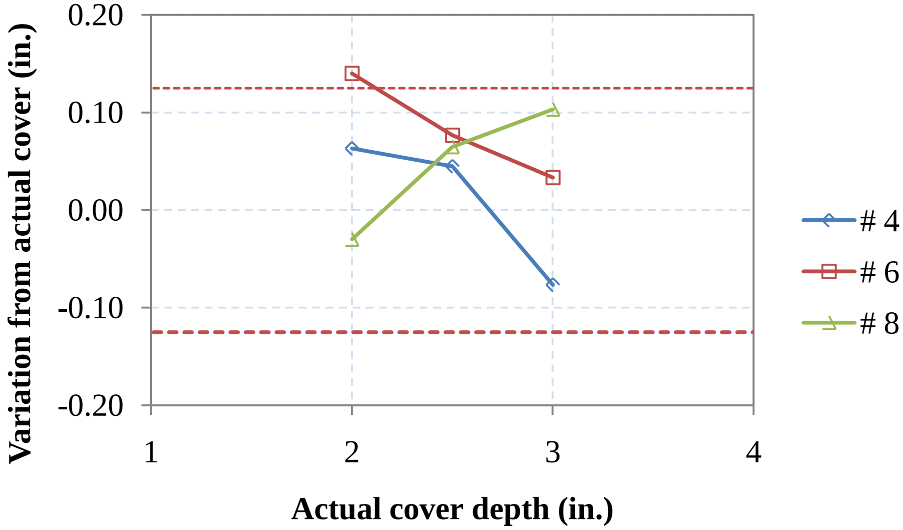
C.3 PTAI Three-way interaction Tabulated Results and Figures.

Table C-11: Three-Way Interaction between Bar Size, Actual Cover Depth, and Meter Brand for PTAI Experiment

Size	Brand	Cover	Error
4	E	2	-0.0550
4	E	2.5	-0.1000
4	E	3	-0.1650
4	H	2	0.0633
4	H	2.5	0.0450
4	H	3	-0.0767
6	E	2	-0.0783
6	E	2.5	-0.0100
6	E	3	-0.0117
6	H	2	0.1400
6	H	2.5	0.0767
6	H	3	0.0333
8	E	2	-0.0450
8	E	2.5	0.0000
8	E	3	0.0433
8	H	2	-0.0300
8	H	2.5	0.0650
8	H	3	0.1033



(a) Meter 1.

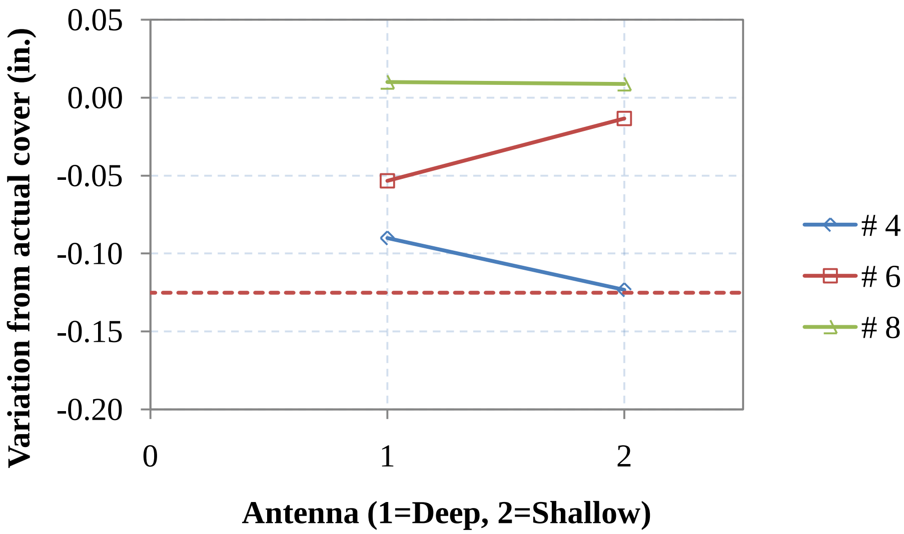


(b) Meter 2.

Figure C-16: Three-way interaction between bar size, actual cover depth, and meter brand for PTAI experiment.

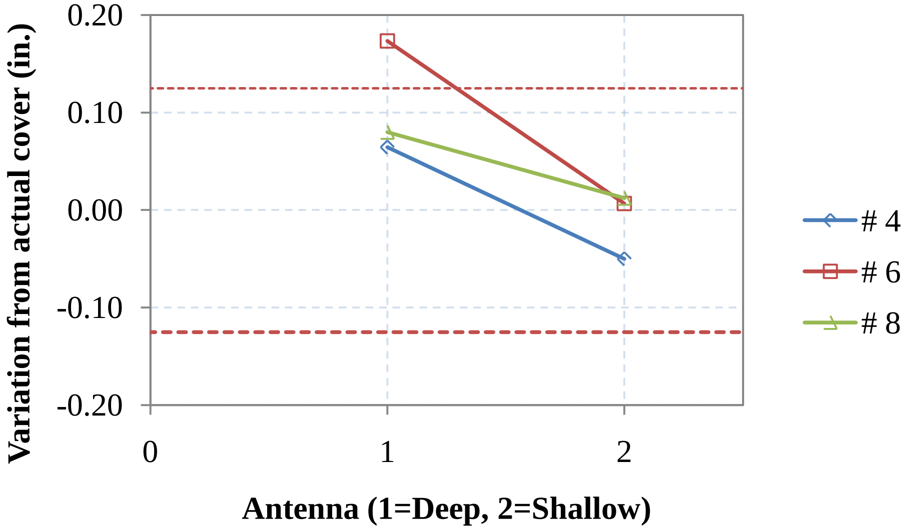
Table C-12: Three-Way Interaction between Bar Size, Antenna Type, and Meter Brand for PTAI Experiment

Size	Brand	Antenna	Error
4	E	D	-0.0900
4	E	S	-0.1233
4	H	D	0.0644
4	H	S	-0.0500
6	E	D	-0.0533
6	E	S	-0.0133
6	H	D	0.1733
6	H	S	0.0067
8	E	D	0.0100
8	E	S	0.0089
8	H	D	0.0800
8	H	S	0.0122



(a) Meter 1.

Figure C-17: Three-way interaction between bar size, antenna type, and meter brand for PTAI experiment.

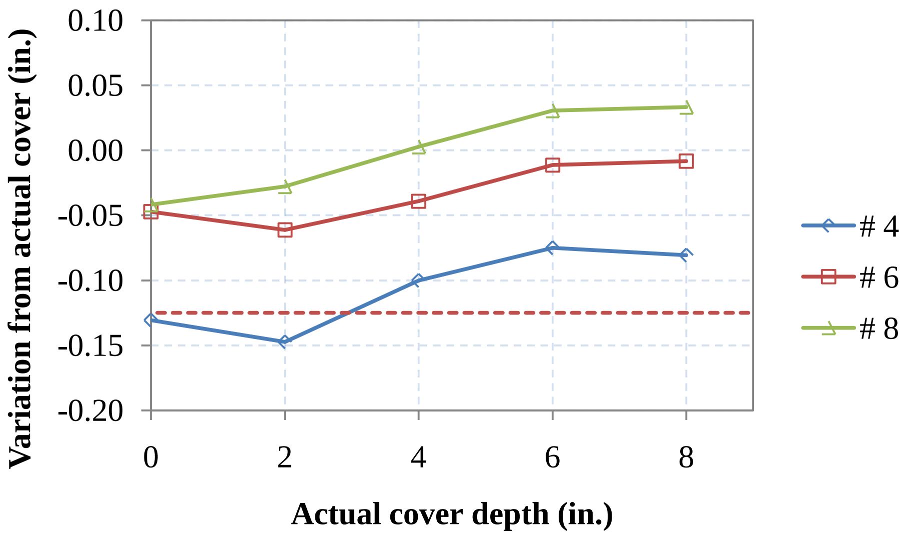


(b) Meter 2.

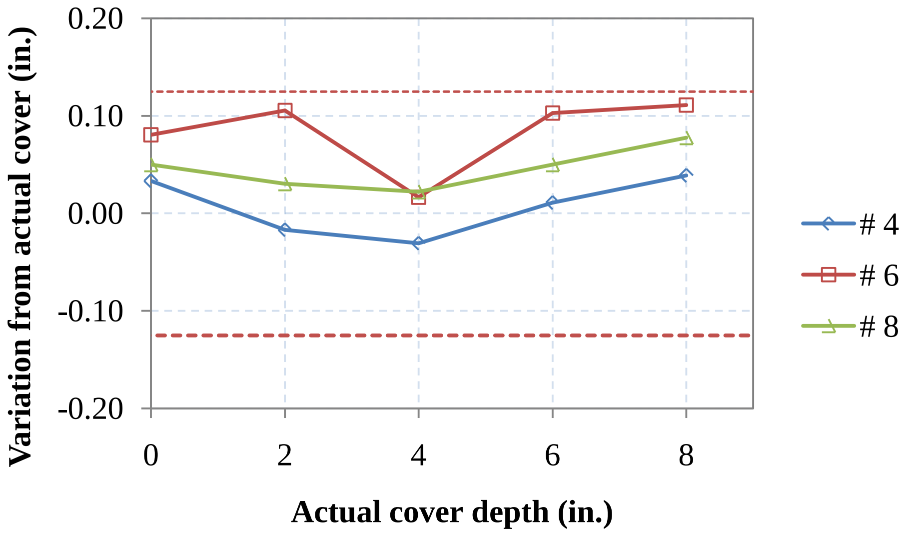
Figure C-17: Three-way interaction between bar size, antenna type, and meter brand for PTAI experiment. (Continued)

Table C-13: Three-Way Interaction between Bar Size, Offset Distance, and Meter Brand for PTAI Experiment

Size	Brand	Spacing	Error
4	E	0	-0.1306
4	E	2	-0.1472
4	E	4	-0.1000
4	E	6	-0.0750
4	E	8	-0.0806
4	H	0	0.0333
4	H	2	-0.0167
4	H	4	-0.0306
4	H	6	0.0111
4	H	8	0.0389
6	E	0	-0.0472
6	E	2	-0.0611
6	E	4	-0.0389
6	E	6	-0.0111
6	E	8	-0.0083
6	H	0	0.0806
6	H	2	0.1056
6	H	4	0.0167
6	H	6	0.1028
6	H	8	0.1111
8	E	0	-0.0417
8	E	2	-0.0278
8	E	4	0.0028
8	E	6	0.0306
8	E	8	0.0333
8	H	0	0.0500
8	H	2	0.0306
8	H	4	0.0222
8	H	6	0.0500
8	H	8	0.0778



(a) Meter 1.

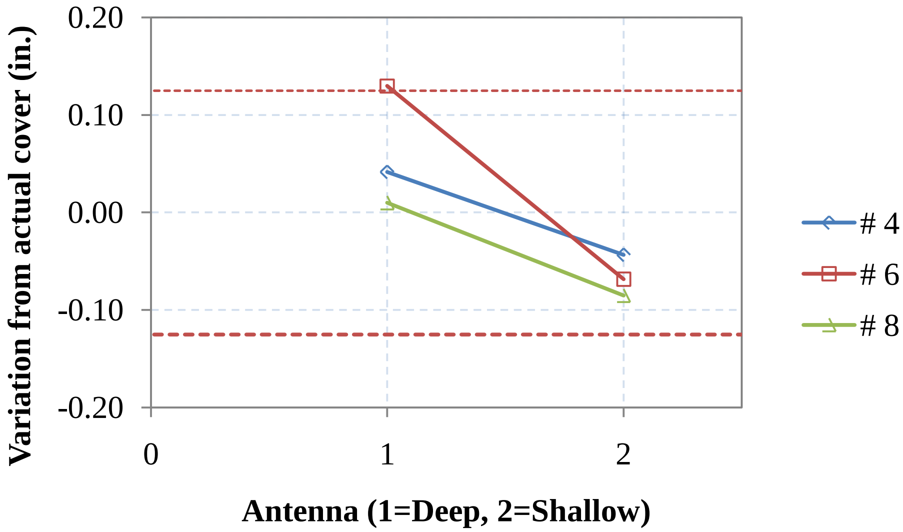


(b) Meter 2.

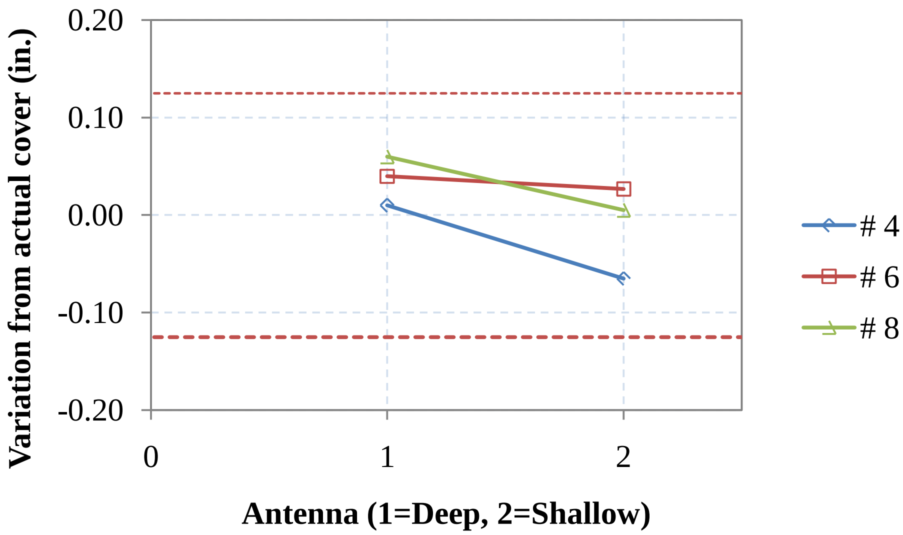
Figure C-18: Three-way interaction between bar size, actual cover depth, and meter brand for PTAI experiment.

Table C-14: Three-Way Interaction between Bar Size, Antenna Type, and Actual Cover Depth for PTAI Experiment

Size	Cover	Antenna	Error
4	2	D	0.0417
4	2	S	-0.0433
4	2.5	D	0.0100
4	2.5	S	-0.0650
4	3	D	-0.0900
4	3	S	-0.1517
6	2	D	0.1300
6	2	S	-0.0683
6	2.5	D	0.0400
6	2.5	S	0.0267
6	3	D	0.0100
6	3	S	0.0117
8	2	D	0.0100
8	2	S	-0.0850
8	2.5	D	0.0600
8	2.5	S	0.0050
8	3	D	0.0350
8	3	S	0.1117

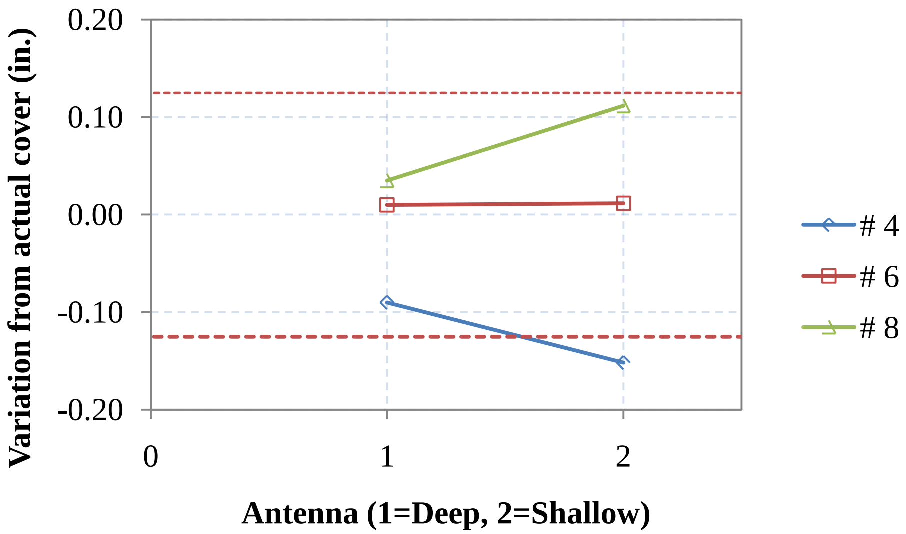


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure C-19: Three-way interaction between bar size, antenna type, and actual cover depth for PTAI experiment.

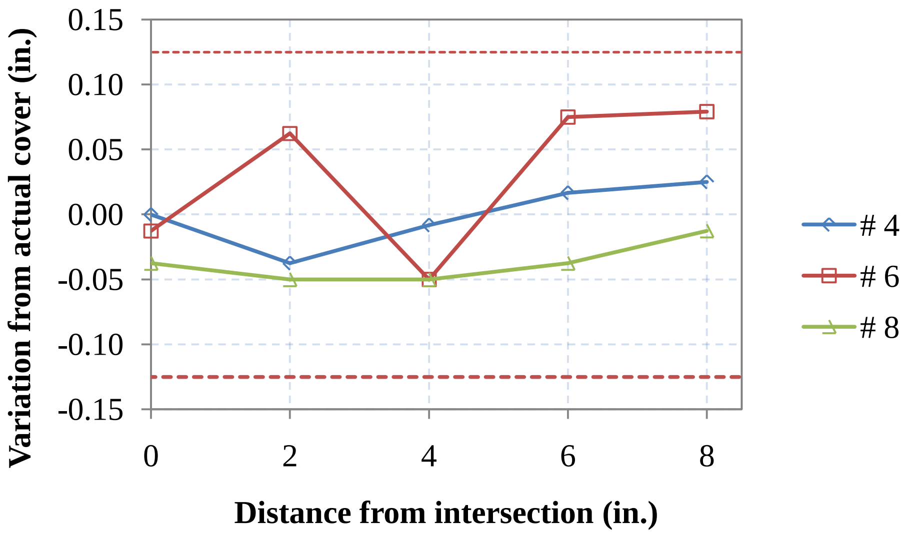


(c) 3.0 in. actual cover depth.

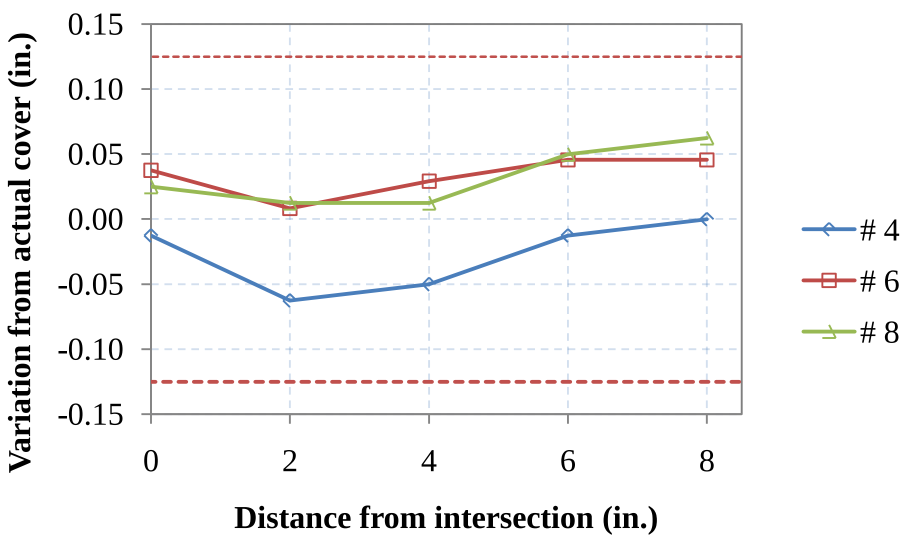
Figure C-19: Three-way interaction between bar size, antenna type, and actual cover depth for PTAI experiment. (Continued)

Table C-15: Three-Way Interaction between Bar Size, Offset Distance, and Actual Cover Depth for PTAI Experiment

Size	Cover	Spacing	Error	Size	Cover	Spacing	Error
4	2	0	0.0000	6	2.5	6	0.0458
4	2	2	-0.0375	6	2.5	8	0.0458
4	2	4	-0.0083	6	3	0	0.0250
4	2	6	0.0167	6	3	2	-0.0041
4	2	8	0.0250	6	3	4	-0.0125
4	2.5	0	-0.0125	6	3	6	0.0167
4	2.5	2	-0.0625	6	3	8	0.0292
4	2.5	4	-0.0500	8	2	0	-0.0375
4	2.5	6	-0.0125	8	2	2	-0.0500
4	2.5	8	0.0000	8	2	4	-0.0500
4	3	0	-0.1333	8	2	6	-0.0375
4	3	2	-0.1458	8	2	8	-0.0125
4	3	4	-0.1375	8	2.5	0	0.0250
4	3	6	-0.1000	8	2.5	2	0.0125
4	3	8	-0.0875	8	2.5	4	0.0125
6	2	0	-0.0125	8	2.5	6	0.0500
6	2	2	0.0625	8	2.5	8	0.0625
6	2	4	-0.0500	8	3	0	0.0250
6	2	6	0.0750	8	3	2	0.0417
6	2	8	0.0792	8	3	4	0.0750
6	2.5	0	0.0375	8	3	6	0.1083
6	2.5	2	0.0083	8	3	8	0.1167
6	2.5	4	0.0291				

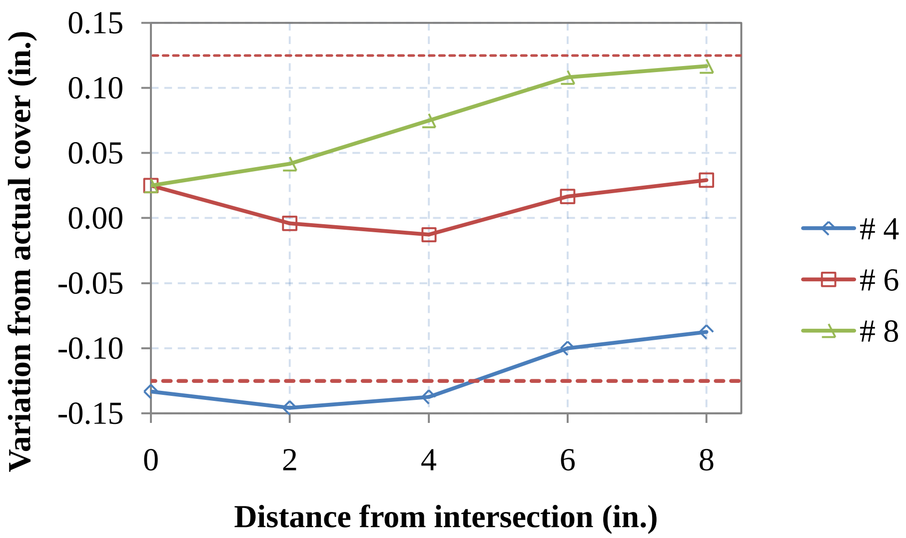


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure C-20: Three-way interaction between bar size, offset distance, and actual cover depth for PTAI experiment.

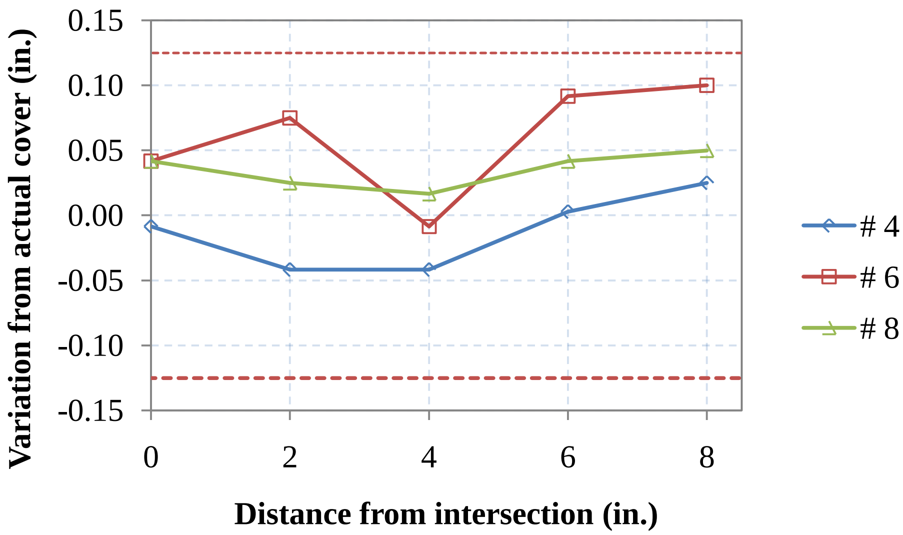


(c) 3.0 in. actual cover depth.

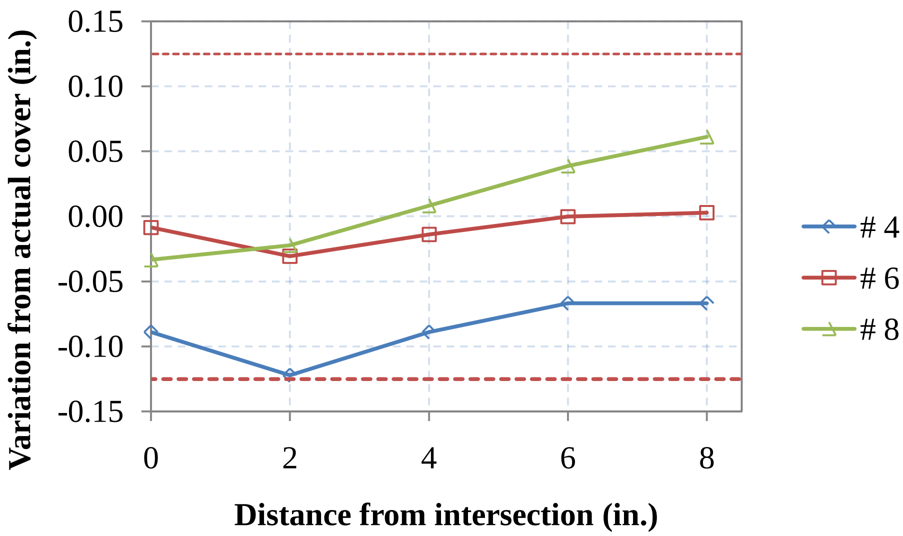
Figure C-20: Three-way interaction between bar size, offset distance, and actual cover depth for PTAI experiment. (Continued)

Table C-16: Three-Way Interaction between Bar Size, Offset Distance, and Antenna Type for PTAI Experiment

Size	Antenna	Spacing	Error
4	D	0	-0.0083
4	D	2	-0.0417
4	D	4	-0.0417
4	D	6	0.0028
4	D	8	0.0250
4	S	0	-0.0889
4	S	2	-0.1222
4	S	4	-0.0889
4	S	6	-0.0667
4	S	8	-0.0667
6	D	0	0.0417
6	D	2	0.0750
6	D	4	-0.0083
6	D	6	0.0917
6	D	8	0.1000
6	S	0	-0.0083
6	S	2	-0.0306
6	S	4	-0.0139
6	S	6	0.0000
6	S	8	0.0028
8	D	0	0.0417
8	D	2	0.0250
8	D	4	0.0167
8	D	6	0.0417
8	D	8	0.0500
8	S	0	-0.0333
8	S	2	-0.0222
8	S	4	0.0083
8	S	6	0.0389
8	S	8	0.0611



(a) Deep antenna.

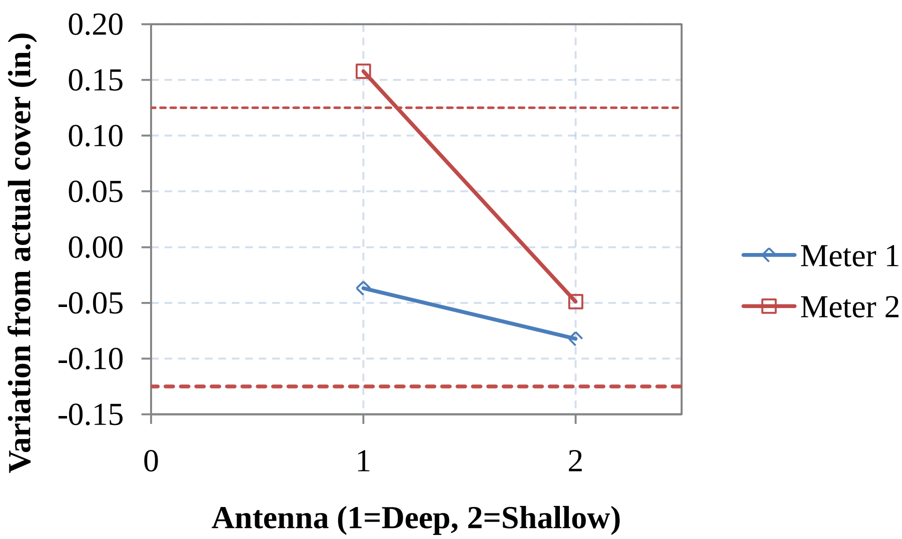


(b) Shallow antenna.

Figure C-21: Three-way interaction between bar size, offset distance, and antenna type for PTAI experiment.

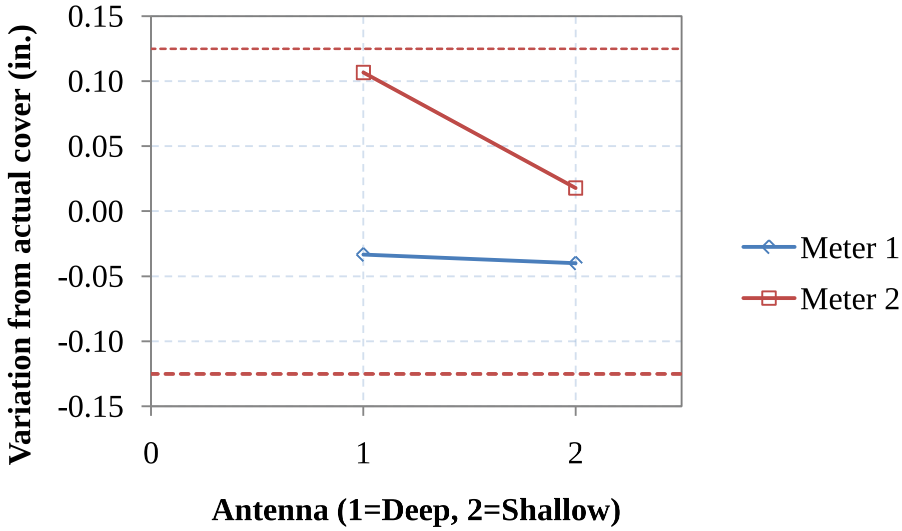
Table C-17: Three-Way Interaction between Meter Brand, Antenna Type, and Actual Cover Depth for PTAI Experiment

Brand	Cover	Antenna	Error
E	2	D	-0.0367
E	2	S	-0.0822
E	2.5	D	-0.0333
E	2.5	S	-0.0400
E	3	D	-0.0833
E	3	S	-0.0056
H	2	D	0.1578
H	2	S	-0.0489
H	2.5	D	0.1067
H	2.5	S	0.0178
H	3	D	0.0533
H	3	S	-0.0133

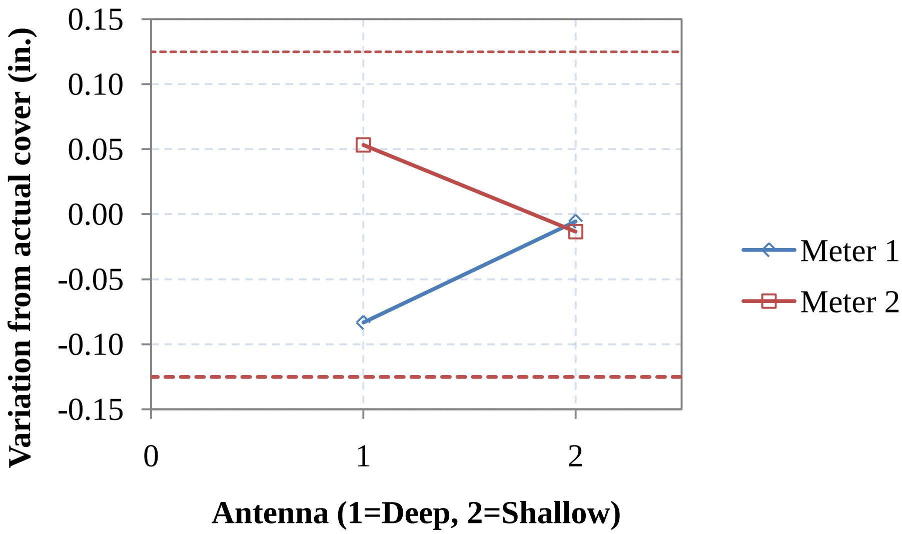


(a) 2.0 in. actual cover depth.

Figure C-22: Three-way interaction between meter brand, antenna type, and 2.0 in. actual cover depth for PTAI experiment.



(b) 2.5 in. actual cover depth.

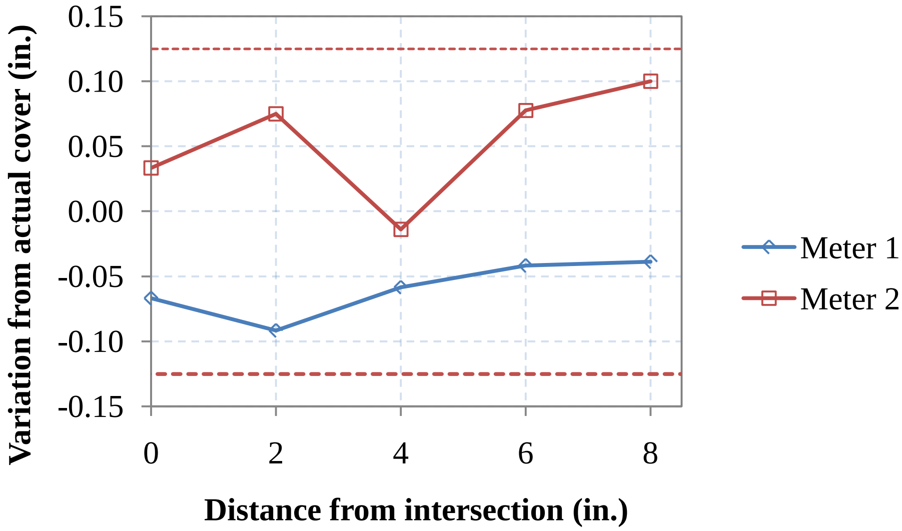


(c) 3.0 in. actual cover depth.

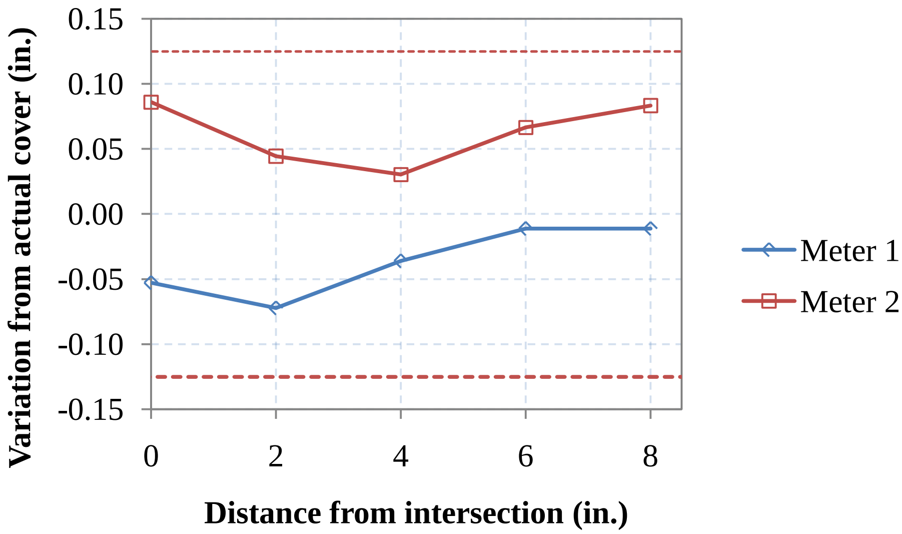
Figure C-22: Three-way interaction between meter brand, antenna type, and actual cover depth for PTAI experiment. (Continued)

Table C-18: Three-Way Interaction between Meter Brand, Offset Distance, and Actual Cover Depth for PTAI Experiment

Brand	Cover	Spacing	Error
E	2	0	-0.0667
E	2	2	-0.0917
E	2	4	-0.0583
E	2	6	-0.0417
E	2	8	-0.0388
E	2.5	0	-0.0527
E	2.5	2	-0.0722
E	2.5	4	-0.0361
E	2.5	6	-0.0111
E	2.5	8	-0.0111
E	3	0	-0.1000
E	3	2	-0.0722
E	3	4	-0.0417
E	3	6	-0.0028
E	3	8	-0.0056
H	2	0	0.0333
H	2	2	0.0750
H	2	4	-0.0139
H	2	6	0.0778
H	2	8	0.1000
H	2.5	0	0.0861
H	2.5	2	0.0444
H	2.5	4	0.0306
H	2.5	6	0.0667
H	2.5	8	0.0833
H	3	0	0.0444
H	3	2	0.0000
H	3	4	-0.0083
H	3	6	0.0194
H	3	8	0.0444

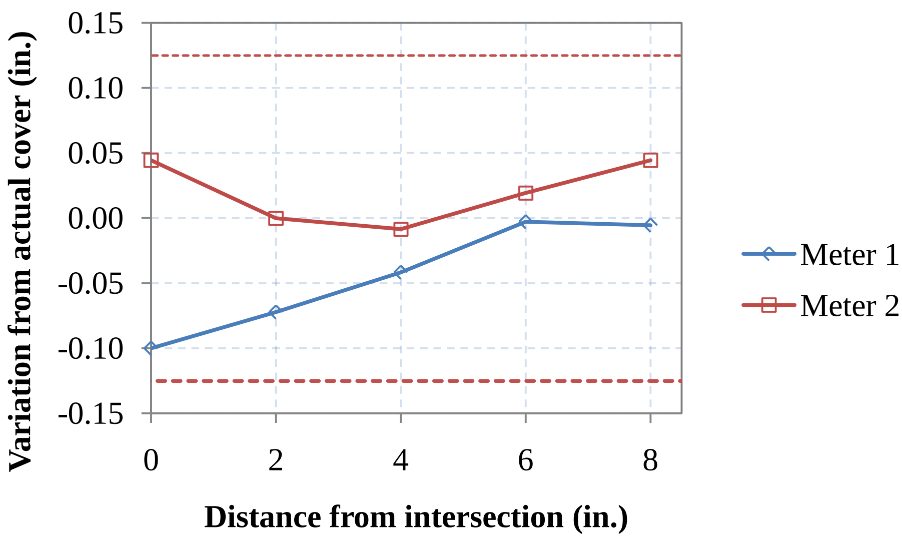


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure C-23: Three-way interaction between meter brand, offset distance, and actual cover depth for PTAI experiment.

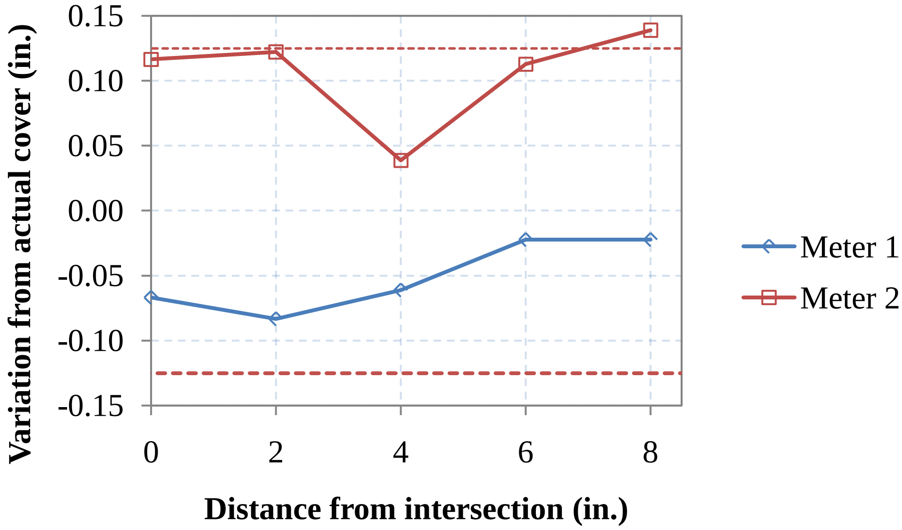


(c) 3.0 in. actual cover depth.

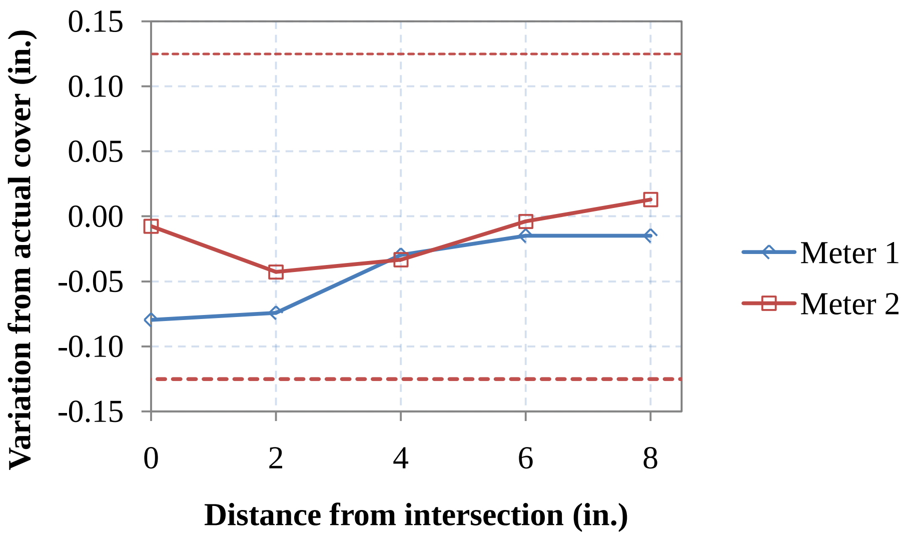
Figure C-23: Three-way interaction between meter brand, offset distance, and actual cover depth for PTAI experiment. (Continued)

Table C-19: Three-Way Interaction between Meter Brand, Offset Distance, and Antenna Type for PTAI Experiment

Brand	Antenna	Spacing	Error
E	D	0	-0.0667
E	D	2	-0.0833
E	D	4	-0.0611
E	D	6	-0.0222
E	D	8	-0.0222
E	S	0	-0.0796
E	S	2	-0.0741
E	S	4	-0.0296
E	S	6	-0.0148
E	S	8	-0.0148
H	D	0	0.1167
H	D	2	0.1222
H	D	4	0.0389
H	D	6	0.1130
H	D	8	0.1389
H	S	0	-0.0074
H	S	2	-0.0426
H	S	4	-0.0333
H	S	6	-0.0037
H	S	8	0.0130



(a) Deep antenna.

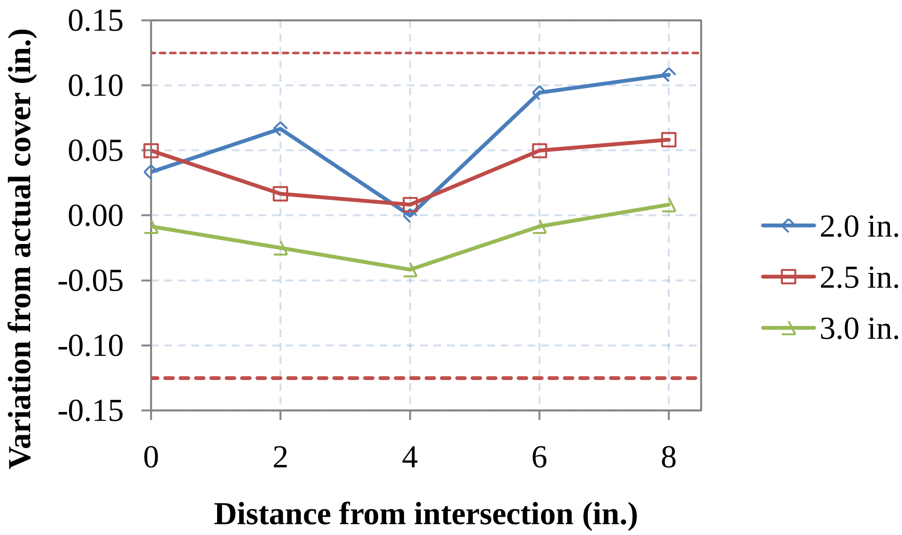


(b) Shallow antenna.

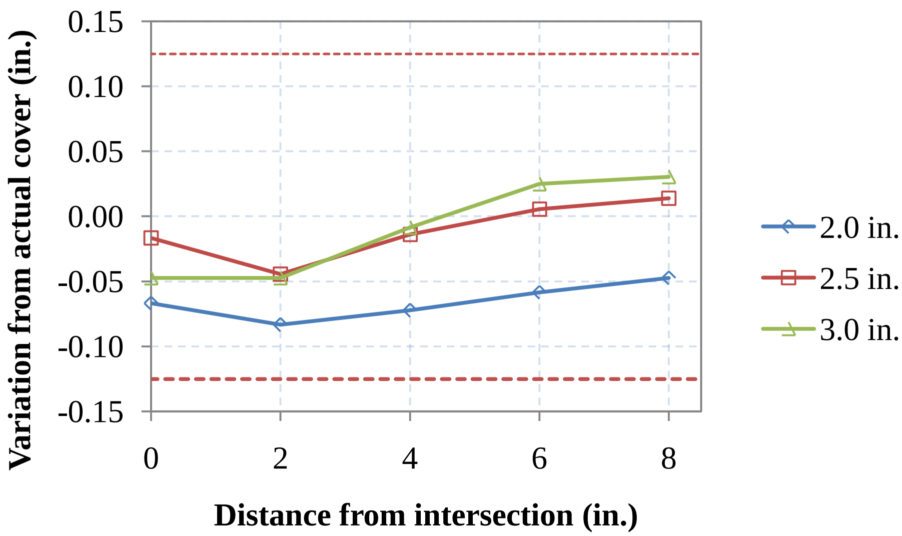
Figure C-24: Three-way interaction between meter brand, offset distance, and antenna type for PTAI experiment.

Table C-20: Three-Way Interaction between Actual Cover Depth, Offset Distance, and Antenna Type for PTAI Experiment

Cover	Antenna	Spacing	Error
2	D	0	0.0333
2	D	2	0.0666
2	D	4	0.0000
2	D	6	0.0944
2	D	8	0.1083
2	S	0	-0.0667
2	S	2	-0.0833
2	S	4	-0.0722
2	S	6	-0.0583
2	S	8	-0.0472
2.5	D	0	0.0500
2.5	D	2	0.0167
2.5	D	4	0.0083
2.5	D	6	0.0500
2.5	D	8	0.0582
2.5	S	0	-0.0167
2.5	S	2	-0.0444
2.5	S	4	-0.0139
2.5	S	6	0.0056
2.5	S	8	0.0139
3	D	0	-0.0083
3	D	2	-0.0250
3	D	4	-0.0417
3	D	6	-0.0083
3	D	8	0.0083
3	S	0	-0.0472
3	S	2	-0.0472
3	S	4	-0.0083
3	S	6	0.0250
3	S	8	0.0306



(a) Deep antenna.



(a) Shallow antenna.

Figure C-25: Three-way interaction between bar size, offset distance, and antenna type for PTAI experiment.

APPENDIX D: DATA FOR WBS EXPERIMENT

D.1 WBS Main Effects Graphs

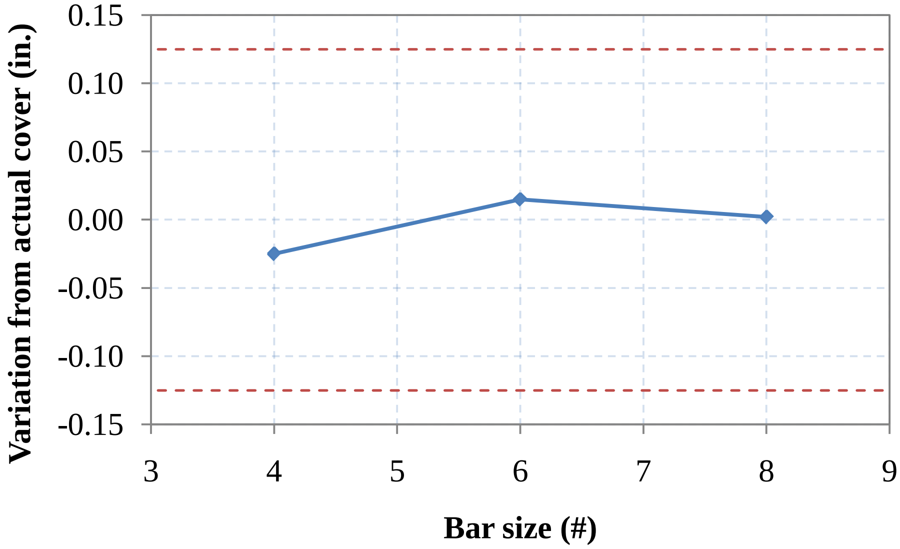


Figure D-1: Main effects of bar size for WBS experiment.

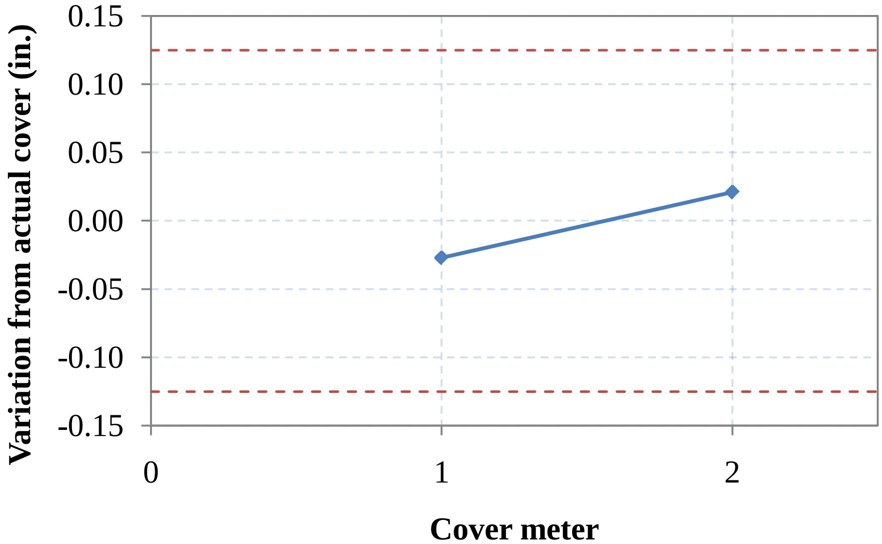


Figure D-2: Main effects of meter brand for WBS experiment.

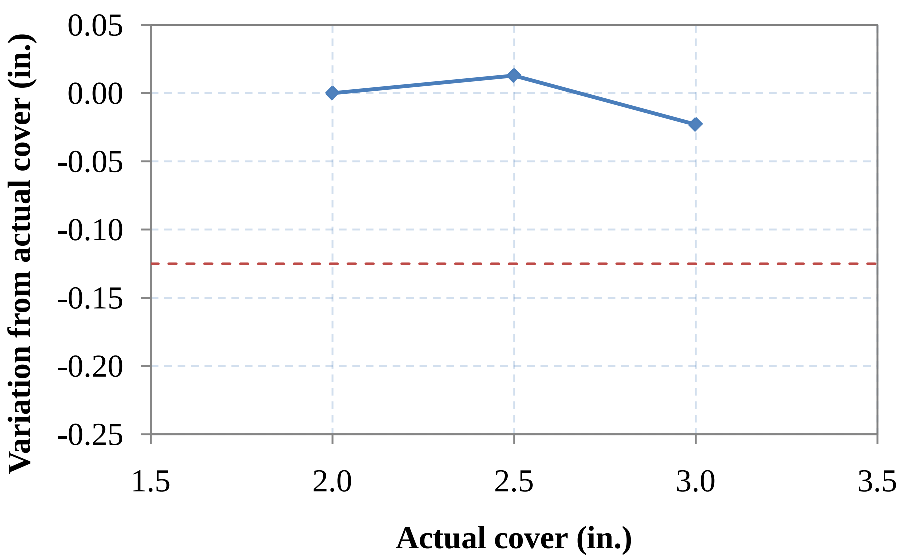


Figure D-3: Main effects of actual cover depth for WBS experiment.

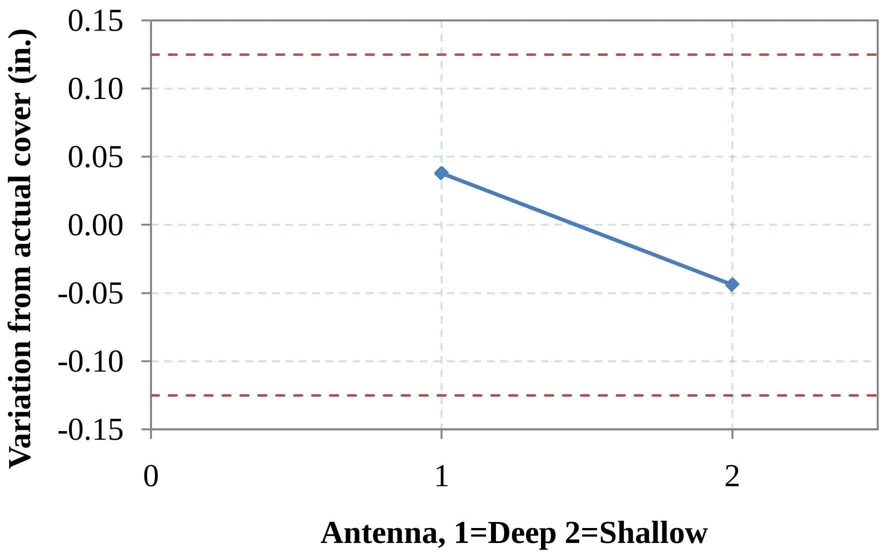


Figure D-4: Main effects of antenna type for WBS experiment.

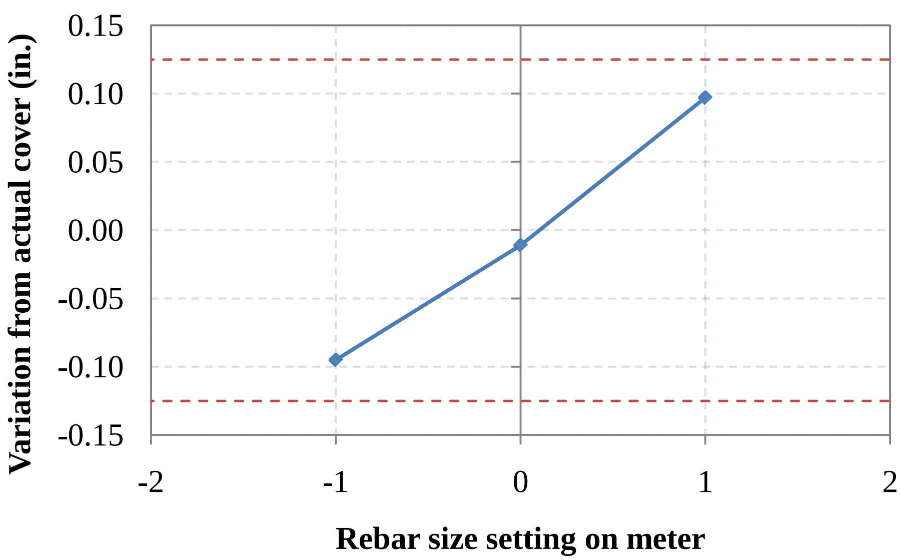


Figure D-5: Main effects of bar size input for WBS experiment.

D.2 WBS Two-way Interaction Tabulated Results and Figures.

Table D-1: Two-Way Interaction between Bar Size and Meter Brand for WBS Experiment

Size	Brand	Error
4	1	-0.037
6	1	-0.027
8	1	-0.018
4	2	-0.014
6	2	0.056
8	2	0.021

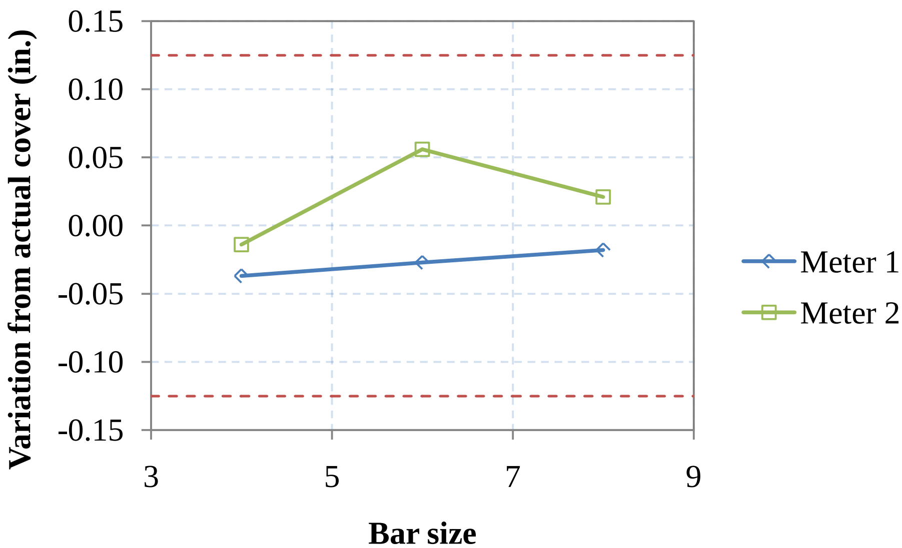


Figure D-6: Two-way interaction between bar size and meter brand for WBS experiment.

Table D-2: Two-Way Interaction between Bar Size and Actual Cover Depth for WBS Experiment

Size	Cover	Error
4	2	-0.036
4	2.5	-0.001
4	3	-0.039
6	2	0.021
6	2.5	0.025
6	3	-0.001
8	2	0.017
8	2.5	0.017
8	3	-0.028

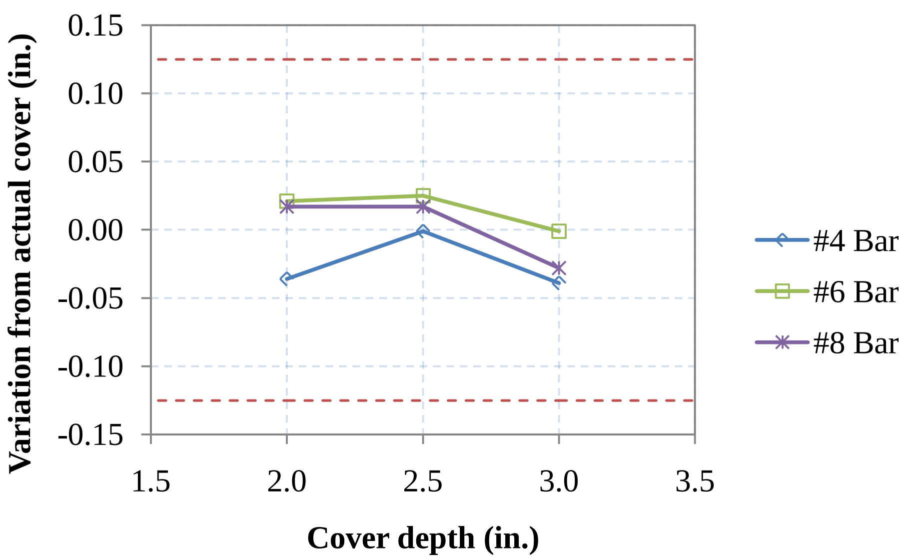


Figure D-7: Two-way interaction between bar size and actual cover depth for WBS experiment.

Table D-3: Two-Way Interaction between Bar Size and Antenna Type for WBS Experiment

Size	Antenna	Error
4	D	0
6	D	0.047
8	D	0.067
4	S	-0.051
6	S	-0.018
8	S	-0.063

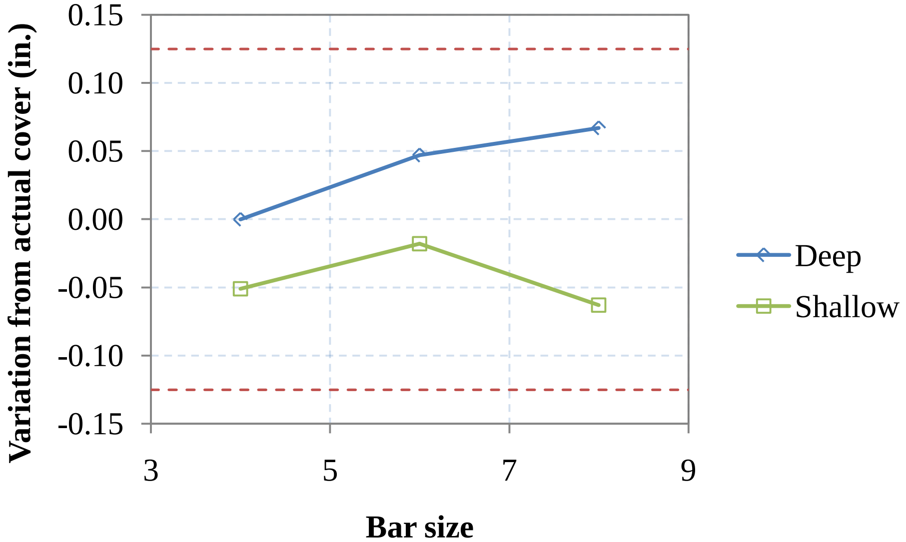


Figure D-8: Two-way interaction between bar size and antenna type for WBS experiment.

Table D-4: Two-Way Interaction between Bar Size and Bar Size Input for WBS Experiment

Size	Input	Error
4	-1	-0.142
4	0	-0.036
4	1	0.101
6	-1	-0.083
6	0	0.006
6	1	0.122
8	-1	-0.06
8	0	-0.001
8	1	0.067

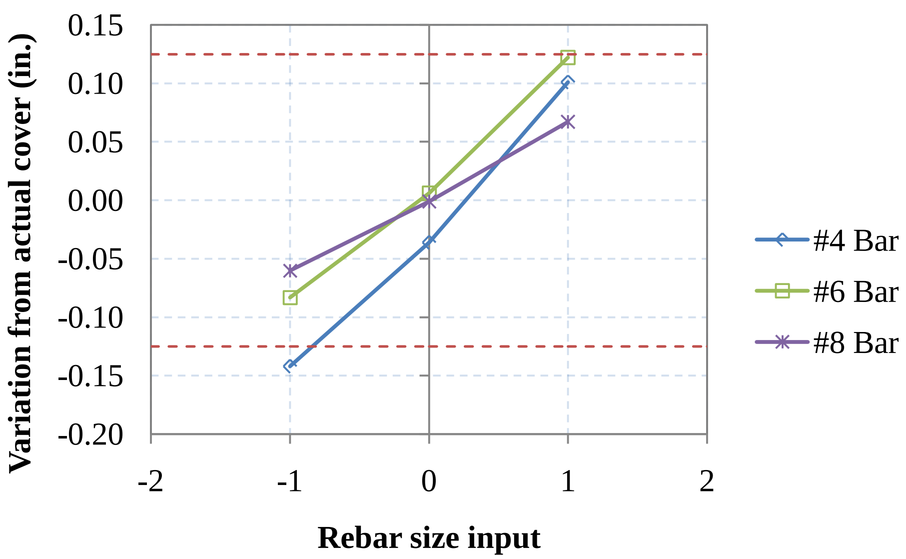


Figure D-9: Two-way interaction between bar size and bar size input for WBS experiment.

Table D-5: Two-Way Interaction between Meter Brand and Actual Cover Depth for WBS Experiment

Brand	Cover	Error
1	2	-0.016
1	2.5	-0.012
1	3	-0.054
2	2	0.017
2	2.5	0.019
2	3	0.008

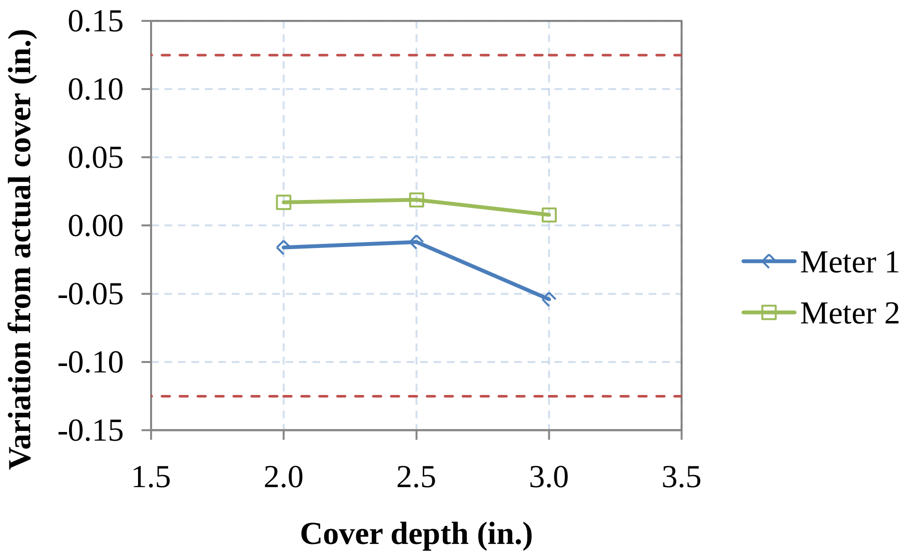


Figure D-10: Two-way interaction between meter brand and actual cover depth for WBS experiment.

Table D-6: Two-Way Interaction between Meter Brand and Antenna Type for WBS Experiment

Brand	Antenna	Error
1	D	-0.011
2	D	0.087
1	S	-0.043
2	S	-0.044

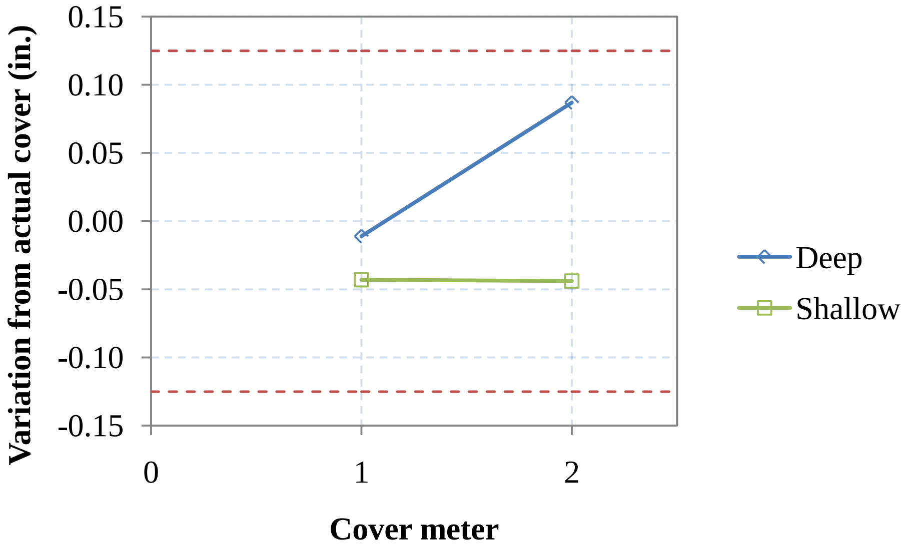


Figure D-11: Two-way interaction between meter brand and antenna type for WBS experiment.

Table D-7: Two-Way Interaction between Meter Brand and Bar Size Input for WBS Experiment

Brand	Input	Error
1	-1	-0.125
1	0	-0.028
1	1	0.081
2	-1	-0.065
2	0	0.006
2	1	0.122

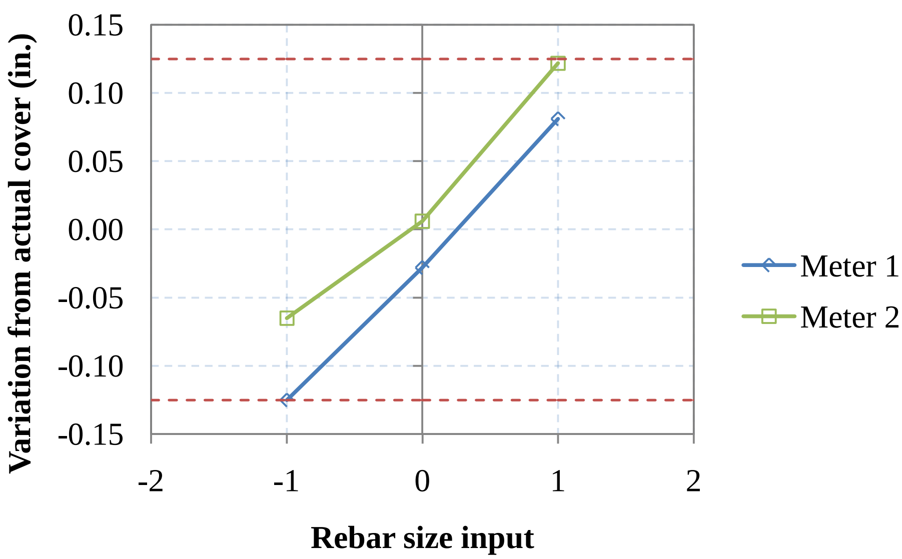


Figure D-12: Two-way interaction between bar size input and meter brand for WBS experiment.

Table D-8: Two-Way Interaction between Actual Cover Depth and Antenna Type for WBS Experiment

Cover	Antenna	Error
2	D	0.047
2.5	D	0.053
3	D	0.014
2	S	-0.046
2.5	S	-0.026
3	S	-0.059

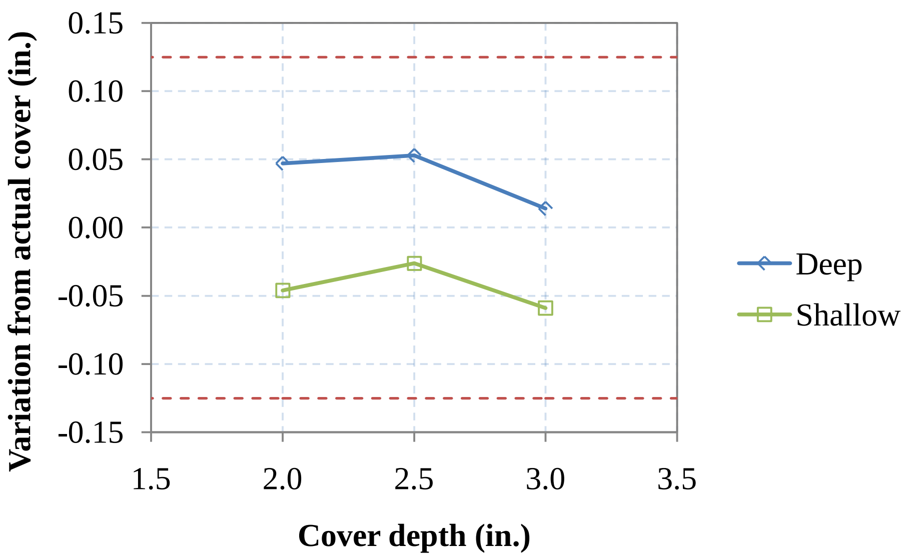


Figure D-13: Two-way interaction between actual cover depth and antenna type for WBS experiment.

Table D-9: Two-Way Interaction between Bar Size Input and Actual Cover Depth for WBS Experiment

Cover	Spacing	Error
2.0	-1	-0.075
2.0	0	-0.004
2.0	1	0.08
2.5	-1	-0.079
2.5	0	0.007
2.5	1	0.113
3.0	-1	-0.131
3.0	0	-0.035
3.0	1	0.097

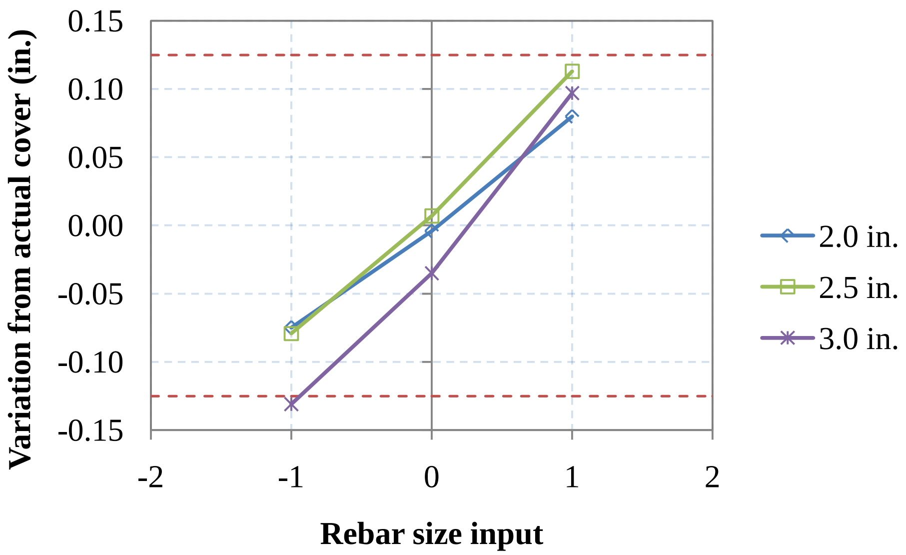


Figure D-14: Two-way interaction results between bar size input and actual cover depth for WBS experiment.

Table D-10: Two-Way Interaction between Antenna Type and Bar Size Input for WBS Experiment

Antenna	Spacing	Error
D	-1	-0.069
D	0	0.033
D	1	0.15
S	-1	-0.12
S	0	-0.055
S	1	0.044

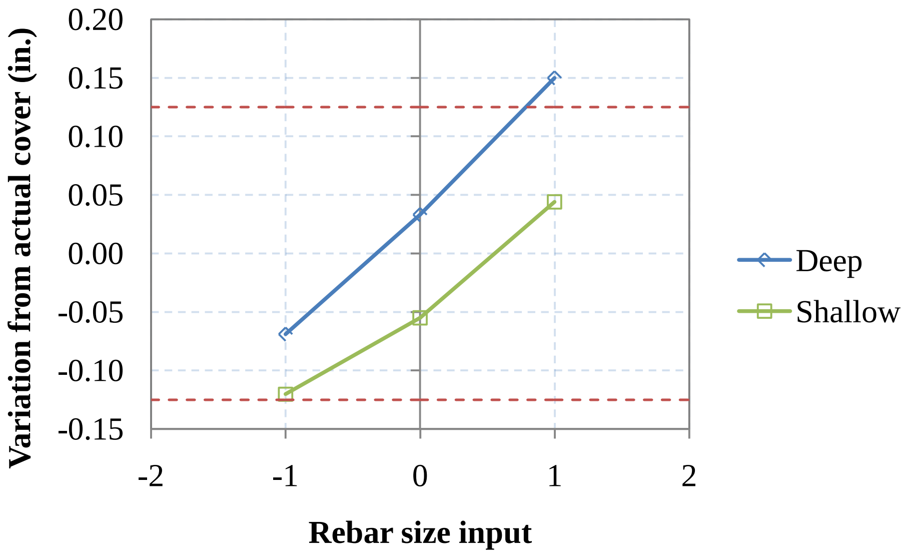
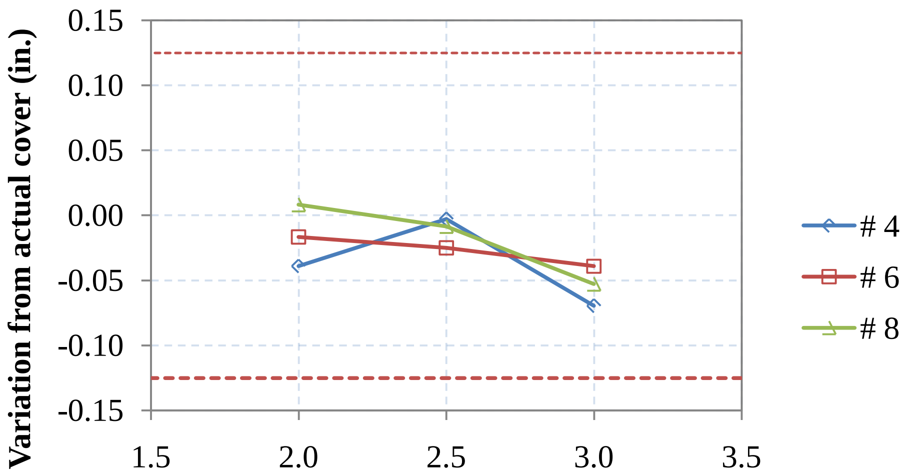


Figure D-15: Two-way interaction between offset distance and antenna type for WBS experiment.

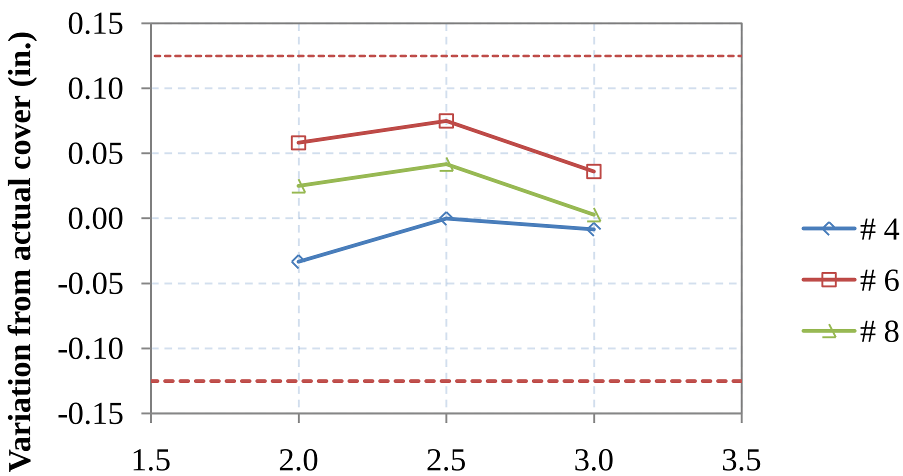
D.3 WBS Three-way interaction Tabulated Results and Figures.

Table D-11: Three-Way Interaction between Bar Size, Actual Cover Depth, and Meter Brand for WBS Experiment

Size	Brand	Cover	Error
4	1	2	-0.039
4	1	2.5	-0.003
4	1	3	-0.069
4	2	2	-0.033
4	2	2.5	0.000
4	2	3	-0.008
6	1	2	-0.017
6	1	2.5	-0.025
6	1	3	-0.039
6	2	2	0.058
6	2	2.5	0.075
6	2	3	0.036
8	1	2	0.008
8	1	2.5	-0.008
8	1	3	-0.053
8	2	2	0.025
8	2	2.5	0.042
8	2	3	0.003



(a) Meter 1.

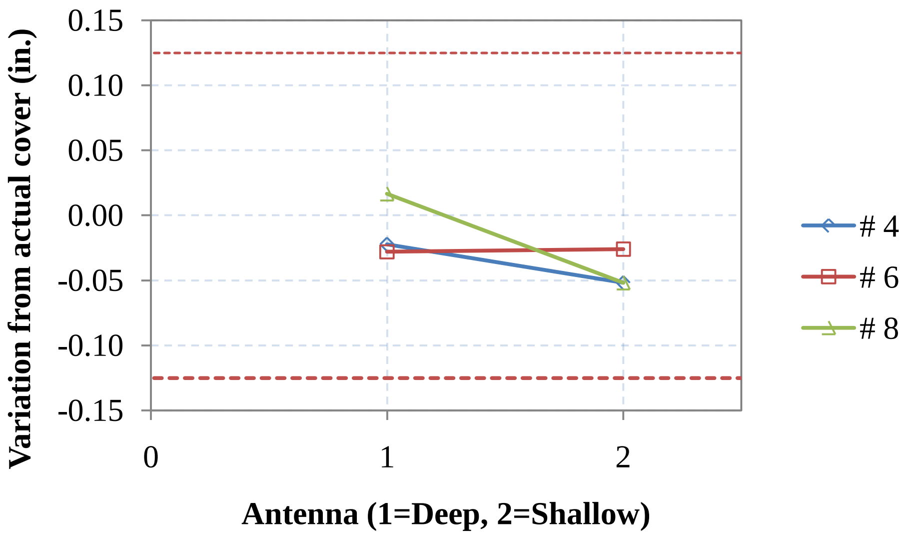


(b) Meter 2.

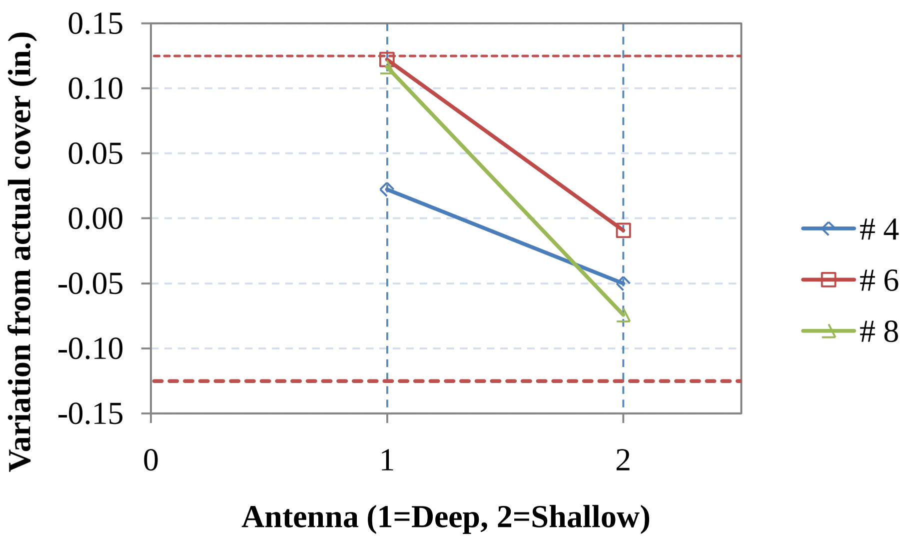
Figure D-16: Three-way interaction between bar size, actual cover depth, and meter brand for WBS experiment.

Table D-12: Three-Way Interaction between Bar Size, Antenna Type, and Meter Brand for WBS Experiment

Size	Brand	Antenna	Error
4	1	D	-0.022
4	1	S	-0.052
4	2	D	0.022
4	2	S	-0.050
6	1	D	-0.028
6	1	S	-0.026
6	2	D	0.122
6	2	S	-0.009
8	1	D	0.017
8	1	S	-0.052
8	2	D	0.117
8	2	S	-0.074



(a) Meter 1.

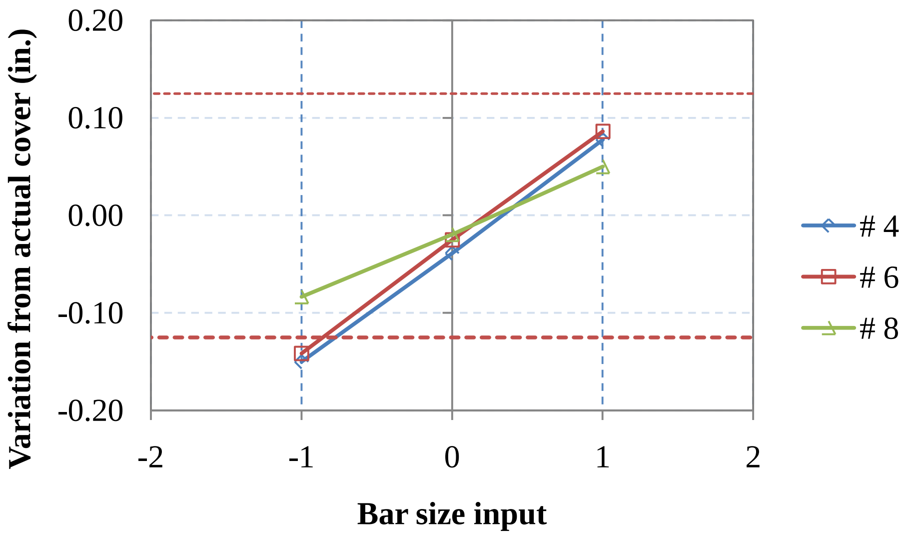


(b) Meter 2.

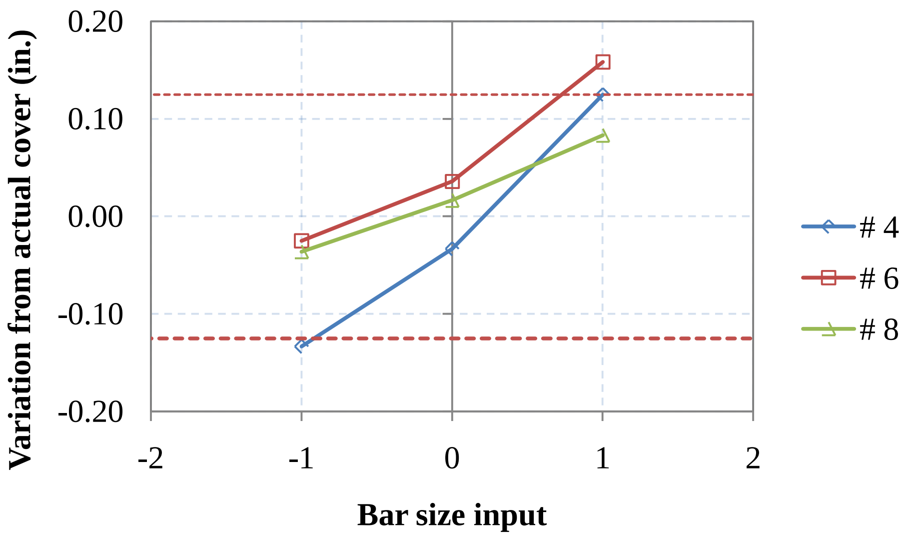
Figure D-17: Three-way interaction between bar size, antenna type, and meter brand for WBS experiment.

Table D-13: Three-Way Interaction between Bar Size, Bar Size Input, and Meter Brand for WBS Experiment

Size	Brand	Input	Error
4	1	-1	-0.150
4	1	0	-0.039
4	1	1	0.078
4	2	-1	-0.133
4	2	0	-0.033
4	2	1	0.125
6	1	-1	-0.142
6	1	0	-0.025
6	1	1	0.086
6	2	-1	-0.025
6	2	0	0.036
6	2	1	0.158
8	1	-1	-0.083
8	1	0	-0.019
8	1	1	0.050
8	2	-1	-0.036
8	2	0	0.017
8	2	1	0.083



(a) Meter 1.

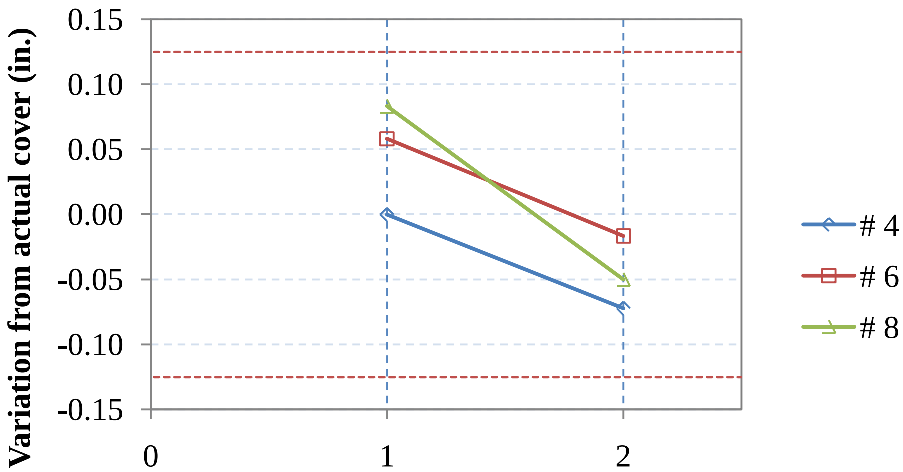


(b) Meter 2.

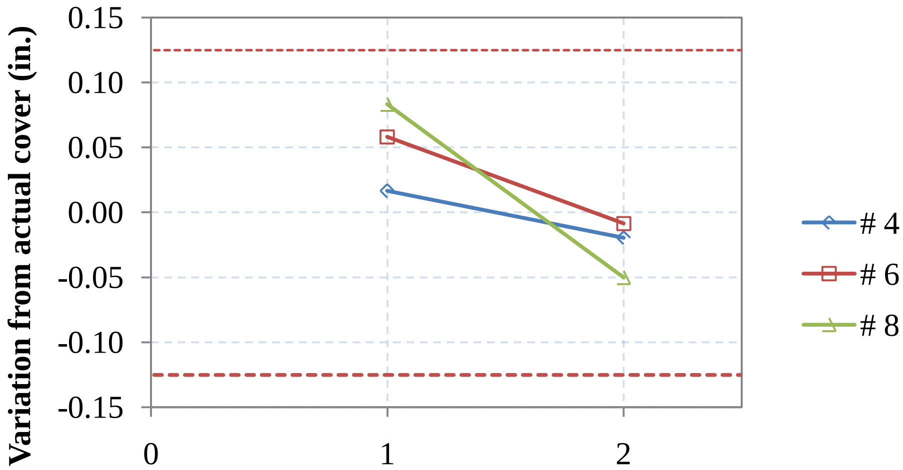
Figure D-18: Three-way interaction between bar size, bar size input, and meter brand for WBS experiment.

Table D-14: Three-Way Interaction between Bar Size, Antenna Type, and Actual Cover Depth for WBS Experiment

Size	Cover	Antenna	Error
4	2	D	0.000
4	2	S	-0.072
4	2.5	D	0.017
4	2.5	S	-0.019
4	3	D	-0.017
4	3	S	-0.061
6	2	D	0.058
6	2	S	-0.017
6	2.5	D	0.058
6	2.5	S	-0.008
6	3	D	0.025
6	3	S	-0.028
8	2	D	0.083
8	2	S	-0.050
8	2.5	D	0.083
8	2.5	S	-0.050
8	3	D	0.033
8	3	S	-0.089

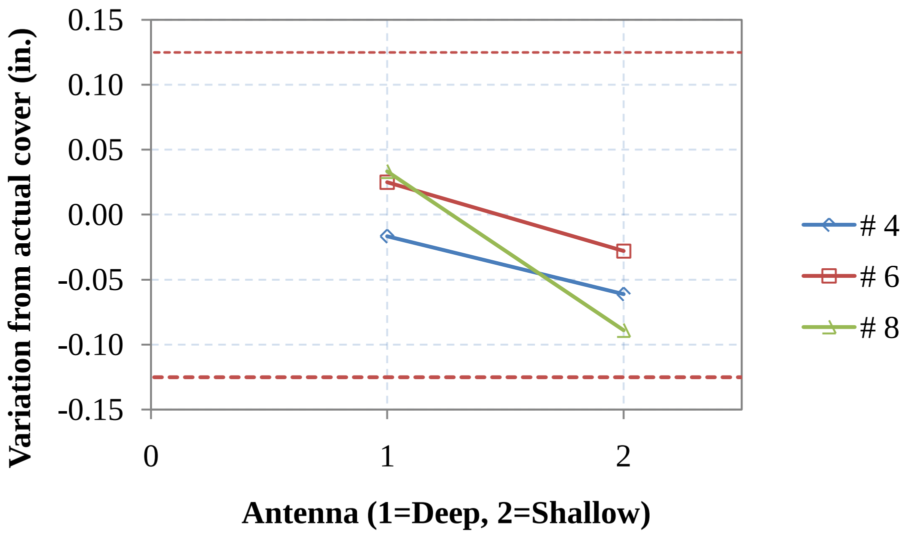


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure D-19: Three-way interaction between bar size, antenna type, and actual cover depth for WBS experiment.

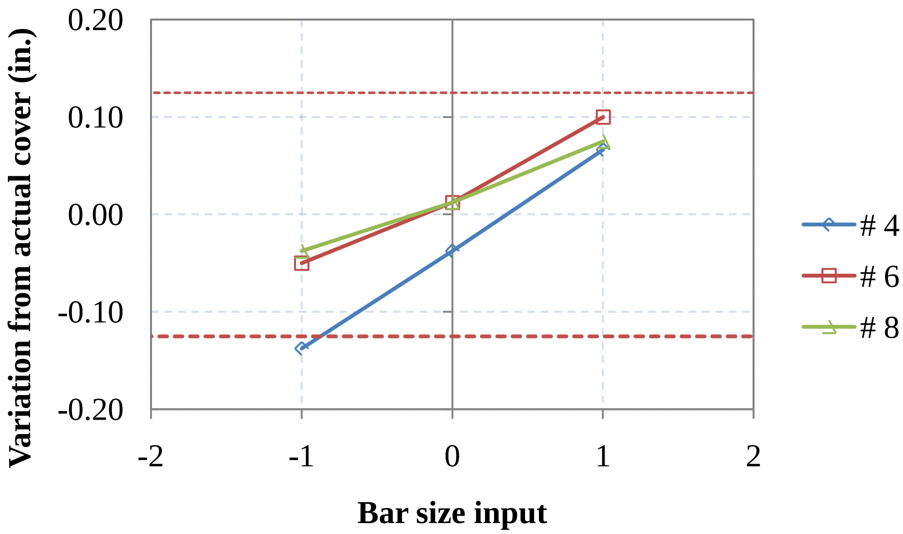


(c) 3.0 in. actual cover depth.

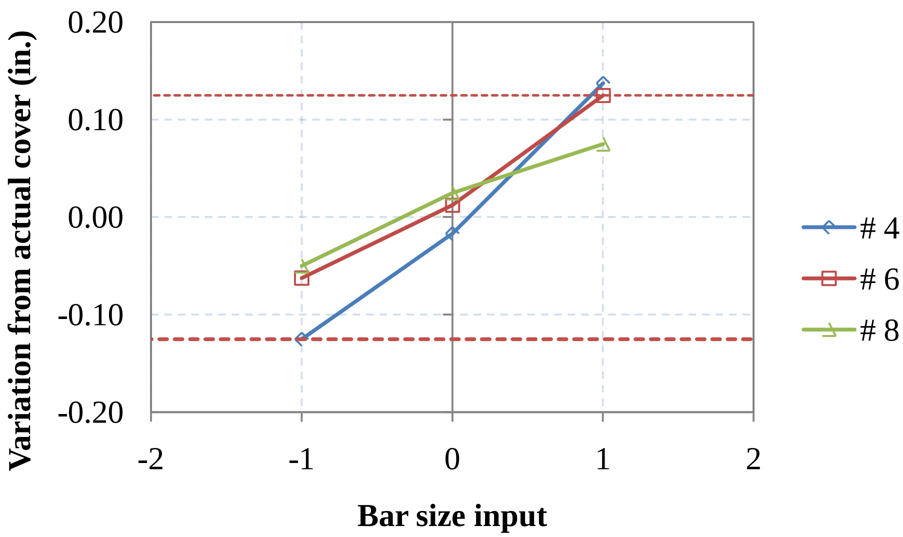
Figure D-19: Three-way interaction between bar size, antenna type, and actual cover depth for WBS experiment. (Continued)

Table D-15: Three-Way Interaction between Bar Size, Bar Size Input, and Actual Cover Depth for WBS Experiment

Size	Cover	Input	Error
4	2	-1	-0.138
4	2	0	-0.038
4	2	1	0.067
4	2.5	-1	-0.125
4	2.5	0	-0.017
4	2.5	1	0.138
4	3	-1	-0.163
4	3	0	-0.054
4	3	1	0.100
6	2	-1	-0.050
6	2	0	0.013
6	2	1	0.100
6	2.5	-1	-0.063
6	2.5	0	0.013
6	2.5	1	0.125
6	3	-1	-0.138
6	3	0	-0.008
6	3	1	0.142
8	2	-1	-0.038
8	2	0	0.013
8	2	1	0.075
8	2.5	-1	-0.050
8	2.5	0	0.025
8	2.5	1	0.075
8	3	-1	-0.092
8	3	0	-0.042
8	3	1	0.050

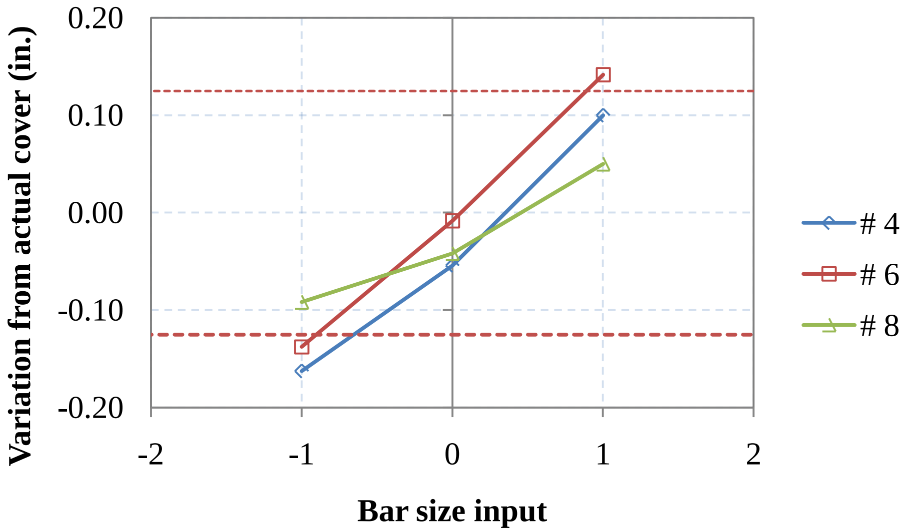


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure D-20: Three-way interaction between bar size, bar size input, and actual cover depth for WBS experiment.

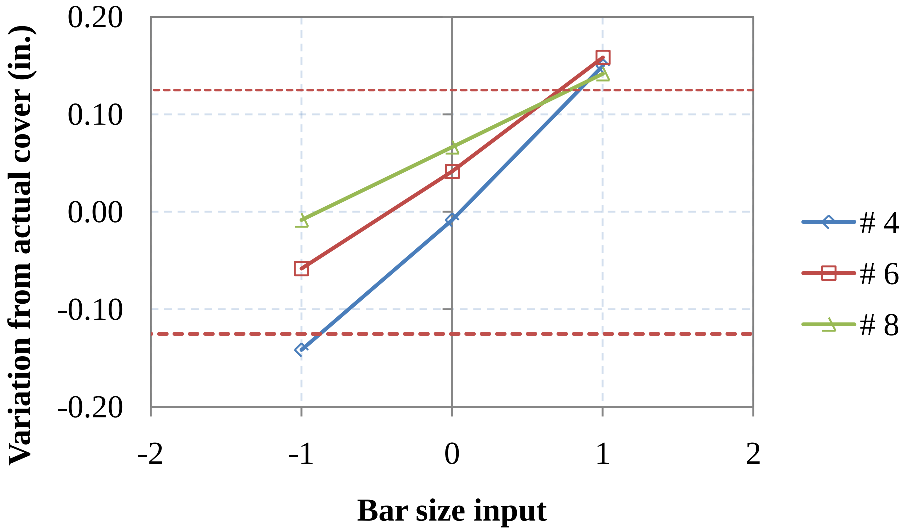


(c) 3.0 in. actual cover depth.

Figure D-20: Three-way interaction between bar size, bar size input, and 3.0 in. actual cover depth for WBS experiment. (Continued)

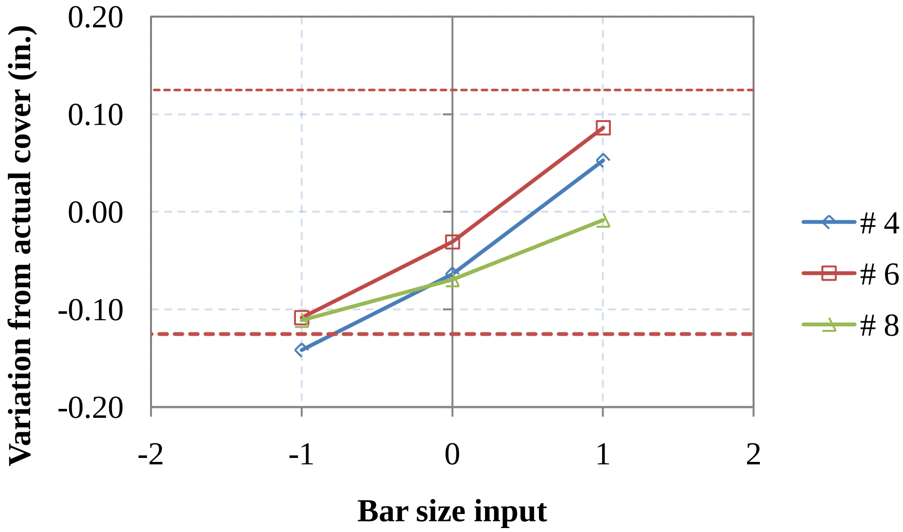
Table D-16: Three-Way Interaction between Bar Size, Bar Size Input, and Antenna Type for WBS Experiment

Size	Antenna	Input	Error
4	D	-1	-0.142
4	D	0	-0.008
4	D	1	0.150
4	S	-1	-0.142
4	S	0	-0.064
4	S	1	0.053
6	D	-1	-0.058
6	D	0	0.042
6	D	1	0.158
6	S	-1	-0.108
6	S	0	-0.031
6	S	1	0.086
8	D	-1	-0.008
8	D	0	0.067
8	D	1	0.142
8	S	-1	-0.111
8	S	0	-0.069
8	S	1	-0.008



(a) Deep antenna.

Figure D-21: Three-way interaction between bar size, bar size input, and antenna type for WBS experiment.

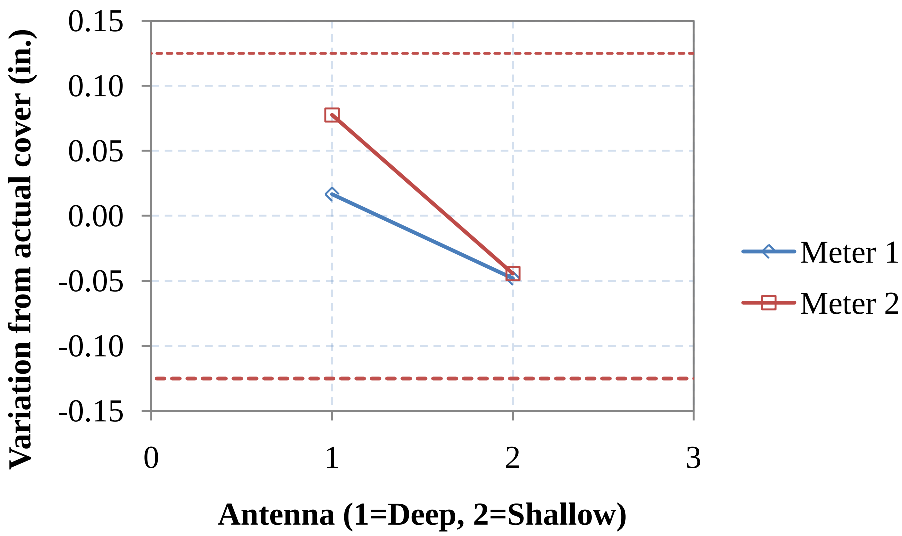


(a) Shallow antenna.

Figure D-21: Three-way interaction between bar size, bar size input, and antenna type for WBS experiment. (Continued)

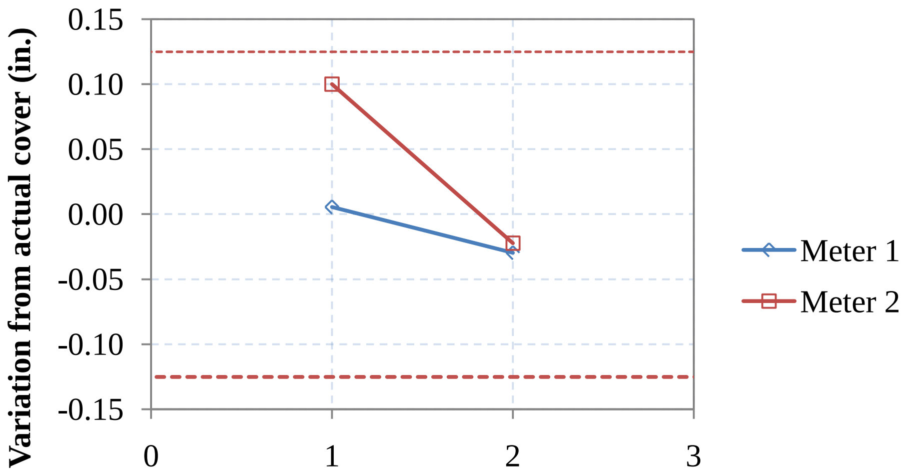
Table D-17: Three-Way Interaction between Meter Brand, Antenna Type, and Actual Cover Depth for WBS Experiment

Brand	Cover	Antenna	Error
1	2	D	0.017
1	2	S	-0.048
1	2.5	D	0.006
1	2.5	S	-0.030
1	3	D	-0.056
1	3	S	-0.052
2	2	D	0.078
2	2	S	-0.044
2	2.5	D	0.100
2	2.5	S	-0.022
2	3	D	0.083
2	3	S	-0.067

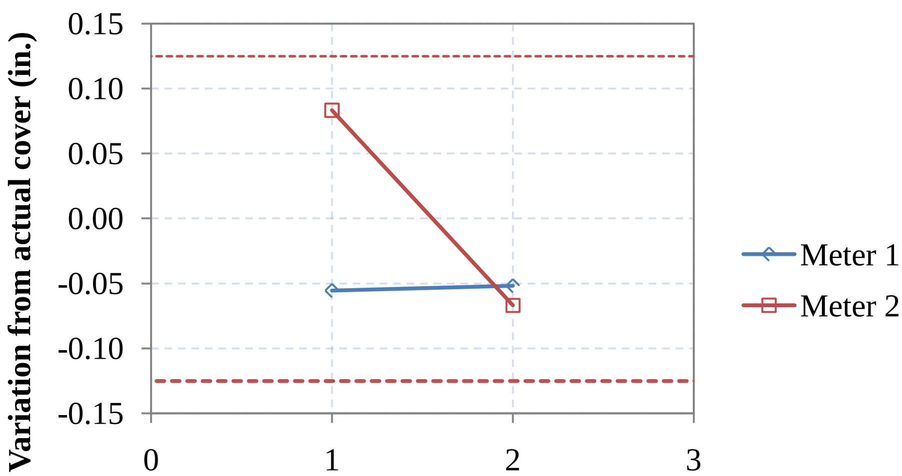


(a) 2.0 in. actual cover depth.

Figure D-22: Three-way interaction between meter brand, antenna type, and actual cover depth for WBS experiment.



(b) 2.5 in. actual cover depth.

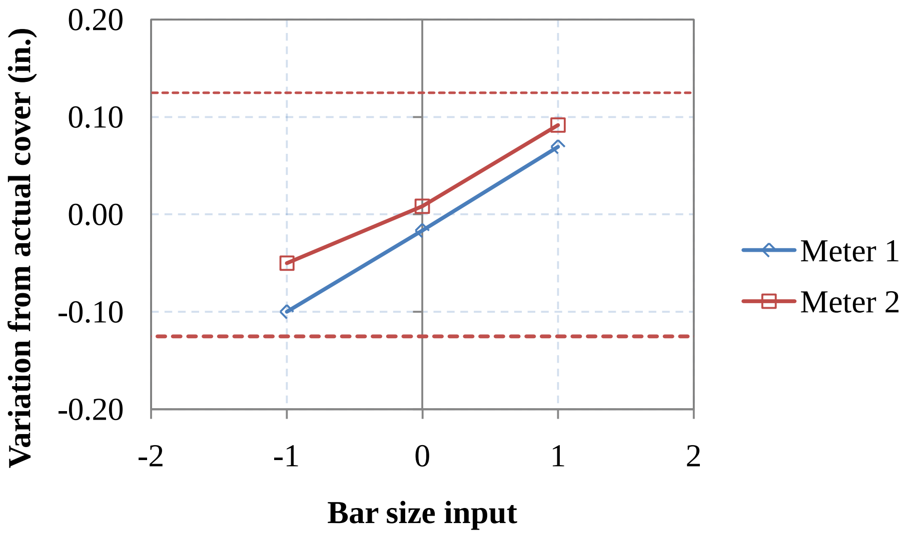


(c) 3.0 in. actual cover depth.

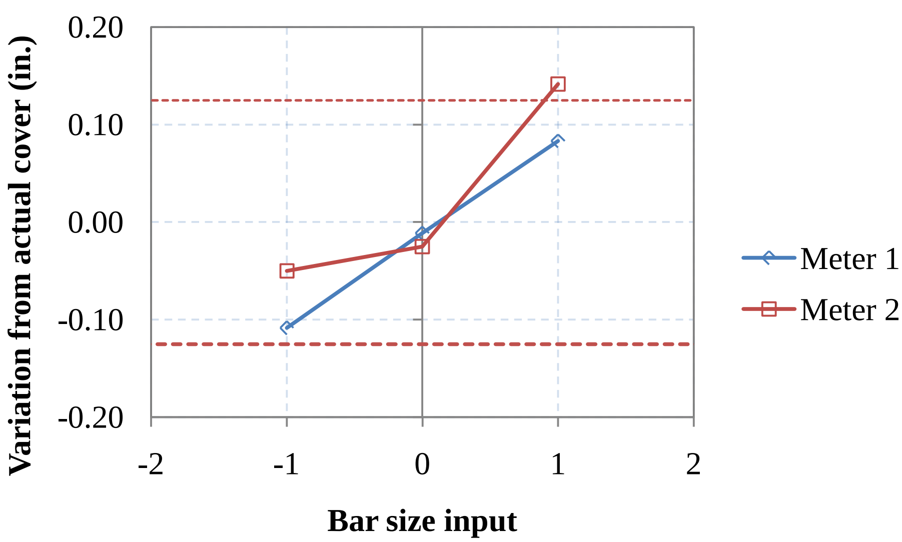
Figure D-22: Three-way interaction between meter brand, antenna type, and actual cover depth for WBS experiment. (Continued)

Table D-18: Three-Way Interaction between Meter Brand, Bar Size Input, and Actual Cover Depth for WBS Experiment

Brand	Cover	Input	Error
1	2	-1	-0.100
1	2	0	-0.017
1	2	1	0.069
1	2.5	-1	-0.108
1	2.5	0	-0.011
1	2.5	1	0.083
1	3	-1	-0.167
1	3	0	-0.056
1	3	1	0.061
2	2	-1	-0.050
2	2	0	0.008
2	2	1	0.092
2	2.5	-1	-0.050
2	2.5	0	-0.025
2	2.5	1	0.142
2	3	-1	-0.094
2	3	0	-0.014
2	3	1	0.133

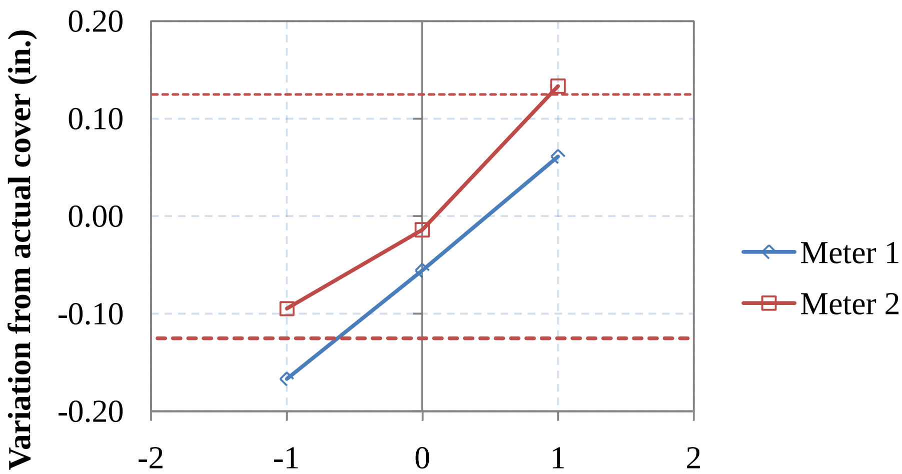


(a) 2.0 in. actual cover depth.



(b) 2.5 in. actual cover depth.

Figure D-23: Three-way interaction between meter brand, bar size input, and actual cover depth for WBS experiment.

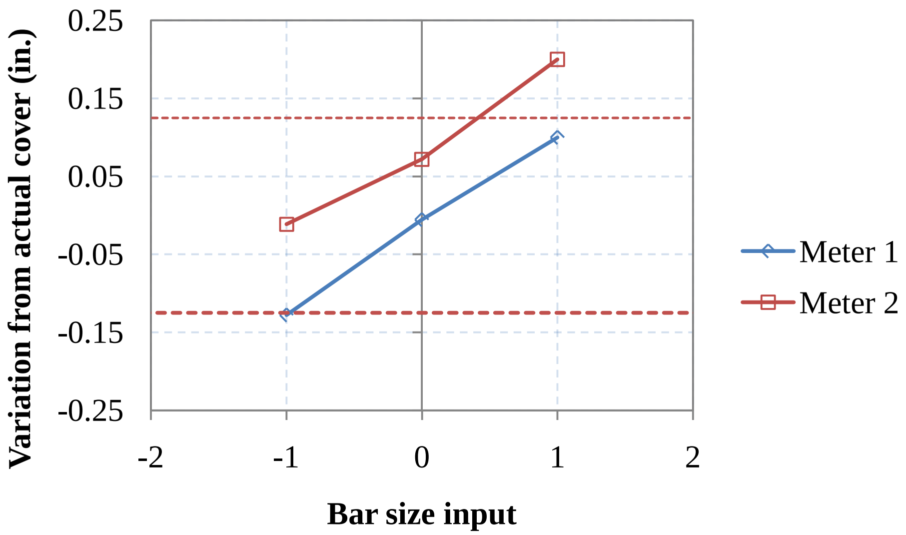


(c) 3.0 in. actual cover depth.

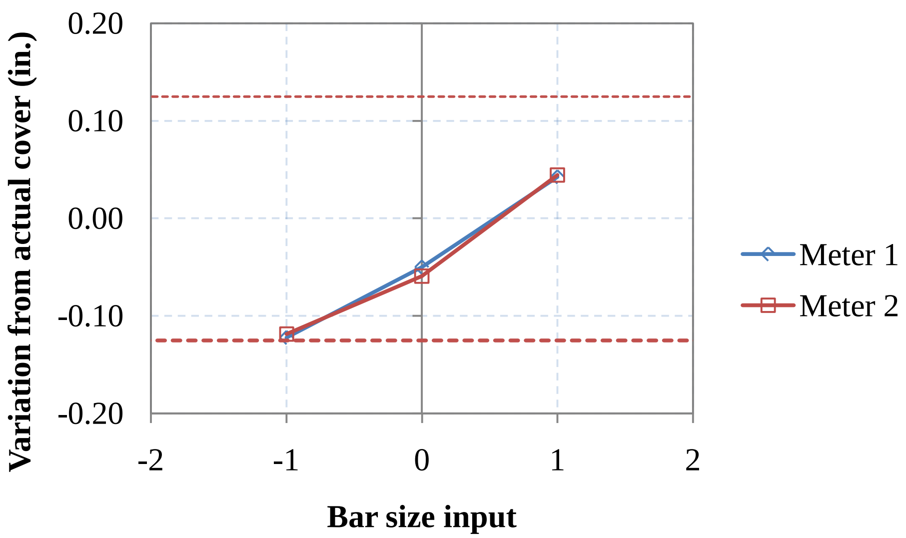
Figure D-23: Three-way interaction between meter brand, bar size input, and actual cover depth for WBS experiment. (Continued)

Table D-19: Three-Way Interaction between Meter Brand, Bar Size Input, and Antenna Type for WBS Experiment

Brand	Antenna	Input	Error
1	D	-1	-0.128
1	D	0	-0.006
1	D	1	0.100
1	S	-1	-0.122
1	S	0	-0.050
1	S	1	0.043
2	D	-1	-0.011
2	D	0	0.072
2	D	1	0.200
2	S	-1	-0.119
2	S	0	-0.059
2	S	1	0.044



(a) Deep antenna.

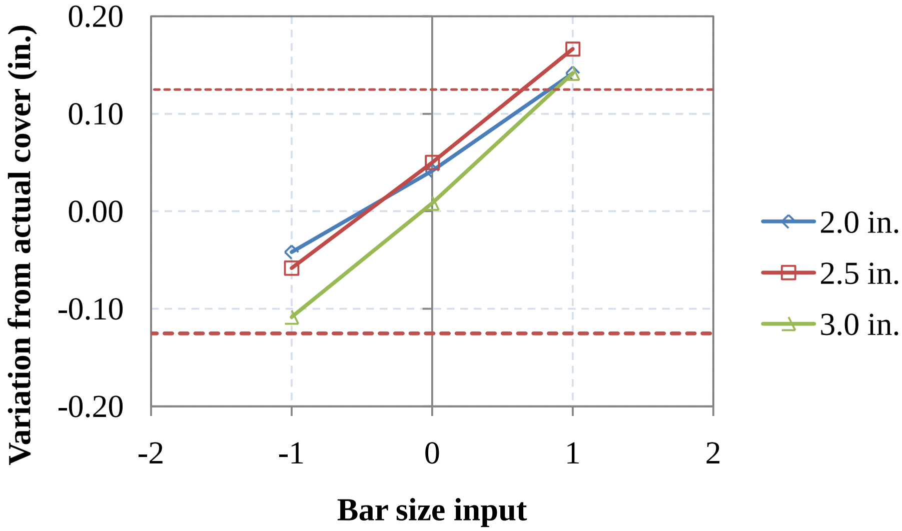


(b) Shallow antenna.

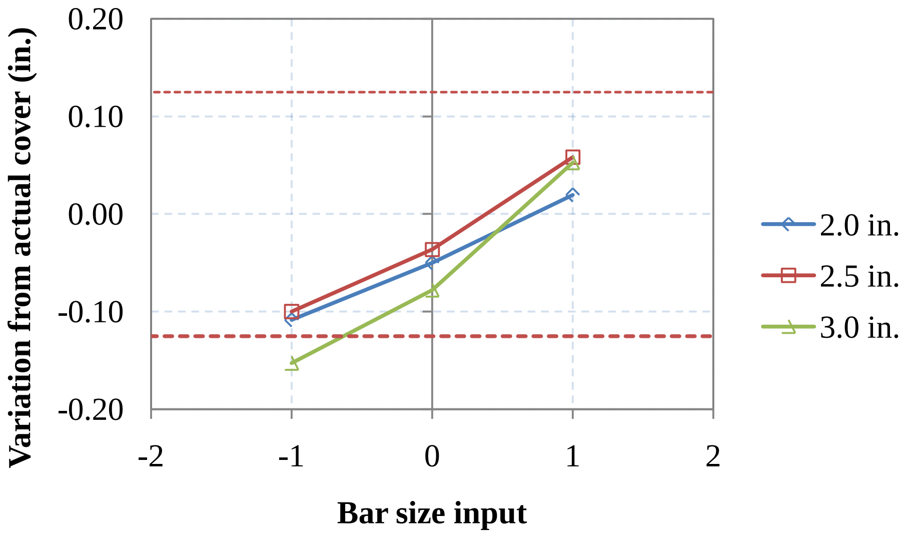
Figure D-24: Three-way interaction between meter brand, bar size input, and antenna type for WBS experiment.

Table D-20: Three-Way Interaction between Actual Cover Depth, Bar Size Input, and Antenna Type for WBS Experiment

Cover	Antenna	Input	Error
2	D	-1	-0.042
2	D	0	0.042
2	D	1	0.142
2	S	-1	-0.108
2	S	0	-0.050
2	S	1	0.019
2.5	D	-1	-0.058
2.5	D	0	0.050
2.5	D	1	0.167
2.5	S	-1	-0.100
2.5	S	0	-0.036
2.5	S	1	0.058
3	D	-1	-0.108
3	D	0	0.008
3	D	1	0.142
3	S	-1	-0.153
3	S	0	-0.078
3	S	1	0.053



(a) Deep antenna.



(b) Shallow antenna.

Figure D-25: Three-way interaction between actual cover depth, bar size input, and antenna type for WBS experiment.