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Continuous Compaction Control MnROAD Demonstration

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16. Abstract (Limit: 200 words)

In September 2004, engineers conducted a Continuous Compaction Control (CCC) demonstration at MnROAD, an outdoor pavement test facility. Continuous Compaction Control (CCC), also called Intelligent Compaction (IC), is a new technique in the United States construction market that uses an instrumented compactor to measure soil or asphalt compaction in real time and adjusts compactive effort accordingly to control the level of compaction. This demonstration used the BOMAG Compactor and focused on Young's soil modulus as the soil parameter of interest.

CCC may potentially provide substantial benefits, including improved quality due to more uniform compaction, reduced compaction costs because effort is applied only where necessary, reduced life-cycle cost due to longer pavement life, and a stronger relationship between design and construction. State departments of transportation have expressed interest in exploring this method as a way of meeting quality-assurance requirements within a tight budget environment.

In general, this study found CCC to be an effective quality-control mechanism for soil compaction. However, further questions arose as a result of the study and certain variables affected the results and measurements, including moisture content and the use of different measurement tools. Further research is needed to determine the level of uniformity in using CCC and the extent of reliability in achieving target values when using this method.

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CONTINUOUS COMPACTION CONTROL MnROAD DEMONSTRATION

Final Report

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Executive Summary

This report documents a Continuous Compaction Control (CCC) demonstration conducted at the MnROAD facility during September 27 through September 30, 2004. Continuous Compaction Control, also called Intelligent Compaction (IC), is a new technique in the United States construction market that uses an instrumented compactor to control soil or asphalt compaction in real time. This technology, which provides one of the first opportunities to apply process control to civil construction, is based on measuring the stiffness of the compacted soil. Initiatives in both the U.S. and Europe, started more than 10 years ago, have demonstrated the technical viability of measuring in situ soil stiffness and modulus. As the name implies, continuous compaction control combines the measurement of compaction level with feedback to adjust the compactive effort. The BOMAG compactor used for this demonstration project adjusts the compactive effort in real time to continue compaction of soils under the established target value, while preventing overcompaction of soils at or above the target value. The Minnesota Department of Transportation and the Federal Highway Administration have formal and informal initiatives to evaluate continuous compaction control. Other state DOTs are in various stages of evaluating continuous compaction control.

The MnROAD demonstration site, section 54 on the low volume road test loop, was about 200 feet long, 8 feet deep and 25 feet wide. Four soils, listed in order from bottom to top, were used to construct the roadway foundation:

1. An ASTM SM soil removed from the excavation and stockpiled onsite, was used for the lower fill material. Pockets of SP sand were sparsely scattered throughout this material.
2. Three-inch-minus railroad ballast, used on top of the loamy sand
3. An ASTM SM soil from offsite was placed over the railroad ballast.
4. An ASTM GW-GM soil (crushed granite meeting Mn/DOT class 6 gradation) was used for the aggregate base.

The bottom of the excavation was relatively wet due to a high water table and heavy rains the week before the demonstration.

The machine used for the demonstration was a BOMAG Model BW 213 DH-3 BVC—pertinent data about this model is in Table 2—BOMAG Machine Characteristics. The BOMAG compactor records modulus measurements as it compacts. These measurements can be printed to paper in the cab of the compactor or saved to a PCMCIA card using the BOMAG Compaction Management (BCM) system. Only one pass is printed at a time with onboard printer and measurements are not saved unless the BCM is used. The BCM logs the measurements every 10 cm and allows the user to create reports of the data showing surface coverage and measured values.

The following portable devices and equipment were used to independently measure soil properties for comparison with the BOMAG measurements: dynamic cone penetrometer (DCP), Humboldt GeoGauge, Loadman light weight deflectometer (LWD), plate load test, nuclear density gauge, sand cone equipment and falling weight deflectometer (FWD). These companion tests were conducted at 23 locations within the test area. The principal companion tests (DCP, GeoGauge, LWD, sand cone and nuclear density) were performed at all locations, plate load tests were performed at only two locations.

Two target values were used for the demonstration, depending upon material type. The Class 6 material used for the base course was compacted to a target value of 100 MPa. All other soils were compacted using a target value of 45 MPa. Because of the excessive moisture content of many of the soils used in the demonstration, the target values were generally not achieved.

The following table provides the average, standard deviation, coefficient of variation, minimum value, maximum value and number of measurements for the four principal test methods. The BOMAG, LWD and GeoGauge data sets had 23 modulus values, and DCP data set had 22 modulus values. The table groups all soil types and compactive efforts.

Method	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation	Minimum (MPa)	Maximum (MPa)	Count
BOMAG Compactor	46.6	42.3	91 %	4.0	130.0	23
LWD	56.0	31.8	57 %	7.5	132.9	23
GeoGauge	67.0	24.8	37 %	30.3	120.4	23
DCP (top 6 inches)	39.3	21.7	55 %	7.4	96.0	22

The histograms and statistical measures all indicate that the modulus values from the four methods are different. The BOMAG data has a wider range and is clustered toward lower values. GeoGauge data tends to be larger than the other methods, while the LWD and DCP data is intermediate between the BOMAG and GeoGauge. Correlations between companion tests were also investigated. The correlation coefficients were small, except for the GeoGauge-DCP relationship.

Because the BOMAG and companion tests produce different soil stresses, the stress dependence of the soil modulus may be inferred from the test results. Data from the GeoGauge, LWD and BOMAG methods are consistent with the modulus-stress correlation from the plate load test. Note that the GeoGauge imparts the lowest stress, and that the LWD and BOMAG have stresses equivalent to the lower unload-reload cycles of the plate load test. Data from FWD testing indicates less stress dependence than other methods.

GeoGauge and DCP modulus values show the trend of moisture content dependence expected for unbound materials. This dependence is similar in form to Proctor curves, with greater modulus values occurring near optimum, and smaller modulus values for moisture contents both wet and dry of optimum.

At 22 of 23 test locations the compacted density was greater than 95 percent standard Proctor density. In the absence of surface-covering documentation and companion tests, the subgrade and base would have been accepted. Because of the additional documentation and testing, the real, observed non-uniform nature of the compacted materials was revealed. CCC provides a far superior quantitative measure of uniformity compared to existing standard QC/QA practice that utilizes point tests.

Specific conclusions are:

1. The BOMAG compactor appears to be well made, rugged and easy to operate (both the traditional controls and the Vario controls and data storage). The BOMAG compactor measures and reports different E_{vib} values depending upon the use of automatic (Variocontrol) or manual (fixed compactive effort) modes.
2. Different companion measurement tools produce different modulus values. Relatively good correlations were obtained between modulus values from the DCP and GeoGauge methods
3. A strong relationship between modulus and average contact stress was found for all devices that load the soil surface
4. Moisture content was found to affect both the compaction process and the measurement of soil modulus. Moisture content versus soil modulus relationships similar to those commonly observed for moisture content versus density were observed.
5. Under conditions similar to the demonstration, non-uniformly compacted soils would pass through traditional quality control and quality assurance procedures.
6. Continuous compaction control is an effective QC mechanism for soil compaction, because the surface-covering documentation adds value.

Specific recommendations are:

1. Research and implementation activities for continuous compaction control should be continued. In particular, demonstrations should be performed on actual trunk highway construction projects, and t Department should integrate related aspects of machine control (including global positioning), pavement management and pavement design
2. Maintain flexibility regarding specific equipment for compaction and companion testing
3. Modify current compaction control, QC and QA practice when surface covering documentation is used.

1 Introduction

1.1 Demonstration Purpose

This report documents a Continuous Compaction Control (CCC) demonstration conducted at the MnROAD facility during September 27 through September 30, 2004. Continuous Compaction Control, also called Intelligent Compaction (IC), is a new technique in the United States construction market that uses an instrumented compactor to control soil or asphalt compaction in real time. This technology provides one of the first opportunities to apply process control to civil construction.

1.2 Continuous Compaction Control (CCC)

1.2.1 Background

Continuous compaction control is based on measuring the stiffness of the compacted soil. Initiatives in both the U.S. and Europe, started more than 10 years ago, have demonstrated the technical viability of measuring in situ soil stiffness. Commonly, the measured soil stiffness is used to estimate or compute in situ soil modulus, based on assumptions about soil behavior and the interaction between the compaction machine and the base or subgrade materials.

1.2.2 Terminology

In any emerging technology, terminology varies among those involved until a standard develops. For the sake of clarity, the following definitions are used herein:

1. Surface covering documentation—This phrase describes the combined location and compaction level data (typically stiffness, modulus, strength or a similar parameter) produced by a compactor over the entire surface of a compaction lift.
2. Continuous compaction control—As the name implies, continuous compaction control combines the measurement of compaction level with feedback to adjust the compactive effort. The BOMAG compactor used for this demonstration project adjusts the compactive effort in real time to continue compaction of soils under the established target value, while preventing overcompaction of soils at or above the target value.
3. Intelligent compaction—In this report, intelligent compaction is synonymous with continuous compaction control.
4. Vibratory versus non-vibratory compaction measurement—The three preceding definitions do not distinguish between vibratory and non-vibratory compaction measurement methods. Most of the European technologies use vibratory methods similar to the methods used in this study, Caterpillar has developed a non-vibratory technology.

1.2.3 Description

Intelligent vibratory compaction machines typically include the following:

1. Sensors to measure vibration of the drum
2. Onboard electronics to record and process sensor output, and record the stiffness
3. Linkages to the machine controls to adjust compaction effort according to the measured stiffness
4. Systems to record machine location
5. Either local storage or wireless communications systems for data transfer

Process control is achieved in real time as the compaction process proceeds. The stiffness of the material is measured continuously as the compactor moves along. If the material stiffness is below the target value, the compactor applies compactive effort to the soil. If the material stiffness is at or above the target value, the compactor changes drum vibration from vertical to horizontal and does not further compact the material.

1.3 CCC Direct Benefits

Continuous compaction control potentially provides substantial quality and cost benefits. Among these are:

1. Improved quality, especially in terms of uniform compaction. The process control capabilities mean that no material is either overcompacted or undercompacted. IC-equipped compactors sense that the material has reached the target stiffness and do not apply additional compactive effort.
2. Reduced compaction costs, both short- and long-term. Costs are reduced in the short term because compactive effort is applied only where necessary, and thicker lifts may be compacted. Long-term costs are reduced because of reduced wear and tear on the compactor.
3. Reduced life cycle cost. European experience with IC clearly demonstrates that greater compaction uniformity increases the useable life of the pavement system.
4. Integration of design, construction, and performance. Intelligent compaction, which provides comprehensive data on the stiffness of all materials compacted, links design, construction, and pavement performance. The data record produced by the compactor, which covers all areas and all lifts, is essential to the pavement management process. Long-term performance may be correlated with the properties produced during construction. Similarly, evaluating subgrade and pavement materials mechanical properties during compaction relates directly to the mechanistic properties used to design the pavement. This data can be correlated to Geogauge readings, dynamic cone penetrometer (DCP) test results, falling weight deflectometer (FWD) test results and other measures of structural strength.

1.4 CCC in the Context of FHWA and Mn/DOT Initiatives

The Mn/DOT and the Federal Highway Administration (FHWA) both have formal and informal initiatives to evaluate continuous compaction control. Other state DOTs also are, or are planning to evaluate continuous compaction control.

Mn/DOT interest in continuous compaction control originates from several factors:

1. Most Mn/DOT Districts are experiencing difficulty in performing the currently required quality assurance spot testing due to reduced personnel and tighter budgets. As a result, several Mn/DOT Districts have expressed interest in facilitating demonstrations of IC to evaluate the potential benefits of this technology.
2. The direct benefits outlined in Section 1.3 above.
3. Mn/DOT's Strategic Plan 2003 includes strategic directions of "Make Mn/DOT Work Better" and "Make our Transportation Network Operate Better." These directions have led Mn/DOT to aggressively investigate machine control technology. Continuous compaction control is a logical partner technology of machine control. See (http://www.dot.state.mn.us/information/statplan00/).
4. Implementation of mechanistic-empirical design methods for pavements requires modulus values during design, and also benefits from construction-time confirmation of the design values. Continuous compaction control provides the construction-time confirmation of both unbound materials and hot mix asphalt (HMA).
5. Design-build is one of several innovative contracting methods that Mn/DOT is using to help deliver projects faster and more efficiently. Contractors responding to design-build requests for proposals (RFPs) have additional flexibility to propose innovative construction techniques like continuous compaction control.
6. Finally, continuous compaction control requires the technology to measure, record, transfer and display modulus information. This technology is now available in several brands of compactors, for incremental costs approximately the same as adding a cab and air conditioning.

As a result, Mn/DOT is partnering with the North Carolina, Wisconsin, and Louisiana Department of Transportations (DOTs) to initiate a National Pooled Fund project that would build on European IC experience and develop IC specifications for the US construction industry.

The FHWA has recently released draft "FHWA Intelligent Compaction Strategic Plan" (December 2004). The following is excerpted from that document:

7. FHWA's Vision—Through the use of creative use of computers, modeling, and innovative software, intelligent soil and asphalt compaction equipment will improve operations, result in more uniform pavement density, reduce inspector requirements, and provide a long-term quality record that can be related to pavement performance.
8. FHWA's Mission—This strategic plan will establish a systematic process to encourage industry and DOTs to develop intelligent compaction capabilities in the US. The encouragement will come through a series of demonstration efforts, long and short term research, and innovative construction specifications.
9. Objectives of FHWA's Strategic Plan—The objectives are:
    a. To accelerate the development of intelligent compaction technology (equipment, software and specifications)
    b. To encourage awareness and acceptance of the technology (education, equipment demonstrations and side-by-side comparisons with conventional compaction techniques on real projects)
    c. To conduct needed research to clarify the advantages and appropriate uses of the technology
    d. To provide organizational support for the process of developing intelligent compaction technologies
    e. Ultimately, by adapting and improving existing intelligent compaction equipment and techniques, US utilization of the technology will be advanced to be the best in the world

1.5 Focus on Soil Modulus

This report focuses on soil Young's modulus as the soil parameter of interest. This focus is warranted, because Young's modulus is a critical input parameter in mechanistic-empirical design techniques. Continuous compaction control compactors report results as a modulus (or as a similar parameter). Many companion tests are available for demonstration purposes, or for quality assurance testing. Companion test results obtained during this demonstration were converted, where possible, to modulus values.

However, there are technical obstacles to address when using soil modulus. For example, Briaud (2001) points out that:

> *"The modulus of a soil is one of the most difficult soil parameters to estimate because it depends on so many factors. Therefore when one says for example: "The modulus of this soil is 10,000 kPa", one should immediately ask: "What are the conditions associated with this number?"*

Some of the factors upon which soil modulus depends, and which are pertinent for this demonstration, are:

1. Soil moisture content
2. Soil stress level
3. Stress history
4. Soil "age"

These dependencies mean that a soil modulus value measured by one method with characteristic size, stress level and depth of measurement may be different than the value measured by another method.

Refer to Sections 3.9.4 through 3.9.6 for an assessment of these dependencies for this demonstration project.

2 Demonstration Protocol

2.1 Site Description

2.1.1 Site Location

The continuous compaction control demonstration occurred at Mn/DOT's MnROAD facility. This facility:

> *is the world's largest and most comprehensive outdoor pavement laboratory, distinctive for its electronic sensor network embedded within six miles of test pavements. Located 40 miles northwest of Minneapolis/St. Paul, its design incorporates 4,572 electronic sensors. The sensor network and extensive data collection system provide opportunities to study how heavy commercial truck traffic and the annual freeze/thaw cycle affect pavement materials and designs.*
>
> *(*See www.mrr.dot.state.mn.us/research/MnROAD_Project/MnROADProject.asp)

The demonstration site at MnROAD was on the low volume road test loop, adjacent to test section 53, as illustrated in Figure 1. The test section was available for the CCC demonstration due to a planned reconstruction after a culvert pipe test, shown in Figure 2. Approximately 200 feet of the test loop was excavated about 7 or 8 feet deep and 25 feet wide, shown in Figure 3.

2.1.2 Materials

Four soils, shown in Figure 4, were used to construct the foundation of the road. A Mn/DOT classified loamy sand (Proctors 1 and 3), which was cut from the excavation and stockpiled onsite, was used for the lower fill material. Pockets of SP sand (Proctor 2) were sparsely scattered throughout the onsite material. Three inch minus railroad ballast (no Proctor) was used on top of this in an attempt to stiffen the fill. More loamy sand (Proctor 4) was brought in from offsite and placed over the railroad ballast. Then crushed granite (Proctor 5) was used for the aggregate base. The crushed granite met Mn/DOT class 6 gradation requirements. Material description is as follows:

Table 1—Material Description Summary

Proctor	ASTM Soil Classification	Mn/DOT Soil Classification	Max. Dry Density	Optimum Moisture Content
1	SM	SL	122.7 pcf	9.3%
2	SP	S	130.2 pcf	8.0%
3	SM	SL	119.2 pcf	11.0%
4	SM	SL	128.3 pcf	9.9%
5	GW-GM	Class 6	131.9 pcf	10.7%

See Appendix C for sieve analysis and Proctor test details.

2.1.3 Construction Sequence

After the pavement and existing test pipes were removed, the soil was excavated to a depth of roughly 7 to 8 feet. The bottom of the excavation was relatively wet due to a high water table and heavy rains the week before the demonstration. The first lift was placed and compacted with difficulty due to saturated material. This material was removed and replaced with dryer onsite material. Lifts 1, 3, 4 and 6 consisted of loamy sand. Lifts 3 and 5 consisted of railroad ballast, placed in an attempt to stiffen the lower fill material. Lifts 1 through 6 were placed with a dozer and compacted with the BOMAG on automatic mode with an E_{vib} target value of 45 MPa. However, the target value was not achieved because of the high moisture content of the loamy sand. Lifts 7 through 10 consisted of Mn/DOT class 6 and were compacted in automatic mode with an E_{vib} target value of 100 MPa. The target value was achieved on all but portions of lifts 7 and 8.

2.2 Continuous Compaction Control Machine

2.2.1 Technology Description

Continuous compaction control technology is based on measuring the stiffness of the compacted soil. Initiatives in both the U.S. and Europe, started more than 10 years ago, have demonstrated the technical viability of measuring in situ soil stiffness. Selected literature references are included later in this report.

Throughout this section, the term “soil stiffness” is used generically to represent the deformational properties of the soil, whether stiffness or modulus.

Continuous compaction control machines typically include the following:

1. Sensors to measure vibration of the drum
2. Onboard electronics to record and process sensor output, and record the stiffness
3. Linkages to the machine controls to adjust compaction effort according to the measured stiffness
4. Systems to record machine location
5. Either local storage or wireless communications systems for data transfer

Process control is achieved in real time as the compaction process proceeds. The stiffness of the material is measured continuously as the compactor moves along. If the material stiffness is below the target value, the compactor applies compactive effort to the soil. If the material stiffness is at or above the target value, the compactor changes drum vibration from vertical to horizontal and does not further compact the material.

Figure 5 illustrates the concept of compactor-based stiffness measurement.

2.2.2 BOMAG Compactor

The machine used for the demonstration was a BOMAG Model BW 213 DH-3 BVC, shown in Figure 6. Pertinent data about this model is in Table 2—BOMAG Machine Characteristics.

Table 2—BOMAG Machine Characteristics

Item	Value
Operating weight	14,660 kg
Axle load, drum	9,070 kg
Axle load, wheels	5,590 kg
Static linear load	42.6 kg/cm
Working drum width	2,130 mm
Track radius, inner	3,494 mm
Speeds	0-3,5 km/h 0-6,3 km/h 0-12,0 km/h
Performance ISO 3046	153 hp
Tire size	23.1/18-26/12 PR
Variocontrol	standard
Frequency	28 Hz
Amplitude directed (hor./vert.)	2,40 mm
Centrifugal force	1 365 kN

Figure 7 illustrates BOMAG Variocontrol technology for continuous compaction control.

2.2.3 CCC Process and Documentation

CCC technology has the following stages (refer to Figure 8):

1. Establish target modulus values for each soil material
2. Define the project on the desktop PC software
3. Transfer the project definition via PCMCIA memory card to the BCM device on the BOMAG compactor
4. During compaction, use the BCM device on the BOMAG compactor to control the compaction process and capture the measured soil stiffness.
5. Conduct companion QA tests

6. At the end of each day, transfer the project definition and measured soil stiffness values back to the desktop PC via the PCMCIA memory card.
7. Produce the surface covering stiffness documentation (in paper and electronic form)
8. Identify locations for QA testing
9. Perform QA testing at the rates specified in Schedule of Materials Control

2.3 Field Measurements

2.3.1 General Description

The subgrade and base were constructed using the materials described in Section 2.1.2, and the sequence described in Section 2.1.3. After each lift was delivered and spread, the BOMAG machine was used to compact the soil, using an E_{vib} target value of 45 MPa for the first six lifts and 100 MPa for the remaining four lifts. Because of poor site drainage and excessive rainfall, the target value was never achieved during recompaction of the natural soils and lower base layers.

After the appropriate number of passes in each lane, the BOMAG was moved to adjacent lanes and companion measurements were done.

2.3.2 CCC Machine Data

The BOMAG compactor records stiffness measurements as it compacts. These measurements can be printed to paper in the cab of the compactor or saved to a PCMCIA card using the BOMAG Compaction Management (BCM) system. Only one pass is printed at a time with onboard printer and measurements are not saved unless the BCM is used. The BCM is a system which logs the measurements every 10 cm and then allows the user to create reports of the data showing surface coverage and measured values. This data can be exported to a Microsoft Excel Data Interchange Format (*.DIF) file. All measurements from the demonstration are found in Appendix A.

2.3.3 Dynamic Cone Penetrometer

Dynamic Cone Penetrometer (DCP) measurements were performed according to ASTM D 6951-03. The DCP, shown in Figure 9, is a device that measures soil shear strength. It functions by striking a cone tipped rod with a freefalling weight, thereby driving the cone into the soil. The distance the cone penetrates is measured and the process is repeated until the desired depth is achieved. The recorded data is most commonly plotted as the number of blows divided by the penetration of the cone. This value is referred to as the DCP Penetration Index (DPI). The following correlation is used to determine the soil modulus from a DCP measurement:

$$\text{Log}(E_{DCP}) = 3.04785 - 1.06166\,(\log(\text{DPI})),\ \text{(DeBeer, 1991)}$$

where E_{DCP} is the effective elastic modulus.

2.3.4 GeoGauge

GeoGauge measurements were performed according to ASTM D 6758-02. The Humboldt GeoGauge, shown in Figure 9, was used to conduct companion tests. The 22-lb device directly measures the stiffness of a 4.5-inch outside diameter by 3.5-inch inside diameter plate (foot) resting on the soil surface. The stiffness is measured dynamically in the frequency range from 100 Hz to 200 Hz, and the average stiffness across the frequency range is reported to the user. Measurements may be taken about every 75 seconds if the device is not moved, and every few minutes if the device is moved to a new location nearby. The Young’s modulus of the soil may be calculated from the foot geometry and an assumed Poisson’s ratio.

Seating of the GeoGauge involves setting it on the test location and giving a slight twist. Twisting the GeoGauge is performed to ensure a minimum of 80% contact between the foot and the soil. Humboldt recommends using a small layer of sand when the 80% contact cannot be achieved. The field engineer determined that contact between the foot and soil was sufficient for all tests without the use of sand.

2.3.5 Loadman

The Loadman, shown in Figure 9, is a portable Light Weight Deflectometer (LWD), which can be used to measure in-situ material stiffness. The device consists of a closed aluminum tube with dimension approximately 5”x6”x47”. A mass freely falls from a known height inside the tube and impacts a plate at the lower end of the tube. Then the impact load and displacement are displayed. The LWD weighs about 40 lbs with approximately half of its weight being in the falling mass (22 lbs).

The following is the testing procedure:

1. Locate a relatively smooth and level spot for the test.
2. Remove the LWD from its case and turn it on.
3. Place the LWD on the testing location, then rotate it slightly to smooth out the contact surface.
4. A spoon or screwdriver may be used to mark the ground around the foot of the LWD to ensure the same spot for sequential tests.
5. Pick up the LWD and tip gently to allow the mass to slide slowly from the bottom of the tube to the top where it connects with a “click” to the magnet.
6. Place the LWD back on the marked circle from step 4.
7. Press the reset button.
8. Press the drop button to drop the mass. There is a few second delay from when the drop button is pressed to when the mass is released.
9. Record the load and displacement displayed.
10. Repeat steps 5 through 9 until five tests have been performed.
11. Turn the LWD off and place it back in the case.

The difference between the results from drops 3, 4 and 5 is quite small compared to the first two drops. The reason is that the LWD impacts the ground with a large force. This force compacts the loose soil near the surface and causes the deflection to decrease and load to increase from drop to drop. Normally, the deflection of the second drop was significantly less than that of the first. Therefore, the first two drops are considered seating drops similar to standard FWD procedure. During the testing, the LWD must be held steady and vertical. The operator should ensure that surface is even and smooth. The experience showed that, if the LWD was tipped during testing, the readings were not correct. In summary, the LWD is a simple device. See http://mnroad.dot.state.mn.us/research/DCP/LRRB_Study_Proposed_New_DCP_Spec.pdf.

2.3.6 Nuclear Density Gauge

Nuclear density testing was performed using Troxler 3430 nuclear density gauge, shown in Figure 9, according to ASTM D 2922. Four nuclear density tests were conducted at each test location. Testing proceeded as follows:

1. The first test was conducted.
2. Using the same hole from the first test, the gauge was rotated 90˚ and the second test was conducted.
3. This was repeated until four tests were conducted at a test location.

2.3.7 Plate Load Test

The small-scale plate load test used in this and other projects was developed by CNA Consulting Engineers to provide an alternative means to measure soil modulus. Using modern sensors and data acquisition equipment, CNA has been able to conduct meaningful plate load tests using readily portable equipment at force levels up to 500 lbs. As many in the past have found, measuring plate deflection at small loads is the most difficult aspect of field plate load tests. The test apparatus is able to resolve vertical deflections of about 0.0001 inch.

The plate load test field apparatus is illustrated in Figure 9. Either a plate foot or a ring foot (like the GeoGauge) may be used in contact with the soil. All testing for this demonstration project was performed using the ring foot identical to the GeoGauge. The concrete masonry units provide the reaction force, a wood 2x4 is the lever arm, a simple three-point frame provides a deformation reference, and the user provides the load while simultaneously monitoring the test on the laptop screen. Several load-unload cycles are applied: typically load to 100 lbs, unload to 50 lbs, reload to 200 lbs, unload to about 100 lbs, etc., up to 500 lbs.

Figure 10 illustrates a typical load-deflection curve obtained. As shown, the load is applied in several increments, separated by unload-reload cycles. Some hysteresis occurs during each unload-reload cycle. Several distinct stiffness values are apparent in the graph:

1. The initial loading stiffness—This stiffness occurs whenever the soil is subject to loads greater than previous values. In Figure 10, the initial loading stiffness does not significantly change with increasing load. For some soils and compactive efforts, the initial loading stiffness increases with increasing load, and in other cases it decreases.
2. Because there is hysteresis in the unload-reload cycles, there are many alternative stiffness values that may be defined.
3. The unloading stiffness—This stiffness occurs when the load is reduced. In Figure 10, the unloading stiffness was determined from the minimum load portion of the unloading curve.
4. The reloading stiffness—This stiffness occurs when the load is reapplied. In Figure 10, the loading stiffness was determined from the majority of the reloading curve.

Note that the unload or reload stiffness is typically 3 to 20 times greater than the initial loading stiffness.

2.3.8 Sand Cone Density

Sand cone density testing was conducted using standard equipment, according to ASTM D 1556.

2.3.9 Falling Weight Deflectometer

Falling Weight Deflectometer testing was conducted according to ASTM D 4694-96.

2.4 Laboratory Measurements

Appendix C lists results from all laboratory measurements conducted on the fill material. Measurements conducted are as follows:

1. Proctor tests were conducted according to ASTM D 698-91 Procedure A Standard.
2. Sieve analyses, were conducted according to ASTM D 2487.

3 Field Measurements and Analysis

3.1 Test Locations

Figures 11 and 12 illustrate the lane widths, number of lifts and lift thicknesses and materials used in constructing the demonstration embankment. The pertinent information includes:

1. The test section was approximately four compactor lanes wide at the bottom, and six lanes wide at the top. The transition from four to six lane widths occurred by overlapping compactor passes.
2. Nine lifts were placed, varying in uncompacted thickness from six inches to twelve inches.
3. The relationship between lifts and materials are illustrated in Figure 11.

3.2 CCC Machine Data

3.2.1 Documentation

Surface-covering documentation was collected for all lifts using the BOMAG compactor. For most lanes and lifts, surface-covering documentation was captured electronically via the PCMCIA card. However, selected lifts and lanes were captured only on paper strips from the compactor. Appendix A contains scanned images of all paper records. Figure A.1 (see Appendix A) is an index to the paper and digital records, with cross-references to the soil type, Proctor test number and test location.

All lifts were compacted in continuous compaction control mode (identified as automatic mode on the paper records) through the initial passes. When the target values were achieved, or because the soils were too moist to compact further, the machine was typically switched to manual mode for a final measurement pass.

For technical reasons that are not fully documented, the BOMAG compactor produces different values depending upon whether in the automatic or manual mode. The likely cause is variations in the vibration amplitude and frequency between the two modes. Understanding these variations is one of the principal recommendations of this report (see Section 5.1).

Figure 13 shows typical output from the BOMAG companion software BcmWin V1.9.1. This software is used to define the project site prior to construction, and to display and analyze surface-covering data during and after construction. Figure 14 shows exported data, which is easily plotted using the BcmWin software.

3.2.2 Target Values

Two target values were used for the demonstration, depending upon material type. The Class 6 material used for the base course was compacted to a target value of 100 MPa. All other soils were compacted using a target value of 45 MPa. Because of the excessive moisture content of many of the soils used in the demonstration, the target values were generally not achieved.

3.3 Companion Test Summary

Companion tests were conducted at 23 locations within the test area (refer to Figures 11,12 and 15). In general, the principal companion tests (DCP, GeoGauge, LWD, sand cone and nuclear density) were performed at all locations. Plate load tests were performed at only two locations. Table 3 summarizes the location and soil type for each companion test location.

Table 3—Companion Test Summary

Unique Location ID	Plan Location	Elevation	Lane	Lift	Proctor Test ID	ASTM Soil Class	Mn/DOT Soil Class
1	-	93.64	5	0	1	SM	SL
2	-	92.55	5	0	1	SM	SL
3	4	92.87	2	1	1	SM	SL
4	5	92.94	2	1	1	SM	SL
5	6	92.66	2	1	1 - 2	SM	SL
6	6	92.33	2	1	2	SP	S
7	4	93.96	2	3	3	SM	SL
8	6	93.96	2	3	1	SM	SL
9	3	93.73	5	3	1	SM	SL
10	1	93.72	5	3	1	SM	SL
11	4	96.81	2	6	4	SM	SL
12	5	96.45	2	6	4	SM	SL
13	6	96.24	2	6	4	SM	SL
14	1	96.09	6	6	4	SM	SL
15	2	96.01	6	6	4	SM	SL
16	3	96.00	6	6	4	SM	SL
17	4	97.87	2	8	5	GW-GM	Class 6
18	5	97.77	2	8	5	GW-GM	Class 6
19	6	97.77	2	8	5	GW-GM	Class 6
20	1	97.35	5	8	5	GW-GM	Class 6
21	2	97.32	5	8	5	GW-GM	Class 6
22	-	97.45	5	8	5	GW-GM	Class 6
23	-	97.45	5	8	5	GW-GM	Class 6

Table 4 summarizes the testing by soil type and test method. Most testing was performed on lifts classified as Mn/DOT SL (ASTM SM).

Table 4—Summary of Testing by Soil Type

Test	Soil Type					
	ASTM SM (SL) P1	ASTM SP (S) P2	ASTM SM (SL) P3	ASTM SM (SL) P4	ASTM GW-GM (Class 6) P5	Total
BOMAG-paper	8	1	1	6	7	23
BOMAG-electronic	6	1	1	0	0	8
Loadman (LWD)	8	1	1	6	7	23
Prima (LWD)	0	0	0	0	4	4
GeoGauge	8	1	1	6	7	23
Plate Load	0	0	0	0	2	2
DCP	8	1	1	6	7	23
Nuclear Density	8	1	1	6	7	23
Sand Cone Density	2	1	1	2	2	8
Proctor	1	1	1	1	1	5
Sieve Analysis	1	1	1	0	1	4

3.4 Dynamic Cone Penetrometer

3.4.1 DCP Data Summary

Table 5 summarizes the Dynamic Cone Penetrometer (DCP) testing done during the demonstration. One DCP test was conducted at each of the 23 test locations. Drive depths ranges from about 0.3 feet to 1.4 feet—variations depended upon the materials and the DCP Penetration Index (DPI). Data reduction followed the procedures described in Section 2.3.3.

Statistical summaries of the DCP data, and comparisons with other companion tests, are in Section 3.9 Comparisons and Correlations.

Table 5—Summary of Dynamic Cone Penetrometer Testing

Location	DPI top 4 in	DPI top 5 in	DPI top 6 in	DPI GG Weight Func	E_{dcp} 4"	E_{dcp} 5"	E_{dcp} 6"	E_{dcp} GG W Func	DPI	E_{dcp}	DCP First Layer	DCP Second Layer	DCP Wtd Ave.
1	43	45	44	38	21	20	**20**	24	32	28	20	41	26
2	50	48	46	47	17	18	**19**	19	36	25	23	23	23
3	47	44	38	33	19	20	**23**	27	33	27	20	103	22
4	28	28	28	25	33	33	**33**	37	22	42	33	106	38
5	28	25	23	24	32	36	**40**	39	25	37	30	101	57
6	11	11	10	11	85	90	**96**	88	14	68	101	101	101
7	121	119	113	104	7	7	**7**	8	58	15	11	11	11
8	90	99	105	87	9	8	**8**	10	118	7	8	8	8
9	51	52	53	49	17	17	**17**	18	57	15	15	15	15
10	52	46	41	38	17	19	**22**	24	37	24	20	20	20
11	25	24	21	25	36	39	**43**	36	11	87	39	88	51
12	19	18	18	19	48	50	**53**	49	15	63	38	66	56
13	20	19	18	17	46	49	**52**	56	16	59	55	119	58
14	26	25	23	26	35	37	**41**	35	13	73	26	80	53
15	14	13	13	13	69	73	**75**	72	11	87	89	89	89
16	15	15	14	14	62	64	**68**	69	12	80	81	81	81
17	9	na	na	9	105	na	**na**	109	10	97	80	106	102
18	31	27	25	26	29	33	**37**	36	19	49	30	89	43
19	30	27	25	27	31	33	**37**	34	18	52	31	70	43
20	35	32	29	31	26	28	**31**	29	18	52	27	73	38
21	27	24	22	23	34	39	**43**	39	15	63	34	93	50
22	23	20	19	21	41	45	**49**	43	12	80	41	100	68
23	21	19	18	21	44	48	**52**	45	12	80	37	94	70

Figure 16 illustrates the variation in soil modulus, computed using the DCP, as a function of soil type and depth. Like most DCP data from stress dependent unbound materials, the results from this demonstration show strength increase with depth. Modulus values at 1 foot below surface are typically two to four times the values from the first, near-surface blow. The data seems to naturally divide into three groups: below, between and above two heavy lines shown in Figure 16. Below the lower line, modulus values are generally less than 50 MPa and the soils are SM (SL) from Proctor tests 1 and 3. Between the heavy lines, modulus values are between 25 and 75 MPa at the surface and increase to 100 to 200 MPa. These soils are generally SP (S), SM (SL), and Class 6 (Proctor tests 2, 4 and 5 respectively). Above the top heavy line is a single DCP on Class 6, that was about 100 MPa near the surface.

3.4.2 DCP Modulus Values as a Function of Depth Limit

The DCP is the sole device used in the demonstration that provides a modulus profile with depth. (Of course, the portable devices may be used to obtain a profile by excavating down and testing of the new surface.) Measuring the modulus profile is a benefit of the DCP, but makes comparison with other methods more difficult.

The difficulty of comparing DCP results to other methods is compounded by the depth (i.e. stress) dependence of modulus (see the preceding section). The methods that measure soil modulus from surface contact (BOMAG, LWD, GeoGauge, Plate load) produce a composite modulus that is a complex function of the loading geometry and soil properties. In this analysis, several methods were used to calculate a single DCP modulus from the measured profile:

1. Weighted average (of drive length) with a cutoff at depth limits of 4, 5 and 6 inches
2. Weighted average corresponding to the approximate weighting of the GeoGauge
3. Weighted average based on soil layers.

None of the methods substantially improved the correlations with other types of measurements. Figure 17 illustrates the influence of depth limit on DCP modulus values. The results presented below and the comparison sections are for a weighted average to a depth limit of 6 inches. This column is bold in Table 5.

3.5 GeoGauge

Two, 3 or 4 Geogauge measurements were taken at each companion test location. The number of GeoGauge measurements depended upon the repeatability of the data. Additional measurements were taken if initial readings were variable. Table 6 summarizes the individual and average test results.

Statistical summaries of the GeoGauge data, and comparisons with other companion tests, are in Section 3.9 Comparisons and Correlations.

Table 6—Summary of GeoGauge Modulus Data

Location	E Geo 1	E Geo 2	E Geo 3	E Geo 4	E Geo Avg (Mpa)
1	79	82	-	-	81
2	62	63	-	-	62
3	83	76	79	-	79
4	19	30	31	-	30
5	49	40	48	50	49
6	72	69	72	-	71
7	37	38	-	-	38
8	50	51	-	-	50
9	45	47	47	-	46
10	54	59	60	-	58
11	90	90	-	-	90
12	120	121	-	-	120
13	101	102	-	-	102
14	89	77	87	-	84
15	103	111	118	-	111
16	98	101	100	-	100
17	69	69	-	-	69
18	43	44	-	-	43
19	59	60	60	-	60
20	51	49	-	-	50
21	55	48	52	-	52
22	45	45	-	-	45
23	50	47	51	-	49

Tests from location 4, test 1 and location 5, test 2 were excluded from the average due to a perceived influence on the GeoGauge measurement from pounding the nuclear density gauge rod into the ground while conducting the measurement.

3.6 Light Weight Deflectometer

Table 7 summarizes the LWD modulus data collected during the demonstration test. Refer to Section 2.3.5 for a description of the methodology used to calibrate the Loadman and calculate the modulus value for each test.

Statistical summaries of the Loadman data, and comparisons with other companion tests, are in Section 3.9 Comparisons and Correlations.

Table 7—Summary of Loadman (LWD) Modulus Data

Location	E LWD (Mpa)	Location	E LWD (Mpa)
1	22	13	42
2	8	14	35
3	8	15	77
4	14	16	68
5	76	17	80
6	133	18	42
7	48	19	35
8	49	20	79
9	64	21	115
10	66	22	91
11	37	23	56
12	44		

3.7 Nuclear Density and Sand Cone Density

A nuclear density gauge was used to measure dry density and moisture content at all test locations. Sand cone equipment was used to measure the same parameters at selected locations. Table 8 summarized the dry density measurements and Table 9 summarizes moisture content results.

Table 8—Summary of Dry Densities Measured at Test Locations

Location	Dry Density Nuclear (North) (pcf)	Dry Density Nuclear (East) (pcf)	Dry Density Nuclear (South) (pcf)	Dry Density Nuclear (West) (pcf)	Dry Density Nuclear Avg (pcf)	Dry Density Sand Cone (pcf)
1	117.9	112.5	116.4	116.6	115.9	120.4
2	117.6	120.4	119.6	117	118.7	-
3	131	124	120.5	120.9	124.1	-
4	125	124.7	123	124.8	124.4	-
5	132.2	130.6	128.4	134.6	131.5	136.8
6	-	-	-	128.6	128.6	124.3
7	118.8	119.8	118.6	117.5	118.7	121.9
8	117.8	117	119.1	118.2	118.0	-
9	123.3	122.2	121.3	123.5	122.6	-
10	128.1	128.6	125.3	128.5	127.6	-
11	127.2	125.6	129.8	126	127.2	128.1
12	127.1	126.2	127.8	127.3	127.1	-
13	127.5	128	127.2	125.8	127.1	-
14	126.4	128.9	128.3	125.5	127.3	-
15	129.1	127.9	131	131.1	129.8	131.9
16	128.2	127.6	130.6	129.8	129.1	-
17	129.5	126.2	128.1	128.5	128.1	-
18	119.6	120.7	120.1	118.9	119.8	-
19	134.7	135.2	136	132.7	134.7	-
20	133	134.7	134.9	133.2	134.0	-
21	131.9	134.4	134.5	130.1	132.7	-
22	131.7	131.3	133.6	134	132.7	140.6
23	133.5	134.3	134.1	130.8	133.2	144.2

Figure 18 compares sand cone and nuclear density test results. For densities above about 135 pcf, the sand cone values are significantly less than the nuclear densities. While evaluating this difference in beyond the scope of this study, the cause is likely the presence of large rock fragments in the soil.

Table 9—Summary of Moisture Content Measurements at Test Locations

Location	Moisture Content Nuclear (North) (%)	Moisture Content Nuclear (East) (%)	Moisture Content Nuclear (South) (%)	Moisture Content Nuclear (West) (%)	Moisture Content Sand Cone (%)
1	13.7	11.5	13.4	12.1	13
2	12.8	11.9	12.2	12	-
3	12.4	13.7	14.1	14.2	-
4	12.9	12.7	13.7	13.9	-
5	6.5	6.5	7.6	6.1	6
6	-	-	-	6.5	7.1
7	13.7	14	13.4	14.4	14.4
8	14.1	14.6	13.1	13.7	-
9	11	10.8	11.9	11.1	-
10	11.4	11.1	12.3	11.4	-
11	7.3	7.5	6.9	6.9	7.5
12	8	7.8	7.6	7.8	-
13	7.2	7.4	7.7	7.5	-
14	7.9	7.2	7.2	7.6	-
15	7.3	7.5	7	7.1	7.9
16	8.1	7.9	7.6	7.7	-
17	4.2	4.7	4.5	4.2	-
18	4.4	4.7	4.4	4.3	-
19	2.8	2.9	2.8	3	-
20	2.9	2.7	2.8	2.7	-
21	3	2.8	2.9	3.1	-
22	3.2	3.3	2.8	2.9	4.1
23	5.1	5	4.9	4.7	4.5

3.8 Plate Load Tests

Plate load tests were conducted at test locations 22 and 23—the results are shown in Table 10. As explained in Section 2.3.7, the plate load tests include several unload-reload cycles up to a total load of about 500 lbs. Hence, each test produces several modulus values. For this report, the modulus values reported in the tables and graphs are for the reload portion of each unload-reload cycle. Figure 19 illustrates the distribution of modulus values for each test location, and includes the equivalent normal distribution curve.

Table 10—Plate Load Modulus Data for All Reload Cycles

Location	Test	Load-Unload Curve	Average Load (N)	Modulus (MPa)	Location Average Modulus (MPa)	Average Stress (kPa)
22	A	1	459	123	125	113
22	A	2	817	97		202
22	A	3	1139	122		281
22	A	4	1525	158		376
22	A	5	1940	223		478
22	B	1	451	62		111
22	B	2	937	93		231
22	B	3	1353	131		334
22	B	4	1891	186		467
22	C	1	526	79		130
22	C	2	1071	98		264
23	A	1	546	112	144	135
23	A	2	896	158		221
23	A	3	1353	198		334
23	B	1	538	112		133
23	B	2	929	132		229
23	B	3	1429	175		352
23	C	1	566	91		140
23	C	2	968	122		239
23	C	3	1322	197		326

3.9 Comparisons and Correlations

3.9.1 Modulus Data for the Four Principal Test Methods

Table 11 provides the average, standard deviation, coefficient of variation, minimum value, maximum value and number of measurements for the four principal test methods. The BOMAG, LWD and GeoGauge data sets had 23 modulus values, and DCP data set had 22 modulus values. The table groups all soil types and compactive efforts.

Table 11—Statistical Measures for the Four Principal Test Methods (Normal Distribution)

Method	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation	Minimum (MPa)	Maximum (MPa)	Count
BOMAG Compactor	46.6	42.3	91 %	4.0	130.0	23
LWD	56.0	31.8	57 %	7.5	132.9	23
GeoGauge	67.0	24.8	37 %	30.3	120.4	23
DCP (top 6 inches)	39.3	21.7	55 %	7.4	96.0	22

Figure 20 compares the histograms for the four test methods. The plots include the equivalent normal distribution for comparison with the actual histograms. Although no statistical tests were conducted, a normal distribution seems to fit the LWD and GeoGauge data fairly well. In contrast, the BOMAG and DCP data seem to be truncated on the left or low modulus side, and skewed to the right or high modulus side. Hence, the statistical values listed in Table 11 may not fairly represent the data for the BOMAG and DCP tests.

Table 12—Statistical Measures for the Four Principal Methods (Lognormal Distribution)

Method	Average (MPa)	Standard Deviation (MPa)	Coefficient of Variation
BOMAG Compactor	28.3	3.0	11%
LWD	45.4	2.1	5%
GeoGauge	62.9	1.4	2%
DCP (top 6 inches)	33.1	1.9	6%

Table 12 lists the statistical measures for lognormal distributions, and Figure 21 shows the histograms and lognormal distributions. The lognormal distributions seem to match all data fairly well.

The histograms and statistical measures all indicate that the modulus values from the four methods are different. The BOMAG data has a wider range and is clustered toward lower values. GeoGauge data tends to be larger than the other methods, while the LWD and DCP data is intermediate between the BOMAG and GeoGauge.

3.9.2 Correlations Between BOMAG Data and Companion Tests

Figure 22 illustrates the relationships between BOMAG data and the other tests on a point by point basis. The upper left graphs shows all data, and the other three are BOMAG vs. LWD, BOMAG vs. GeoGauge and BOMAG vs. DCP, respectively. The graphs show little correlation between the BOMAG data and the other test methods. There are several reasons for this result:

1. The depth and stress dependency of soil modulus. Depth and stress dependency is addressed in Section 3.9.4.
2. The heterogeneity of the soils used precludes correlations. Soil heterogeneity may affect correlations because the BOMAG senses the properties of a large volume of soil, while the companion tests are clustered near the surface in a small area in the middle of the drum.

3.9.3 Correlations Between Companion Tests

Correlations between companion tests were also investigated. Figure 23 shows correlations between the GeoGauge, and BOMAG, LWD and DCP. The correlation coefficients are small, except for the GeoGauge-DCP plot in the lower right of the figure. In this graph, two outliers (high DCP for GeoGauge values of about 70 MPa) have been removed. There are technical justifications for removing these outliers.

1. The first outlier is on a thin layer of soil over compacted railroad ballast.
2. The second outlier is on a small pocket of SP soil under about 4 inches of SM soil. In the later test, the overlying SM soil was removed prior to testing.

After removal of the outliers, there is a moderate correlation between the GeoGauge and DCP.

Figure 24 shows correlations between the DCP, and the BOMAG, LWD and GeoGauge. The correlation coefficients are small for the BOMAG and GeoGauge (with outliers, lower left). There is moderate correlation for the LWD and GeoGauge (without outliers, lower right).

3.9.4 Influence of Stress on Soil Modulus

Soil modulus is commonly recognized to be dependent upon the mean stress level and the deviator stress. Because soil stresses increase with depth, soil modulus also increases with depth. This depth dependence influences the relationships between different test methods used in this demonstration project.

Because the plate load test is conducted at varying load levels, the stress dependence of the soil modulus may be inferred from the test results. Figure 25 shows the load-displacement data for one of the plate load tests conducted at location 22. The figure clearly shows that the slope of the unload-reload load-displacement data increases with increasing load. The data for all plate load tests is in Table 10.

Figures 26 and 27 show the data from Table 10, plotted as a function of the vertical stress. The graph distinguishes between the three separate plate load tests conducted at each location. For both location 22 and location 23, there is a good correlation between stress and modulus for the plate load tests. The slopes are about 325 kPa / kPa and 410 kPa / kPa, for locations 22 and 23 respectively.

The graphs also include single data points for the GeoGauge and LWD tests, a range for the BOMAG compactor, and data points for the FWD tests, which were conducted after compaction of the top lift was complete. The range of stress levels for the BOMAG is necessary because of the variable contact area of the compactor drum. Contact widths of 6 inches to 18 inches, and a drum axle static weight of 15,300 lbs were used to calculate the range of average stresses. The peak stress from the LWD and FWD analysis was used.

Data from the GeoGauge, LWD and BOMAG methods are consistent with the modulus-stress correlation from the plate load test. Note that the GeoGauge imparts the lowest stress, and that the LWD and BOMAG have stresses equivalent to the lower unload-reload cycles of the plate load test.

3.9.5 Influence of Moisture Content

Figure 28 compares inplace moisture content to the optimum moisture content. Five Proctor tests were performed on the soils compacted during the demonstration (refer to Section 2.1.2 Materials). Optimum moisture contents ranged from about 9 percent to 11 percent.

Three soils comprising 8 of 23 test locations were placed, compacted and tested at moisture contents from 2 percent to 5 percent greater than optimum. Seven of eight of the test locations were in SM soils. Most of the remaining test locations were SP (one Proctor) and Class 6 (one Proctor). These granular materials were generally 2 percent to 7 percent dry of optimum moisture content.

Despite the high moisture contents in the SM soils, the relative compaction results generally meet minimum compaction requirements of 95% standard Proctor, as shown in Figure 29. However, this is no guarantee for adequate stiffness.

Figure 30 shows the modulus values measured by the four principal methods, as a function of difference between actual and optimum moisture content. The different soil types are indicated by different symbols. Note that the compactive effort may be different for each test location. Nevertheless, the GeoGauge and DCP modulus values show the trend of moisture content dependence expected for unbound materials. This dependence is similar in form to Proctor curves, with greater values occurring near optimum, and smaller values for moisture contents both wet and dry of optimum.

3.9.6 Other Factors Influencing Modulus Measurements

Figure 31 is a composite section of test results at plan location 6, tests 5, 6, 8, 13 and 19. Different soils in the section are indicated by different colors in the chart background, and a horizontal white bar indicates the top of each lift. A vertical bar drawn from the top of the lift to the approximate depth of measurement represents E_{vib}, GeoGauge, LWD tests. DCP results are drawn at the center of the depth interval of each blow. The graph clearly shows the depth dependence of the test methods.

Table 13 compares the sensing depth, soil volume and stress level of the five test methods. Each of these test characteristics influences the soil modulus measured by the test methods:

1. Sensing depth—Test methods that sense deeper will be influenced by the (likely) greater compaction and higher stress level of deeper soils. Hence, BOMAG compactors should in general measure greater modulus than the other methods. However, a soft layer underlying a stiffer layer would lower the overall stiffness measured by the BOMAG. In that case the other test methods would show higher stiffness measurements.
2. Soil heterogeneity—Soil properties are heterogeneous at the scale of the volumes sensed by the test methods. These heterogeneities present within the volume sensed by a particular method are averaged out. However, there is a 500-fold variation in the volume sensed. Hence, methods that sense a smaller volume should be more variable than methods that sense a greater volume.
3. Vertical stress level—There is a three to ten fold variation in vertical stress level between methods. Based on the data described in Section 3.9.6, there should be a two to three fold effect on soil modulus.

Table 13—Approximate Characteristics of the Testing Methods

Test	Approximate Sensing Depth	Approximate Sensing Area	Approximate Soil Volume Sensed	Approximate Vertical Stress Level
BOMAG compactor	2-4 ft	500 – 1500 sq in	20 cu ft	70-210 kPa
LWD	0.5-1 ft	50.3 sq in	0.1 cu ft	100 kPa
GeoGauge	0.5-1 ft	6.28 sq in	0.1 cu ft	25 kPa
Dynamic cone penetrometer	Up to 2 ft	0.49 sq in	0.04 cu ft	na
Plate load test	0.5-1 ft	6.28 sq in	0.1 cu ft	100-500 kPa

3.9.7 Identification of Potential Problem Areas

The surface-covering documentation provided by the BOMAG compactor used for the demonstration is effective in identifying the location of potential compaction problem areas. The extensive documentation of the nature of the subgrade provided by CCC technology is in stark contrast to standard earthwork QC/QA practice, where sampling and testing rates may be only 1:100,000 to 1:1,000,000 on a volume basis (see White, et al, 2005). The effective sampling rate for surface covering documentation is 1:1.

Figure A.3 (see Appendix A) is a good example. This figure is for lanes 2 through 5 for lift 1B. The third strip from the left, for lane 3, shows two zones (5 meters and 20 meters from the start of the trace) where is less than 25 MPa. In comparison, most of the center of the strip, more than 10 meters long, has a modulus of greater than 100 MPa.

Note that at 22 of 23 test locations the compacted density was greater than 95 percent standard Proctor density. In the absence of surface-covering documentation and companion tests, the subgrade and base would have been accepted. Because of the additional documentation and testing, the real, observed non-uniform nature of the compacted materials was revealed. CCC provides a far superior quantitative measure of uniformity compared to existing standard QC/QA practice that utilizes point tests.

3.10 Other Experience

The BOMAG compactor used in this demonstration was in Minnesota for several months, and was used to conduct other demonstrations. These other demonstrations were conducted without the constraints of specific calendar dates, and the soils were compacted under more desirable moisture conditions.

The soils were generally more granular than used in this demonstration. While the data from these other demonstrations is proprietary, the general nature of the results is not. It was found that the machine:

1. Was affective at compacting soils up to the target value, without overcompaction
2. Produced surface-covering documentation using solely the paper strips (although the digital data is preferred)
3. Identified and recompacted a trench cut without overcompacting adjacent undisturbed soils

4 Conclusions

4.1 Conclusions Related to the Site, Materials and Procedures

1. The MNROAD facility provides substantial resources that facilitate demonstration projects.
2. Pre-demonstration weather conditions, specifically heavy rainfall, impacted the demonstration by raising the moisture content of the test soils.
3. The scattered funding sources and limited budget impacted the demonstration in several ways:
    a. The soils came from several sources and were heterogeneous.
    b. Soil placement was irregular.
    c. The schedule was short and fixed, which did not allow time to reduce the moisture content.
    d. There was no equipment available to work the soil to reduce the moisture content.
4. In order to better achieve the demonstration objectives, the demonstration should have been conducted with under better conditions. The demonstration was conducted under conditions near the limit of normal construction practice. No compaction technology performs well under such conditions.
5. Overall procedures and coordination were excellent, except as noted in the following section.

4.2 Conclusions from Experience with BOMAG Compactor

1. The BOMAG compactor appears to be well made, rugged and easy to operate (both the traditional controls and the Vario controls and data storage).
2. Data transfer between the compactor and the office computer is functional, but could be made more seamless.
3. The BOMAG companion software BcmWin is functional, but better suited to large-scale production projects than smaller-scale demonstration projects.
4. The BOMAG compactor measures and reports different E_{vib} values depending upon the use of automatic (Variocontrol) or manual (fixed compactive effort) modes.
5. The objectives of the demonstration may have been better achieved if BOMAG modulus data had been retained for every pass. In particular, few of the data sets from automatic (Variocontrol) mode were saved.

4.3 Conclusions from Companion Testing

1. As expected from existing research and experience, different measurement tools produce different modulus values
2. Relatively good correlations were obtained between E_{dcp} and E_{gg}
3. A strong relationship between modulus and average contact stress was found for all devices that load the soil surface

4. Moisture content was found to affect both the compaction process and the measurement of soil modulus
5. Moisture content versus soil modulus relationships similar to those commonly observed for moisture content versus density were observed.

4.4 Conclusions from Observation of Continuous Compaction Control

1. Continuous compaction control is an effective QC mechanism for soil compaction.
2. Surface-covering documentation adds value.

5 Recommendations

5.1 Recommendations Specific to the Demonstration

1. Research and implementation activities for continuous compaction control should be continued
2. Future research and construction projects should initially be done with more uniform soils and moisture contents
3. Demonstrations on actual trunk highway construction projects should be performed

5.2 Recommendations Regarding Geotechnical Data Management

The information collected by a CCC compactor is an invaluable resource, which may be used throughout the life cycle of the roadway.

1. Develop an initiative that involves the related aspects of machine control (including global positioning), pavement management and pavement design.
   a. Encourage machine manufacturers to implement GPS-based location documentation
   b. Encourage companion test equipment manufacturers to also implement GPS-based location documentation
   c. Develop and implement geotechnical data management standards and practices, so the valuable field data may be maintained and used throughout Mn/DOT. See for example the papers presented in the Geotechnical Database Management System session at TRB 2005.
   d. Integrate CCC documentation into the pavement management and pavement design processes

5.3 Recommendations Regarding Implementation of Continuous Compaction Control

5.3.1 General

1. Maintain flexibility regarding specific equipment for compaction and companion testing
2. Modify current compaction control, QC and QA practice when surface covering documentation is used.

5.3.2 Develop an Integrated Research and Implementation Program

The research and implementation program should evaluate continuous compaction control as a means for compaction of unbound materials in Minnesota roadway construction. The following key questions should addressed:

1. Do compactors equipped with CCC reliably measure the modulus (or a related parameter) of the unbound materials?
2. Are the measured values independent of machine model and manufacturer, or at least correlated?
3. Is CCC an acceptable Quality Control procedure?

4. What Quality Assurance procedures are necessary or appropriate when CCC is used?
5. Do the unbound materials commonly used in Minnesota roadway construction represent any special problems in the application of CCC?
6. How should target values be established and confirmed?
7. What Special Provisions or Standard Specifications are necessary for CCC?

5.3.3 Top Research and Implementation Priorities

1. Reliability of establishing target values, achieving the target values via CCC and confirming the results with QA tests
2. Benefits of CCC in uniformity
3. Identify any special cases or problems with commonly used Minnesota materials (difficult to compact, poor relationships between CCC and companion tests, materials that achieve modulus but not density, flat or decreasing modulus with additional passes)
4. Develop draft specifications
5. Investigate the modulus—density—moisture—compactive effort relationships

5.3.4 Strawman Research and Implementation Plan

1. Determine five (consider if this number is appropriate) most commonly used types of unbound materials used for Minnesota roadway construction
    a. Possible types include: one or two kinds of Select Granular Borrow, one or two kinds of base (e.g. Class 5 or Class 6), one or two kinds of natural soil, maybe more cohesive
    b. Establish target modulus values based on current Mn/DOT ME design procedures, and past history of modulus testing the lab and field
    c. Identify projects/locations/sources in the state for these commonly used materials
    d. At least one of the projects or locations will be in a controlled environment (e.g. an aggregate pit or similar) not subject to the limitation of construction schedules and similar factors
2. Conduct side-by-side field tests of two CCC equipped compactors, and a traditional compactor (without CCC)
    a. Describe here the protocol for these field tests, probably taken from the MnROAD demo description
    b. Include the relative size of each field test (cubic yards, number of companion tests, etc.)
3. At the same two sites, instrument the CCC machines to (write an objective)
4. At two sites, instrument the subsurface layers to determine the effects of CCC
5. Establish the relationship, if any, for the five unbound materials, between laboratory properties, design modulus, CCC modulus and modulus from companion tests
    a. Document the relationships
    b. Document the uniformity, compare and contrast the uniformity differences between CCC-equipped and traditional compactors
6. If CCC continues to be suitable for use on Minnesota roadway projects, prepare draft protocols and specifications:
    a. For establishing target values
    b. Conducting CCC and its acceptance for Quality Control
    c. Submittal of CCC records
    d. The Quality Assurance testing appropriate for verifying the CCC

7. Document the findings:
    a. Selection of the most commonly used types of unbound materials used for Minnesota roadway construction
    b. Establishment of target modulus values
    c. Results of side-by-side field tests
    d. Results from instrumentation of the subsurface layers and the CCC machines
    e. The relationships determined for the five unbound materials, between laboratory properties, design modulus, CCC modulus and modulus from companion tests
    f. Draft protocols and specifications for CCC

5.3.5 Critical Research and Implementation Issues

1. Establish funding versus priority relationships
2. Establish how many sites and materials to test, and whether under controlled or uncontrolled conditions.
3. Identify and mobilize funding sources and industry partners
    a. FHWA Experimental Features Initiative
    b. Other state DOTs via a pooled fund study
    c. Individual local contractors
    d. Associated General Contractors
    e. Compactor manufacturer(s)
4. Integrate this program with local and national research and implementation initiatives

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Figures

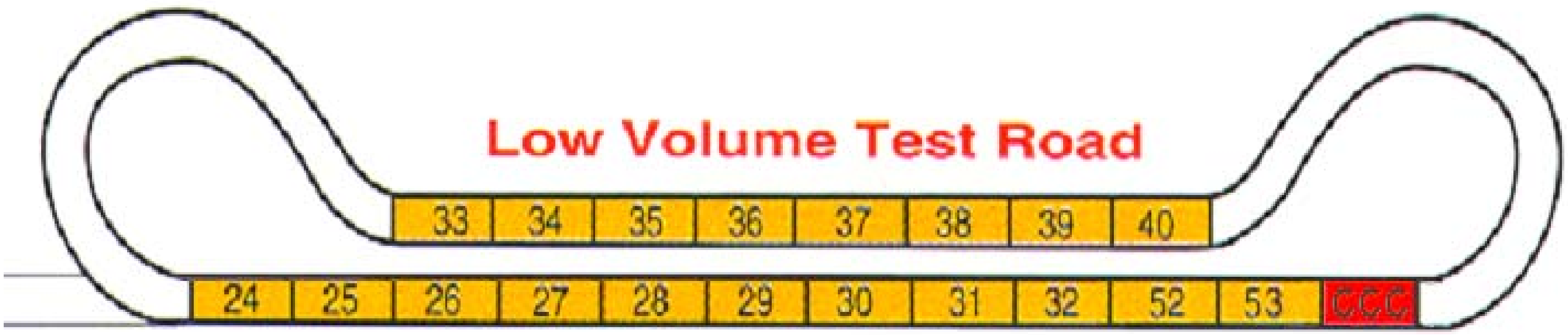


Figure 1

Demonstration Test Location at the MnROAD Site

Figure 2

Test Section Prior to Excavation

Figure 3

Partially Excavated Test Section

Railroad Ballast

Offsite Loamy Sand over Railroad Ballast

Onsite Loamy Sand

Mn/DOT Class 6

Figure 4

Four Soils Used in the Demonstration

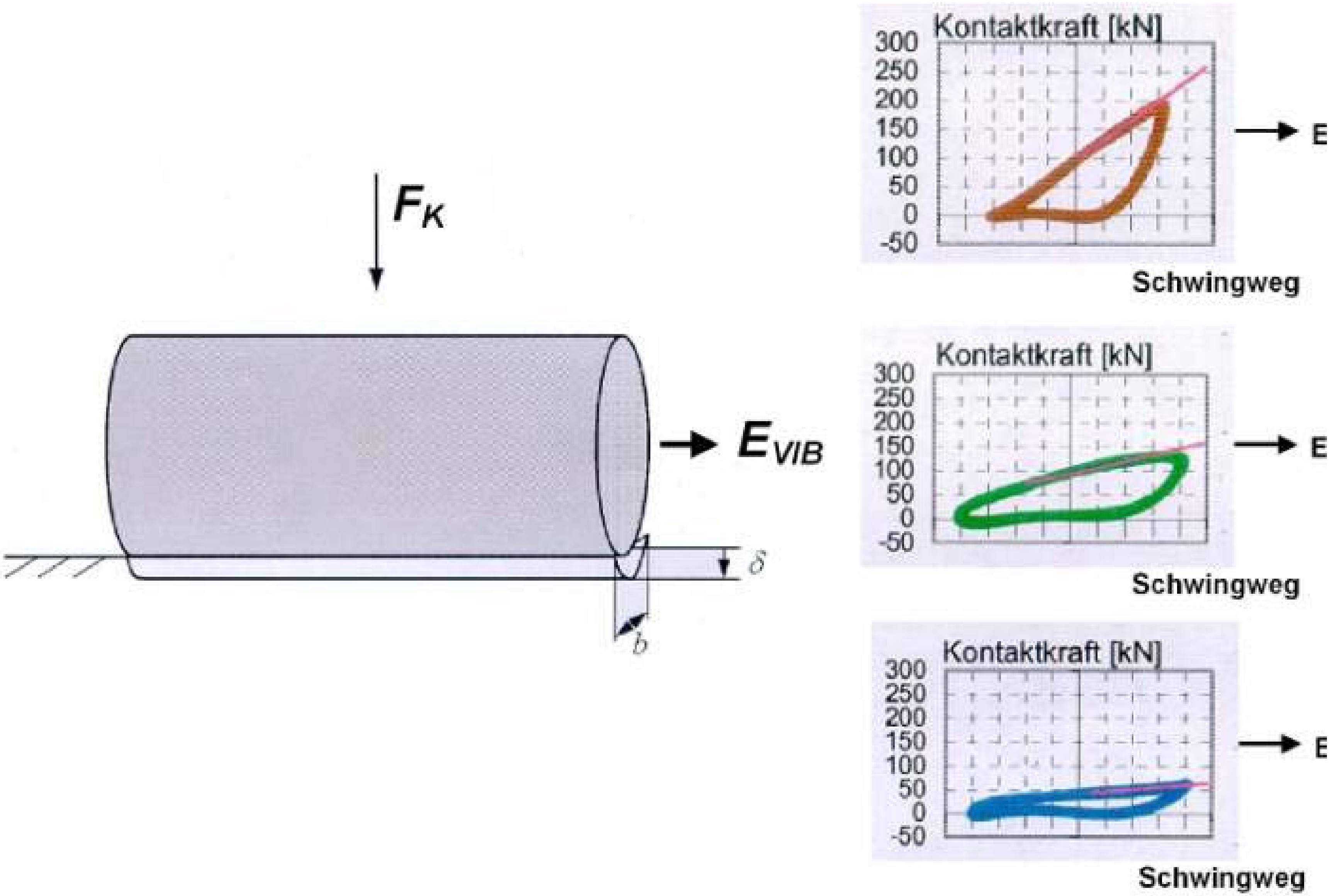


Figure 5

Concept of Stiffness and Modulus Determination from a Compactor Drum Vibration

Figure 6

BOMAG Compactor Used in the Demonstration

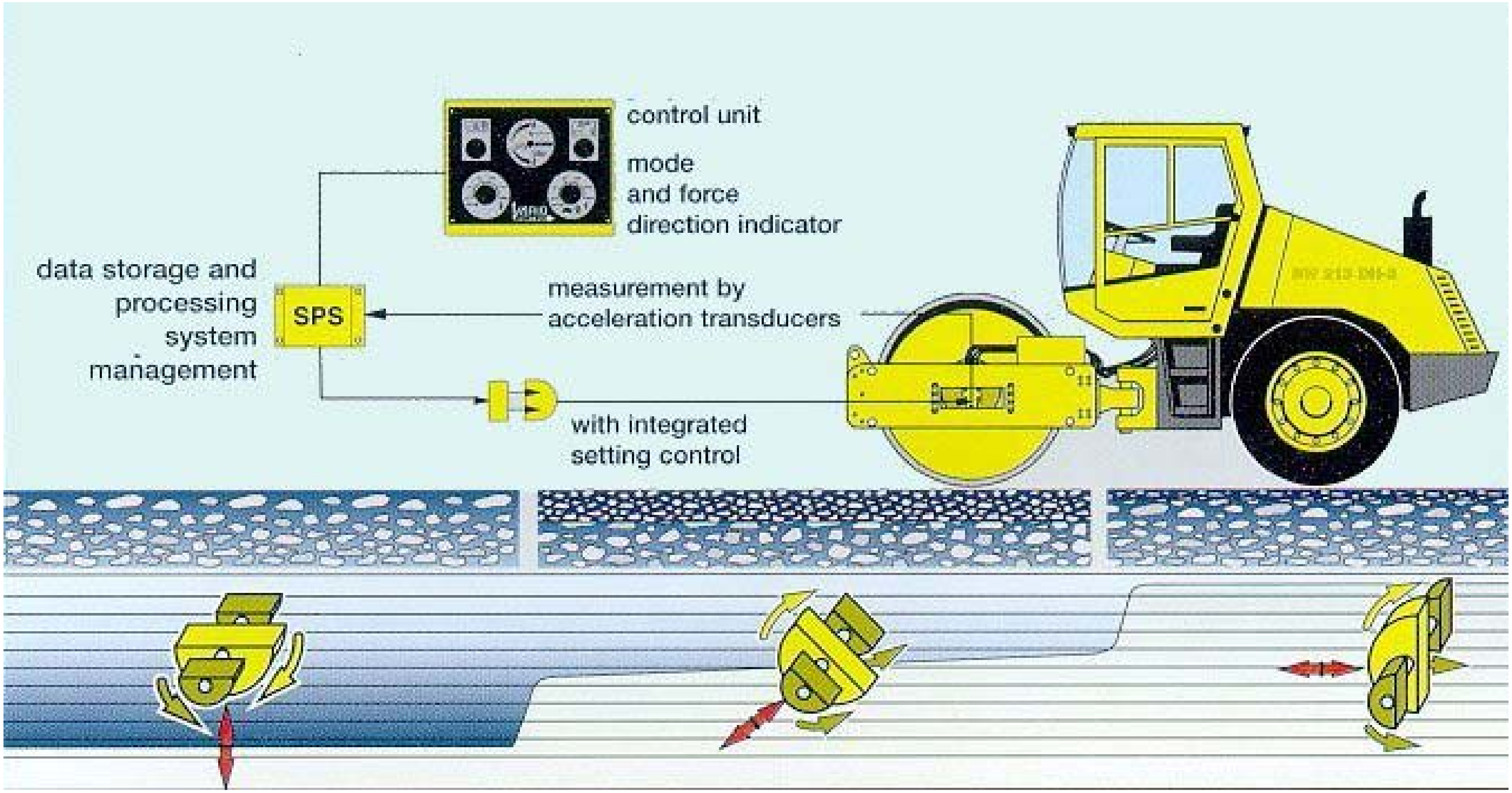


Figure 7

Schematic of BOMAG Variocontrol Technology for Continuous Compaction Control

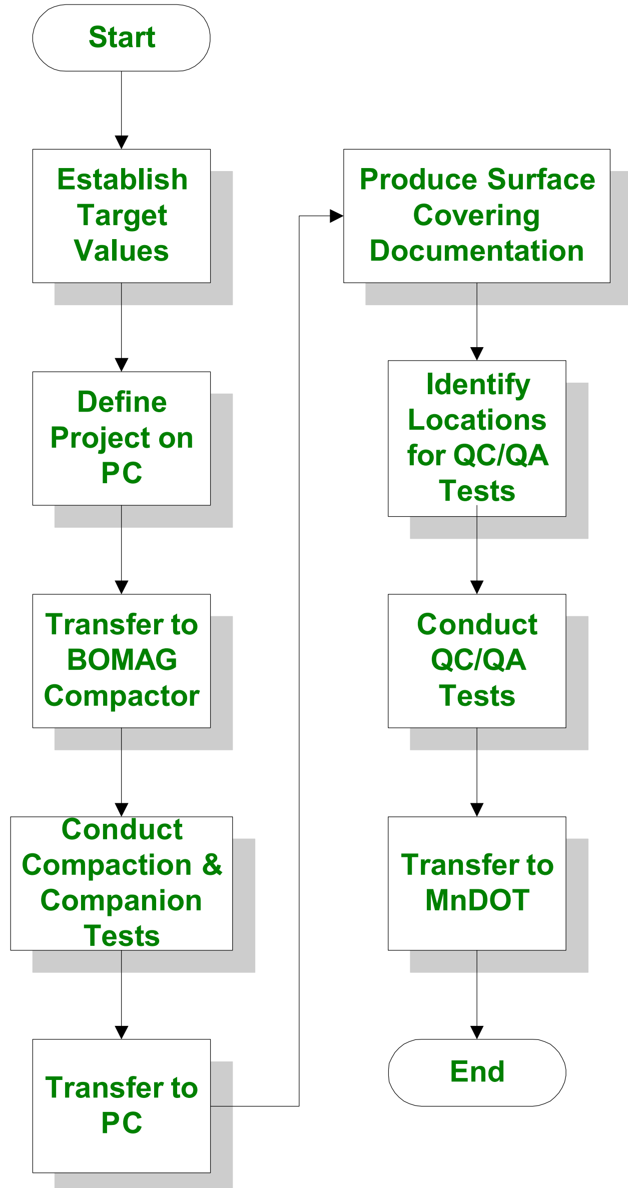


Figure 8

Possible Sequence of Collecting Surface-Covering Compaction Documentation

Dynamic Cone Penetrometer

Humboldt Geogauge

Troxler 3430 Nuclear Density Gauge

Plate Load Test Equipment

Loadman

Figure 9

Photos of Companion Testing Devices

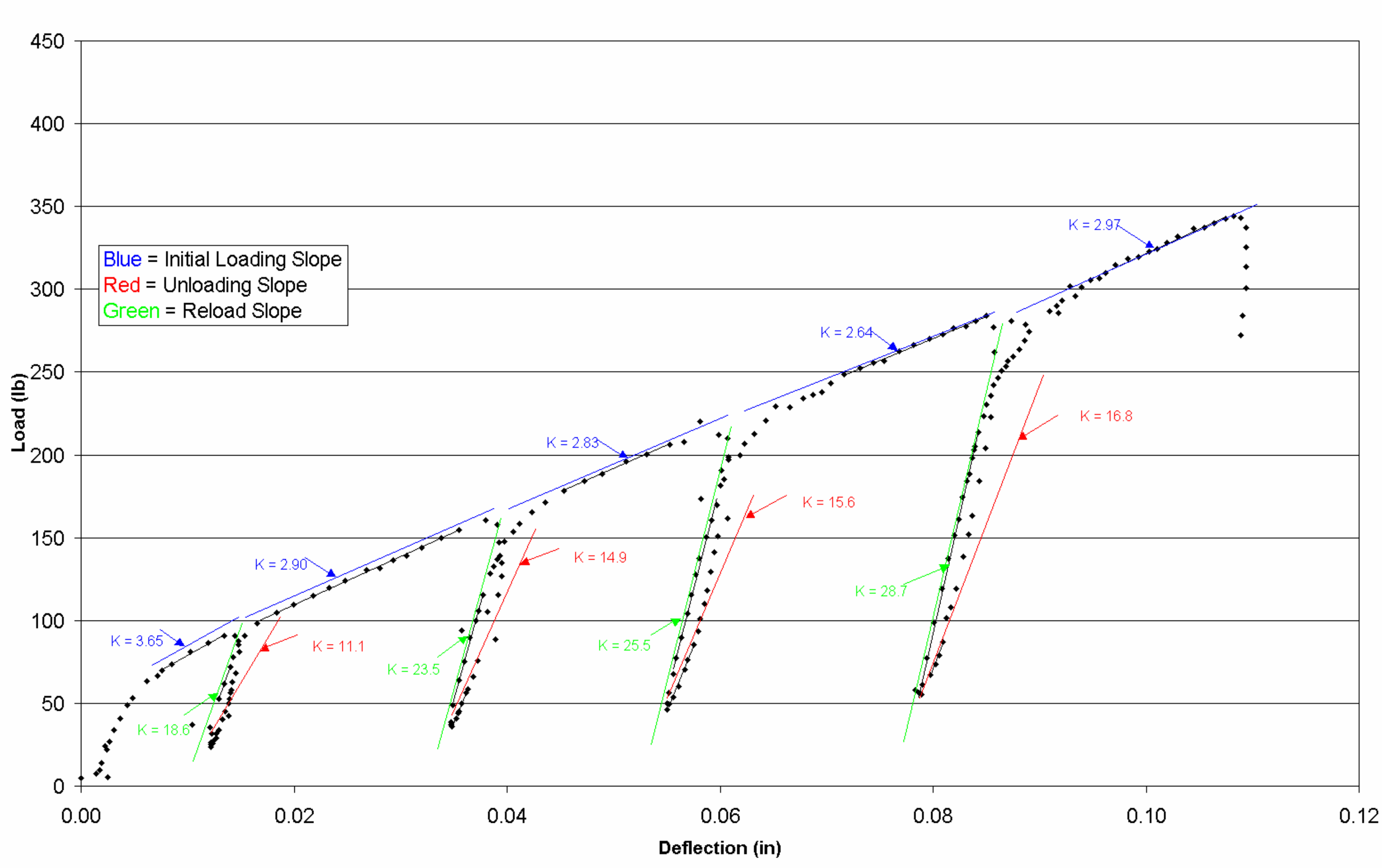


Figure 10

Typical Plate Load Test Load-Deflection Data

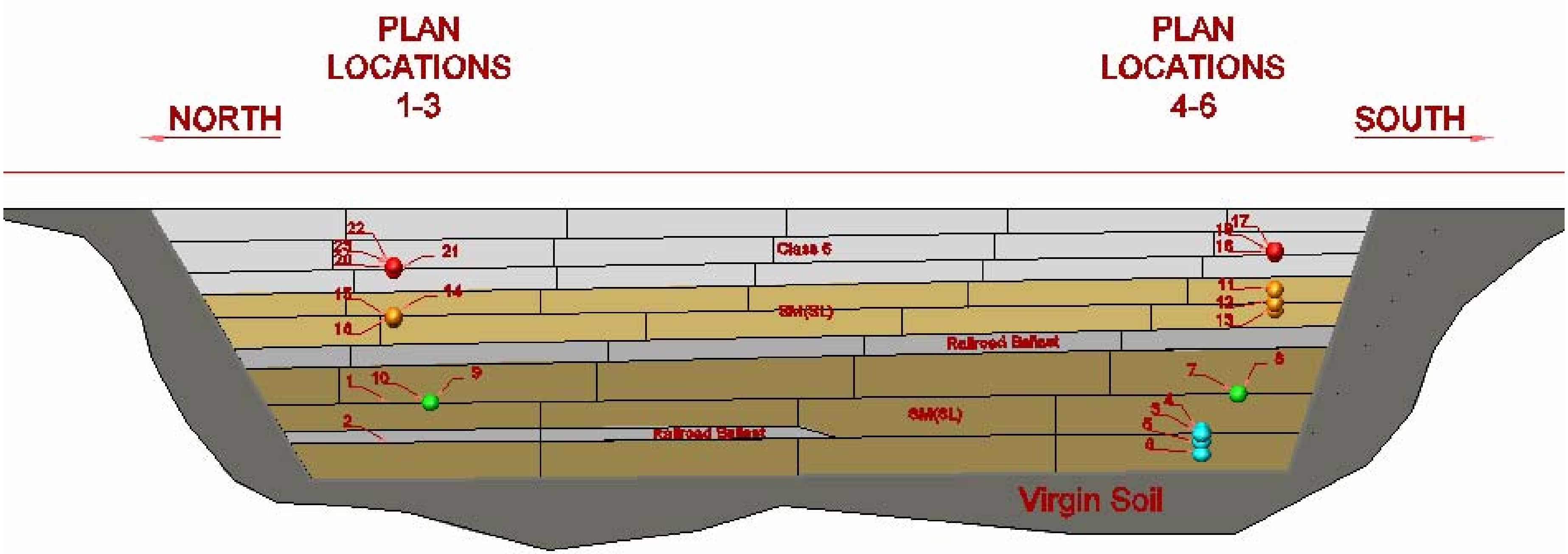


Figure 11

Demonstration Site Cross Section

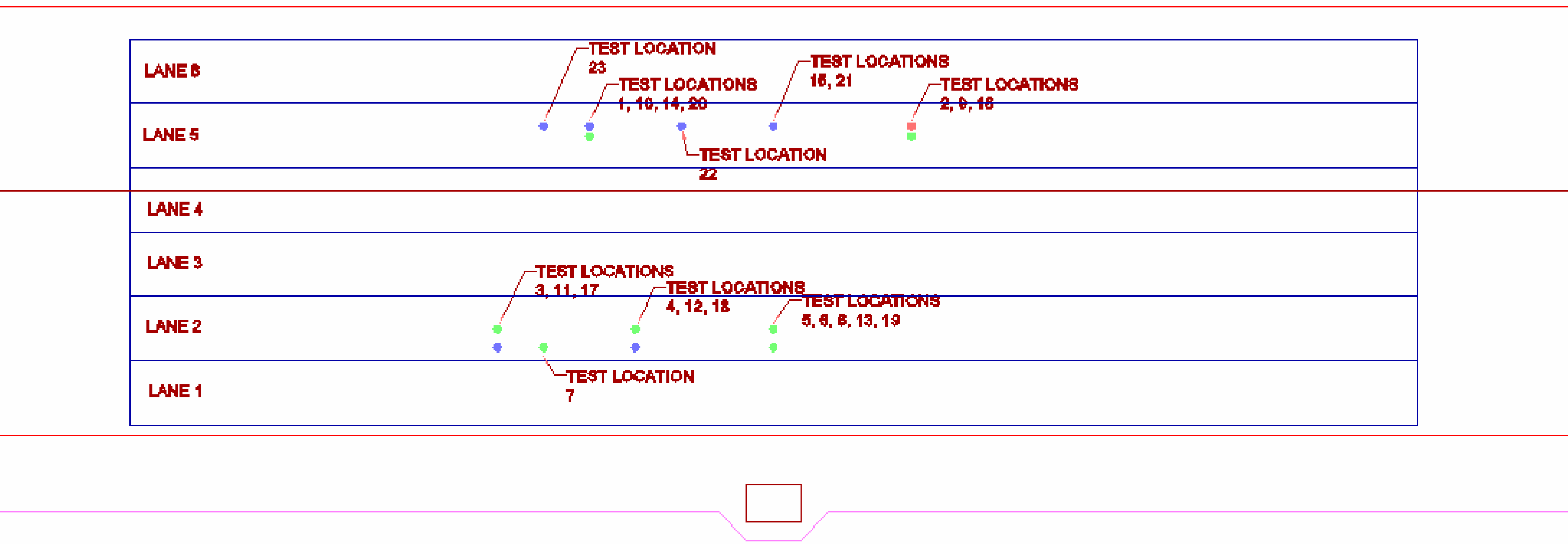


Figure 12

Demonstration Site Plan View

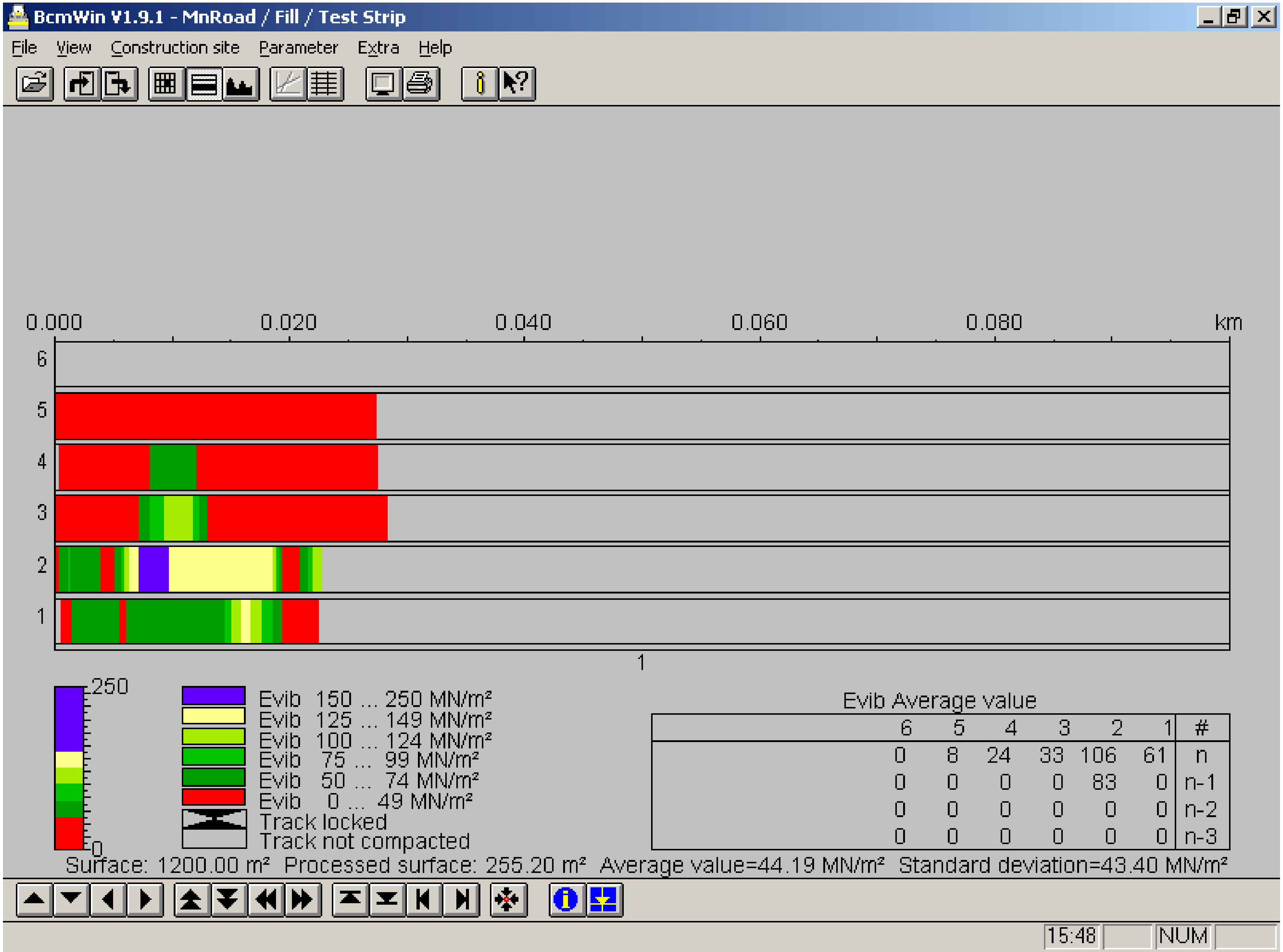


Figure 13

Example of Surface-Covering Compaction Documentation

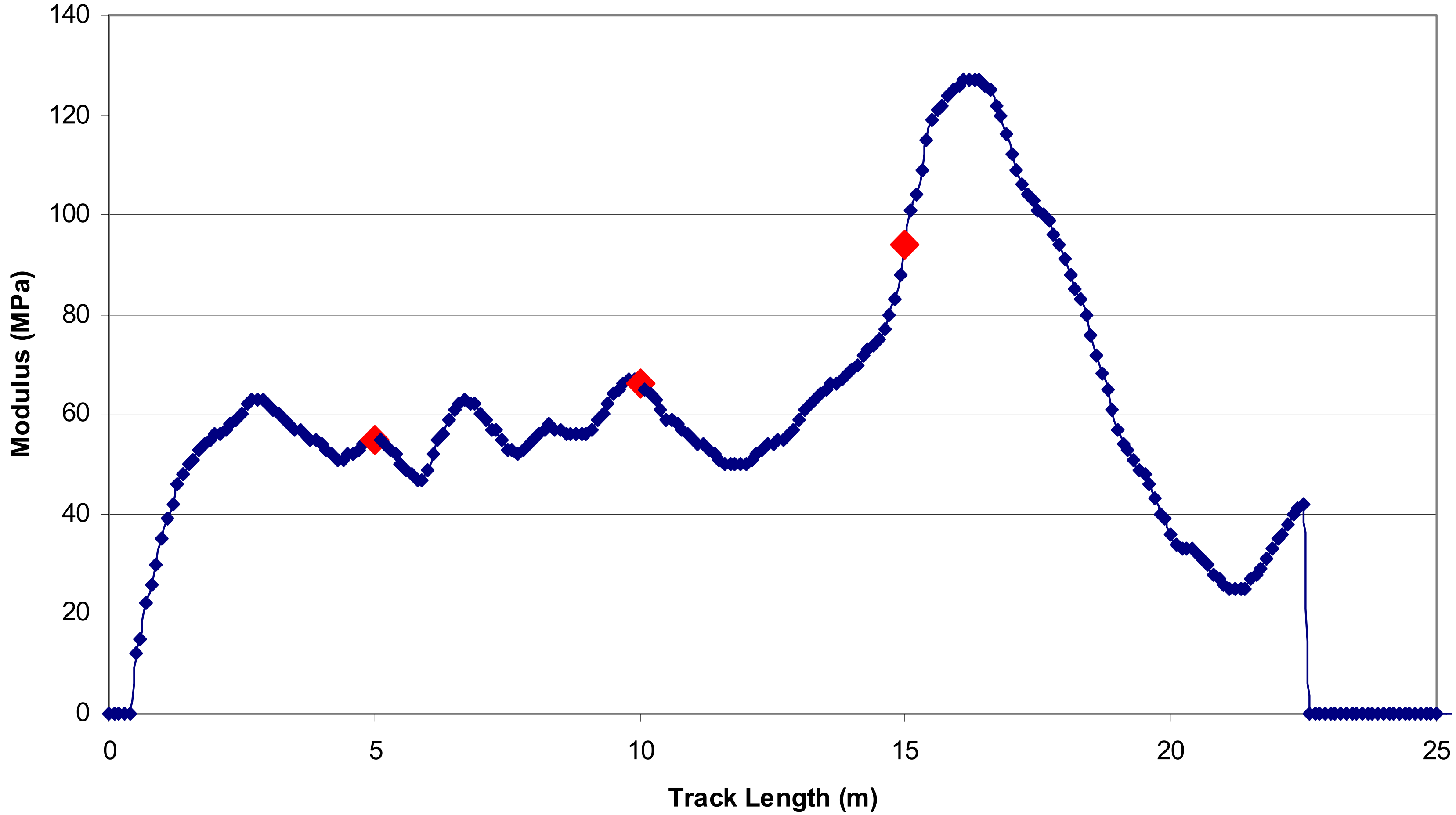


Figure 14

Example of Exported Data From BCMWin, with Companion Test Points Highlighted

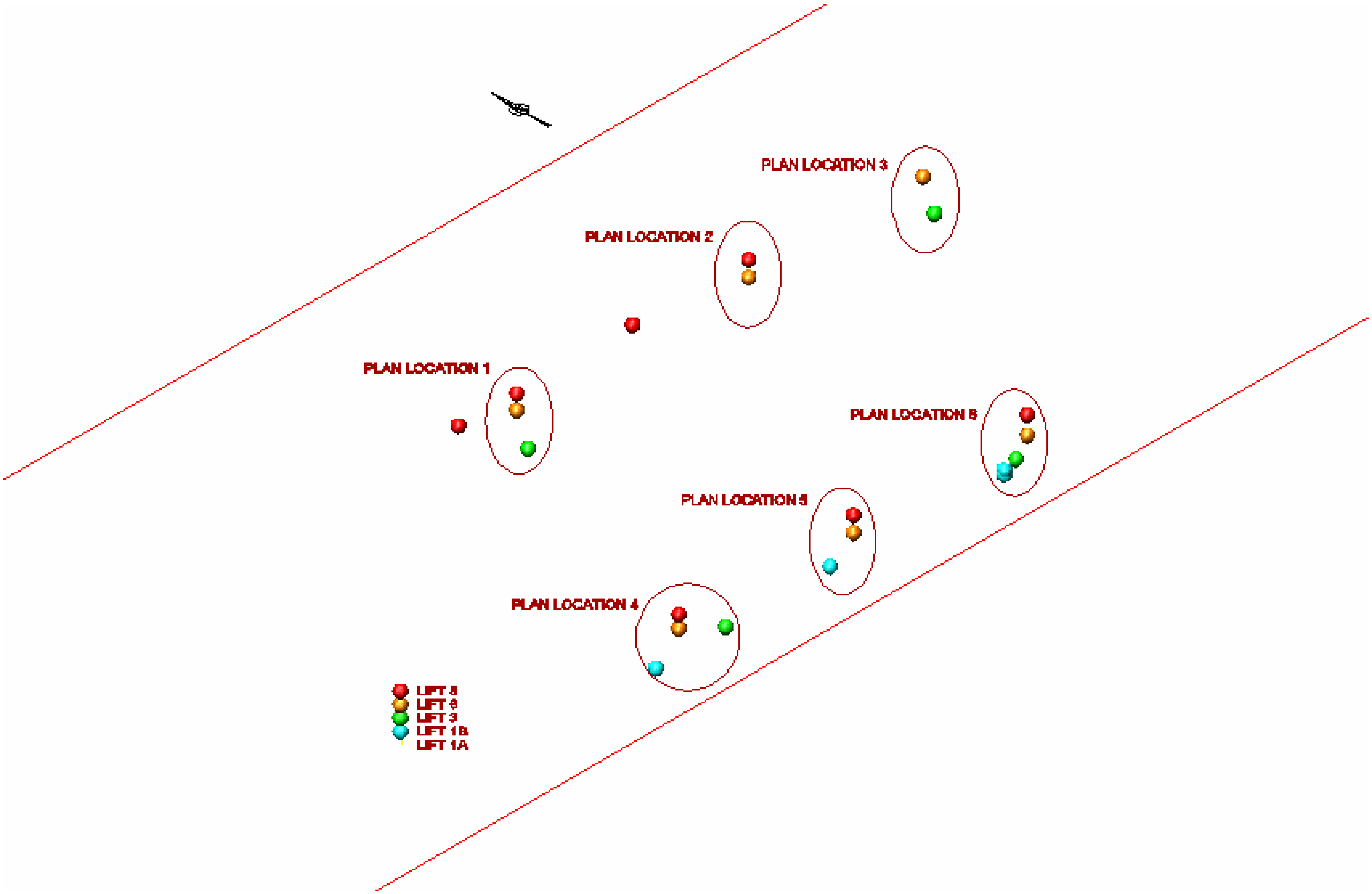


Figure 15

Demonstration Site Isometric View

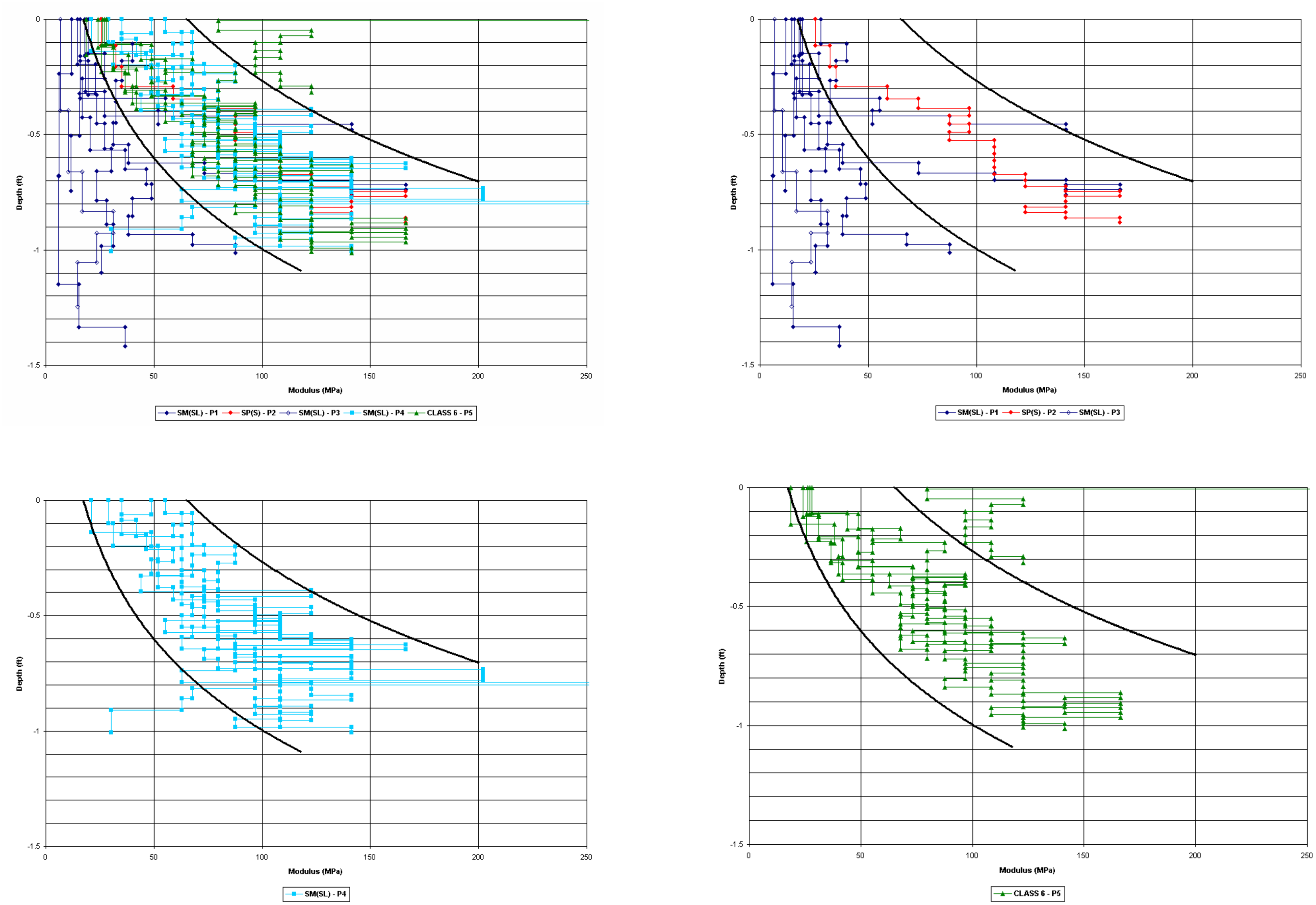


Figure 16

DCP Modulus for All Tests

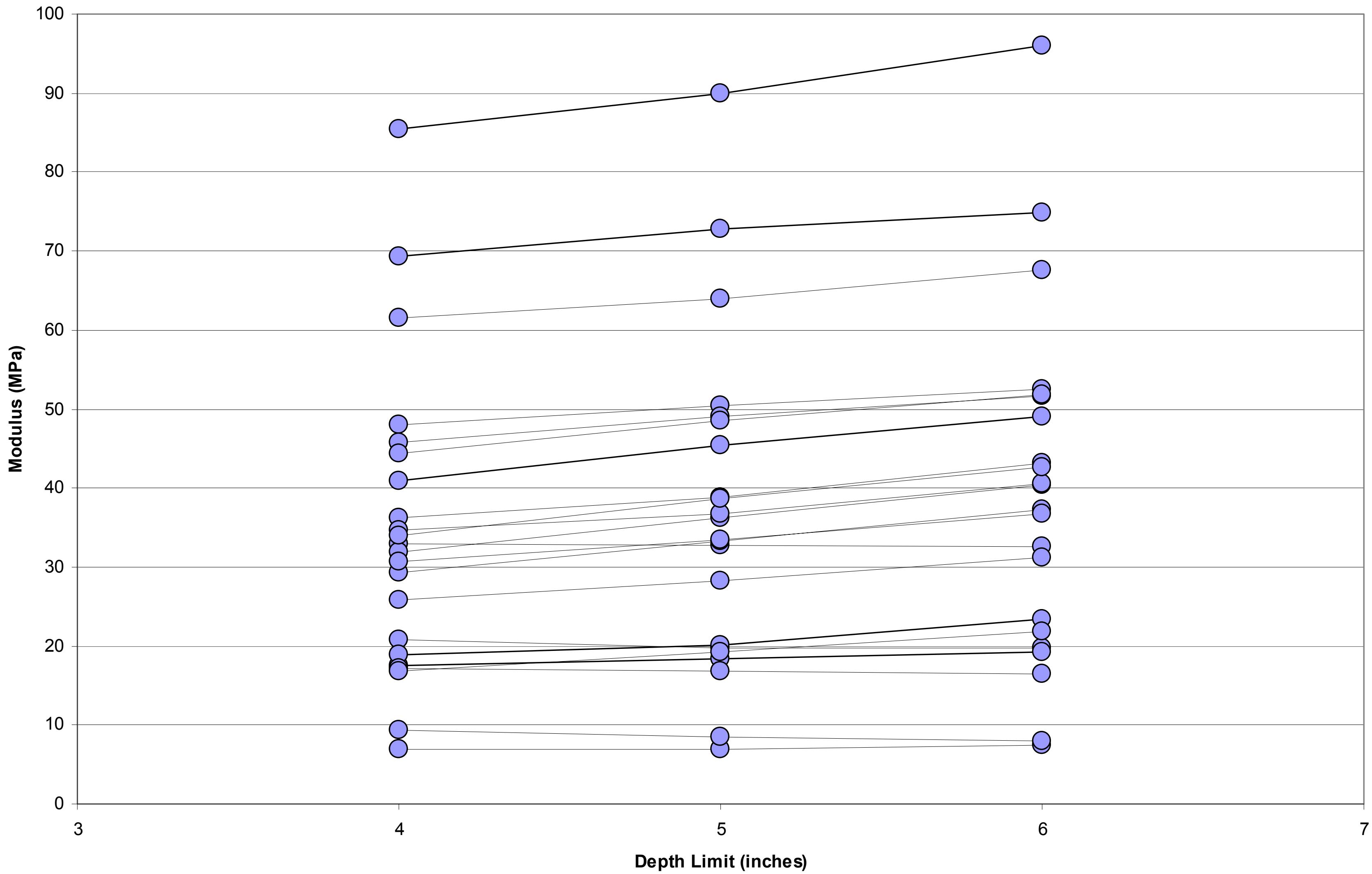


Figure 17

DCP Modulus Values as a Function of Depth Limit

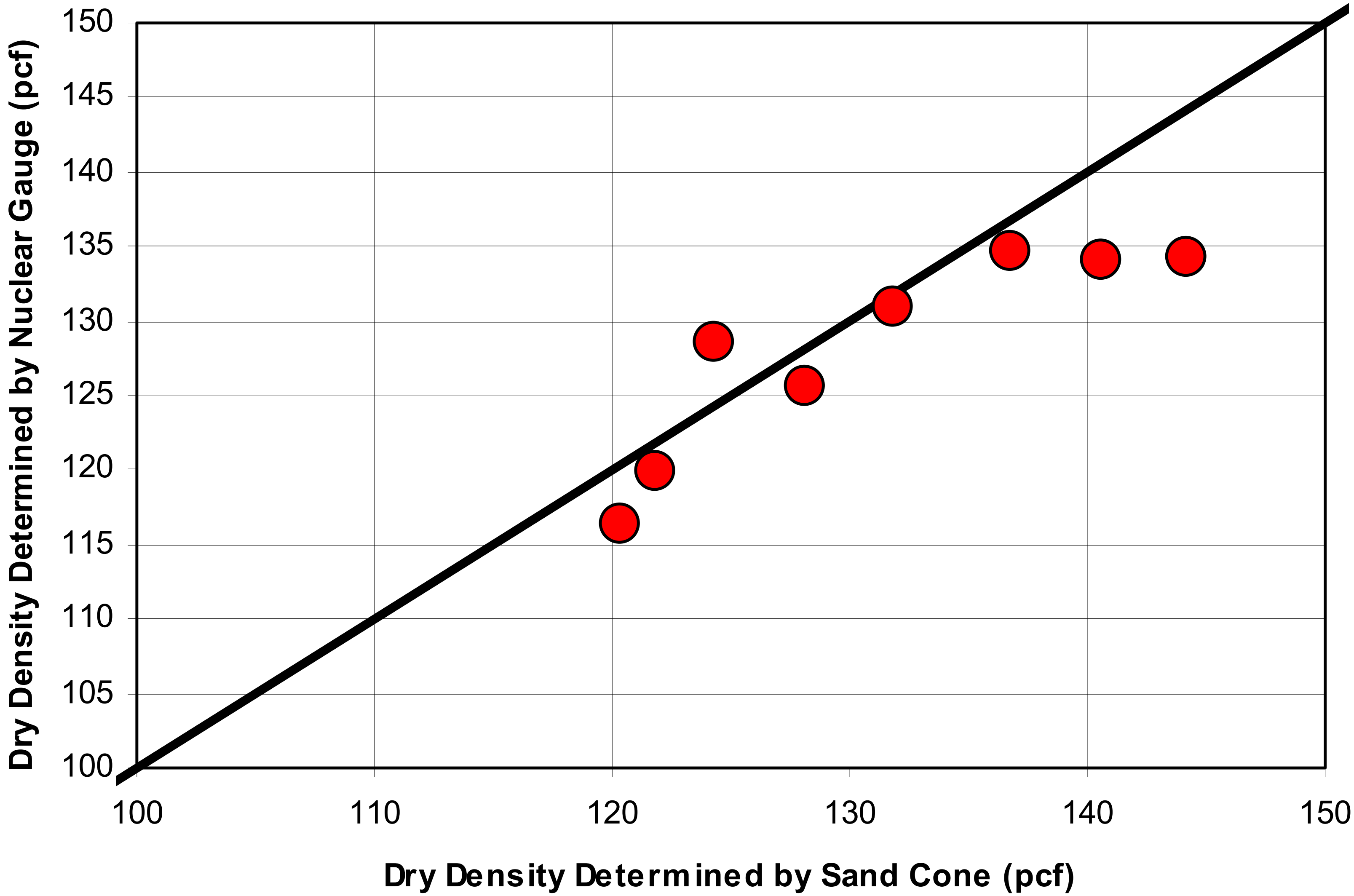
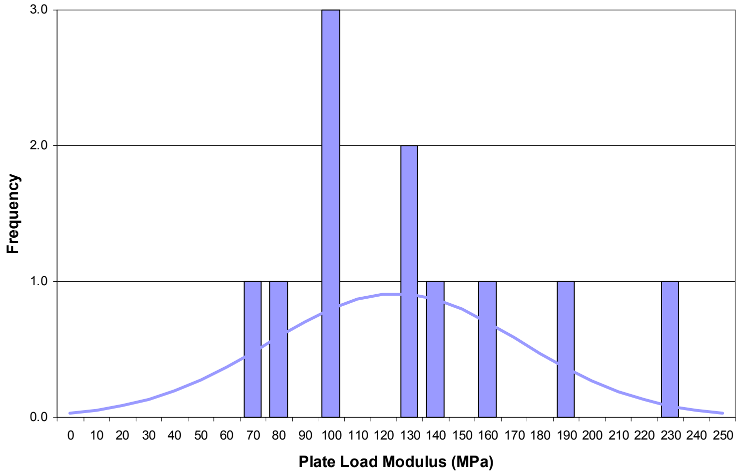


Figure 18

Companion Density Tests

Location 22



Location 23

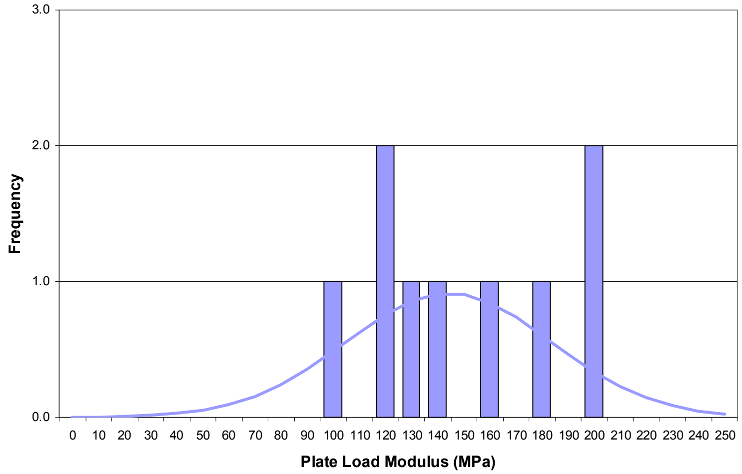


Figure 19

Plate Load Test Values for All Reload Cycles

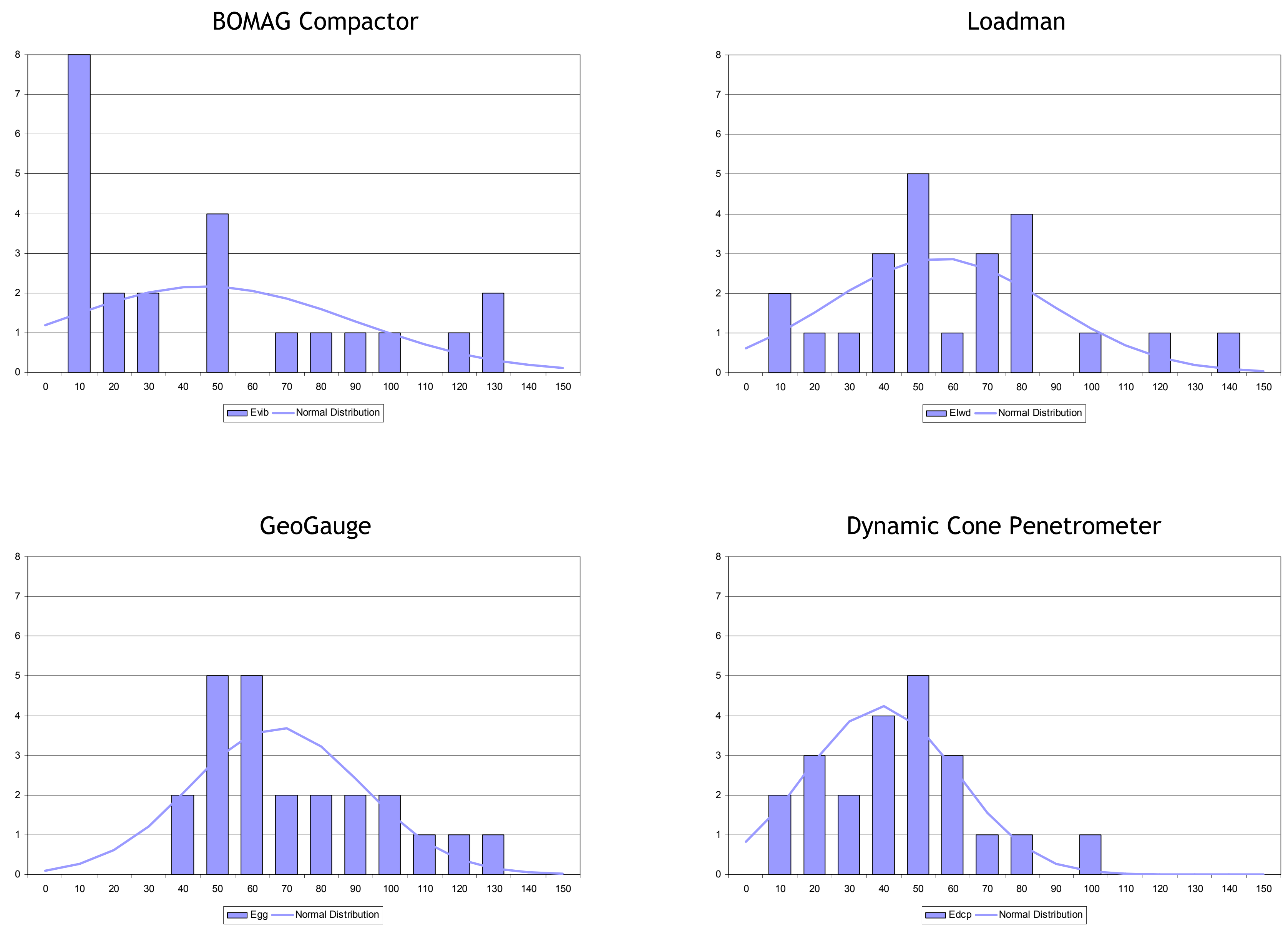


Figure 20

Distribution of Young's Modulus for Four Principal Test Methods

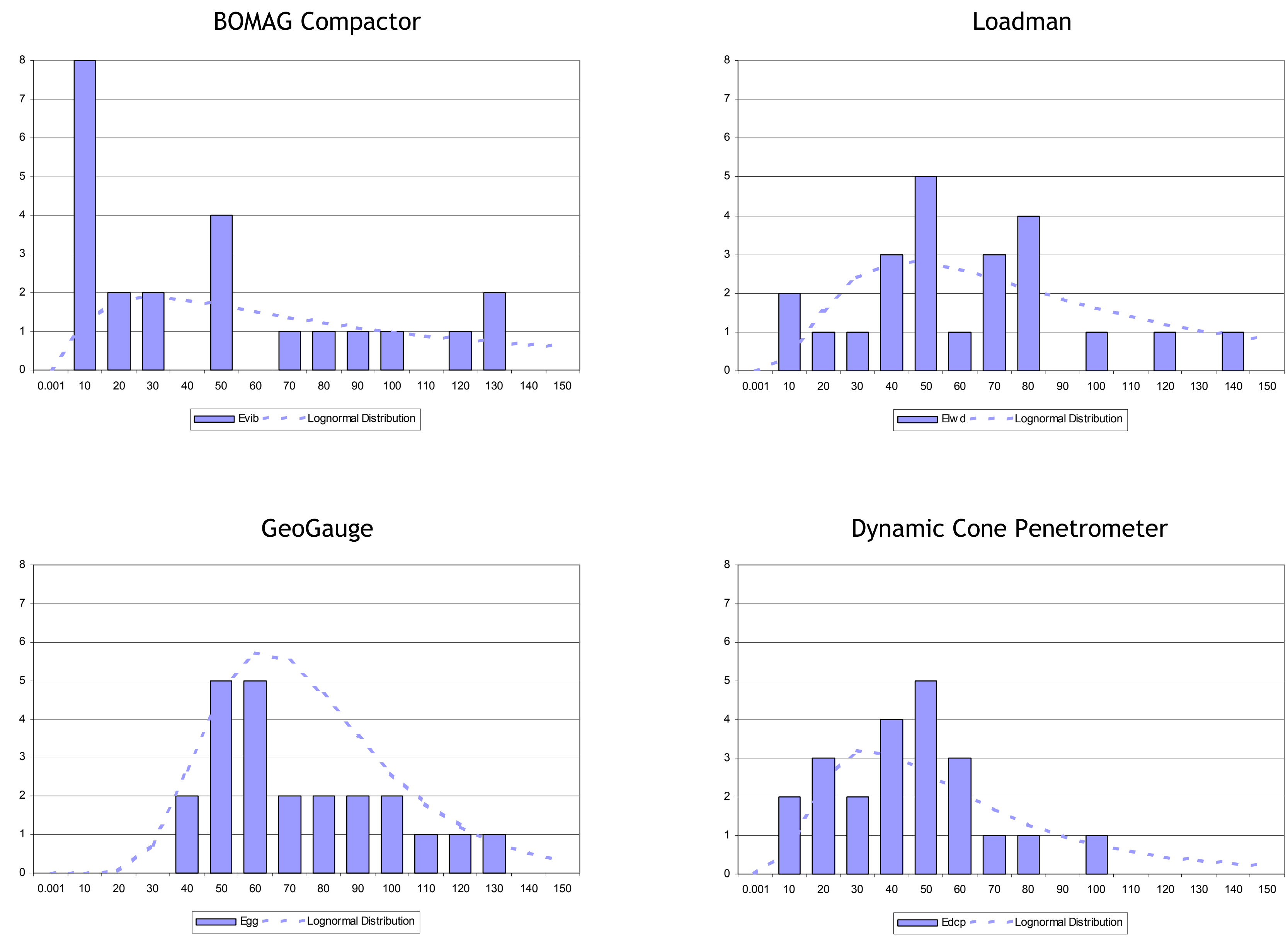


Figure 21

Distribution of Young's Modulus for Four Principal Test Methods (compared to lognormal distribution)

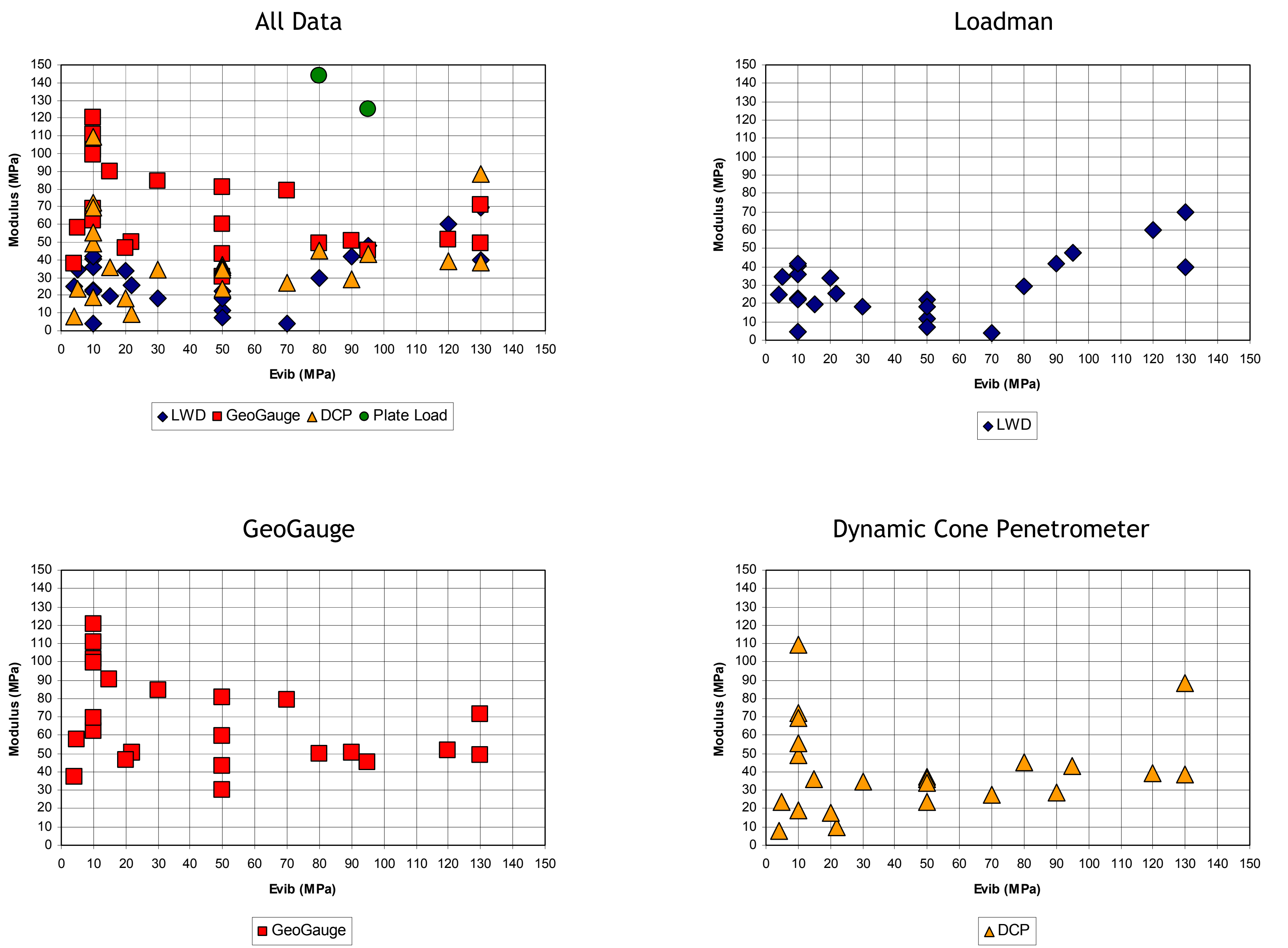


Figure 22

Comparisons Between the BOMAG Data and Other Methods

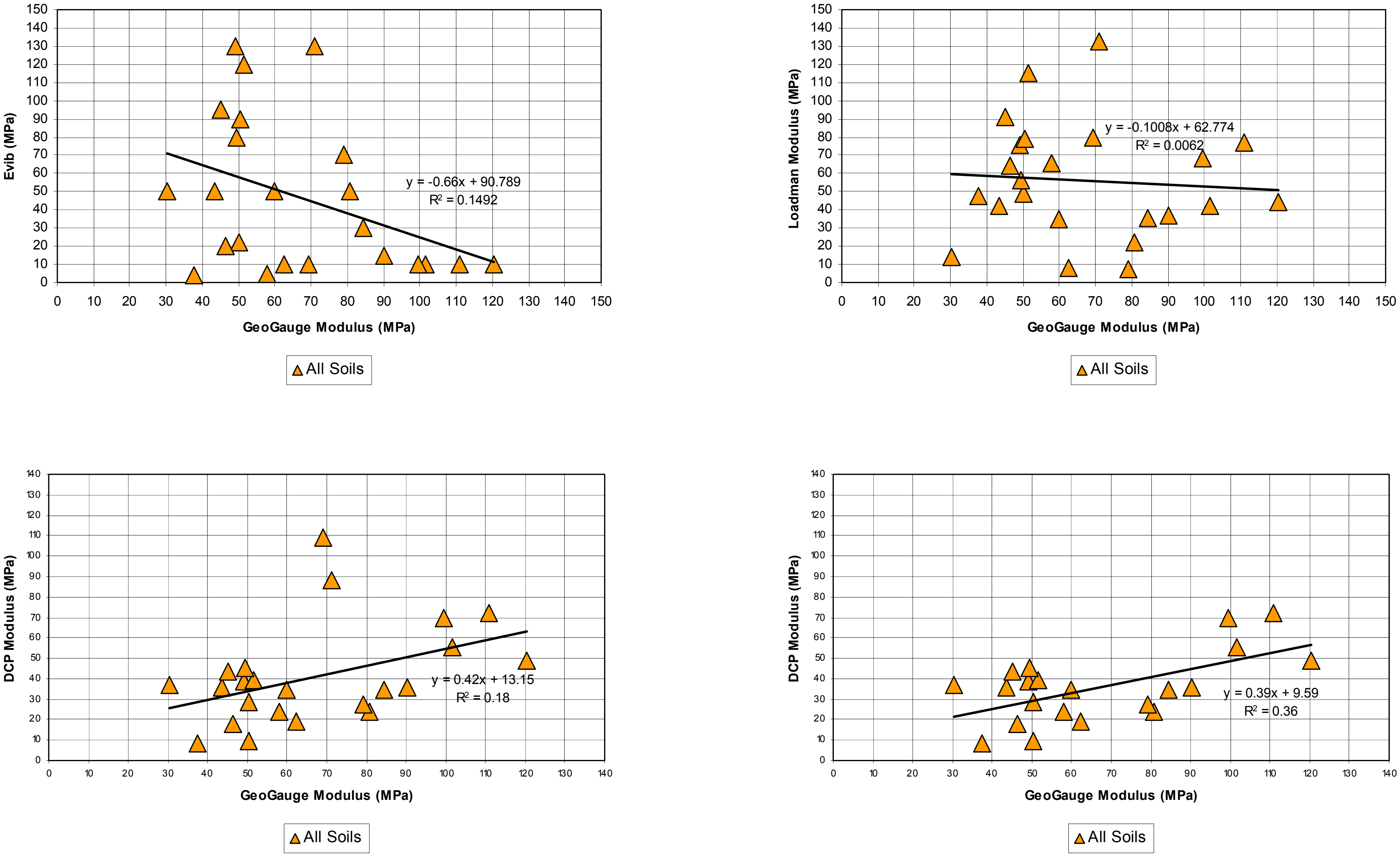


Figure 23

GeoGauge Test Comparison

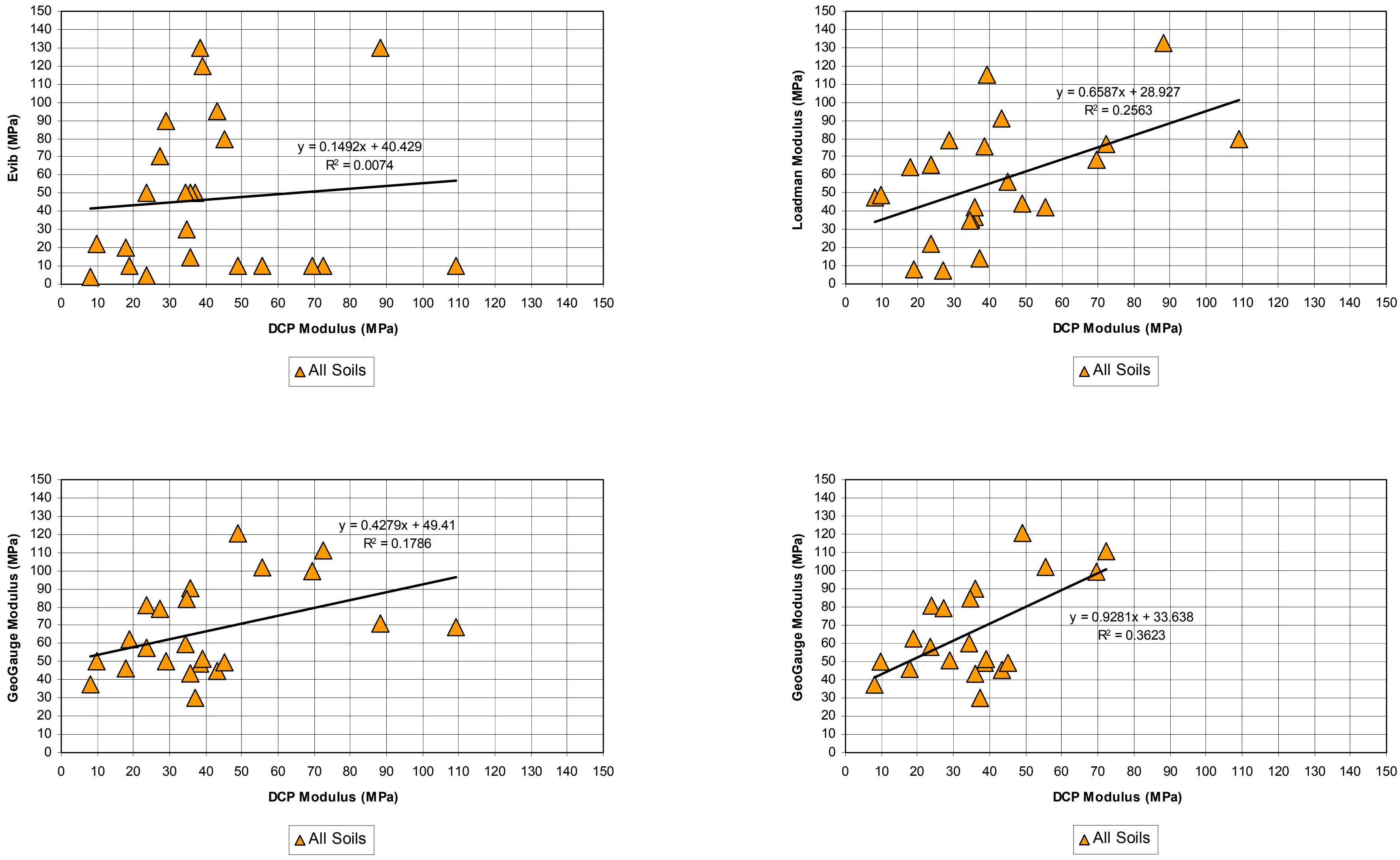


Figure 24

DCP Test Comparison

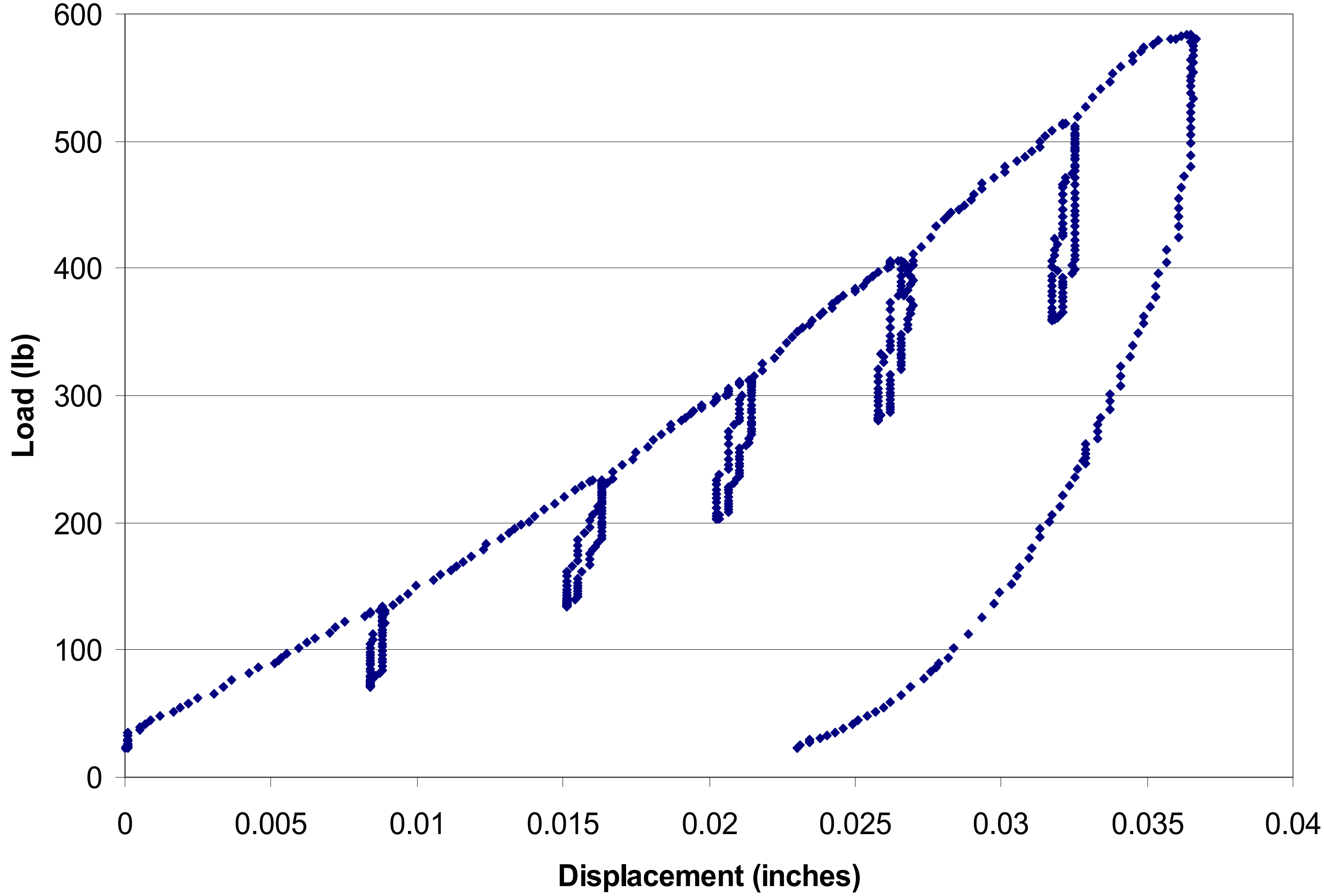


Figure 25

Load-Displacement Data for Plate Load Test, Location 22a

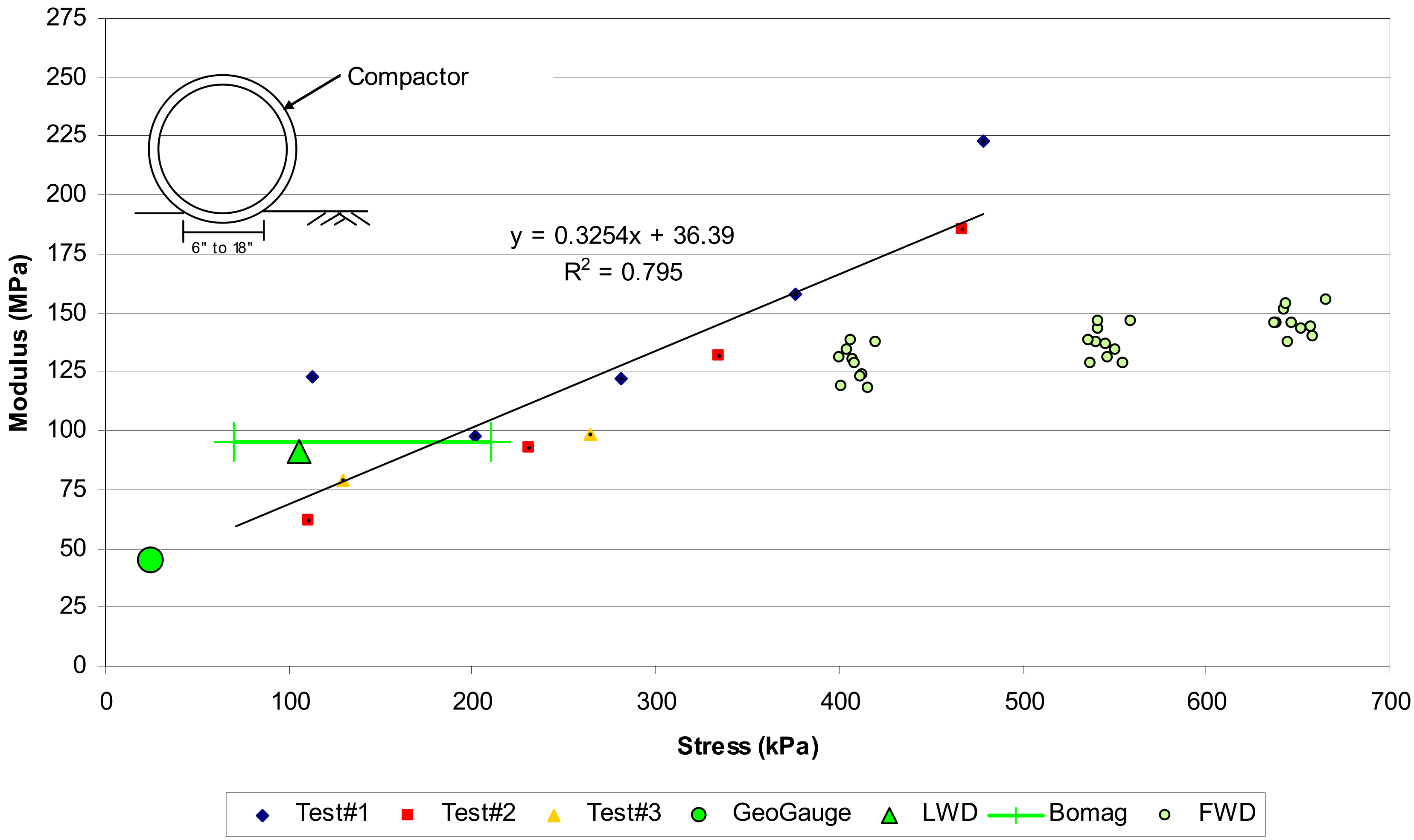


Figure 26

Stress Dependency of Modulus Measurements, Location 22

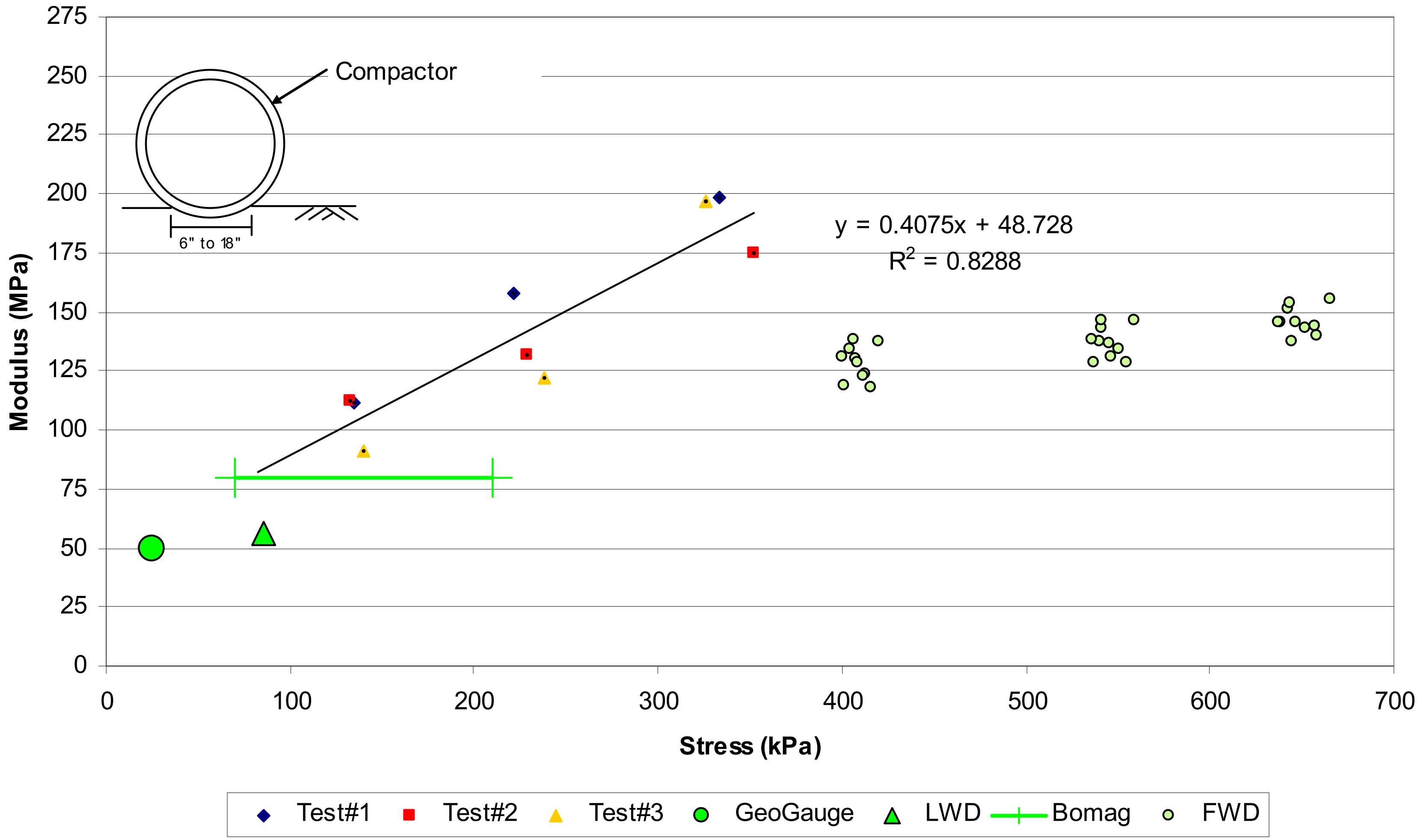


Figure 27

Stress Dependency of Modulus Measurements, Location 23

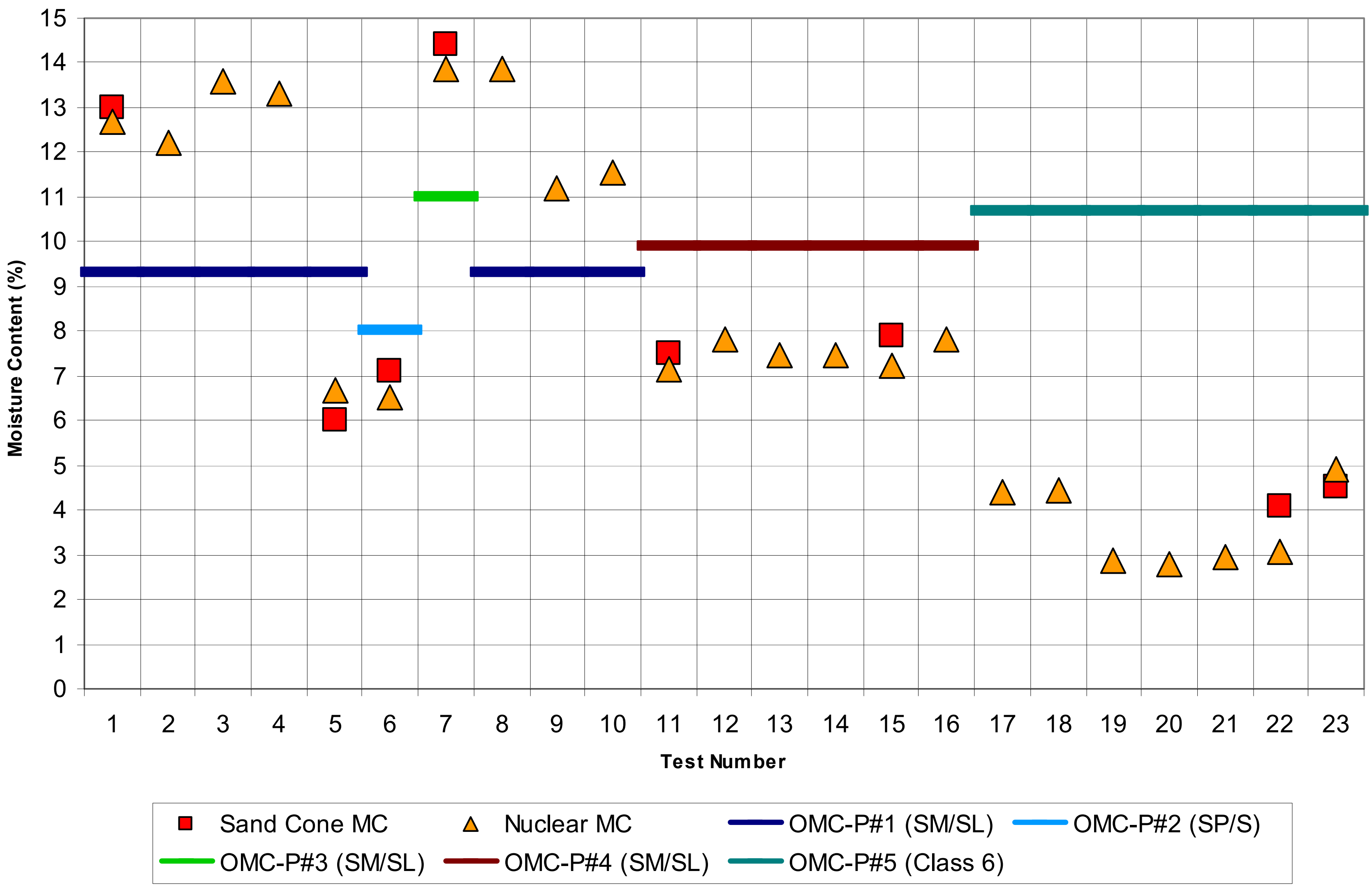


Figure 28

Comparison of Optimum to As-Compacted Moisture Content

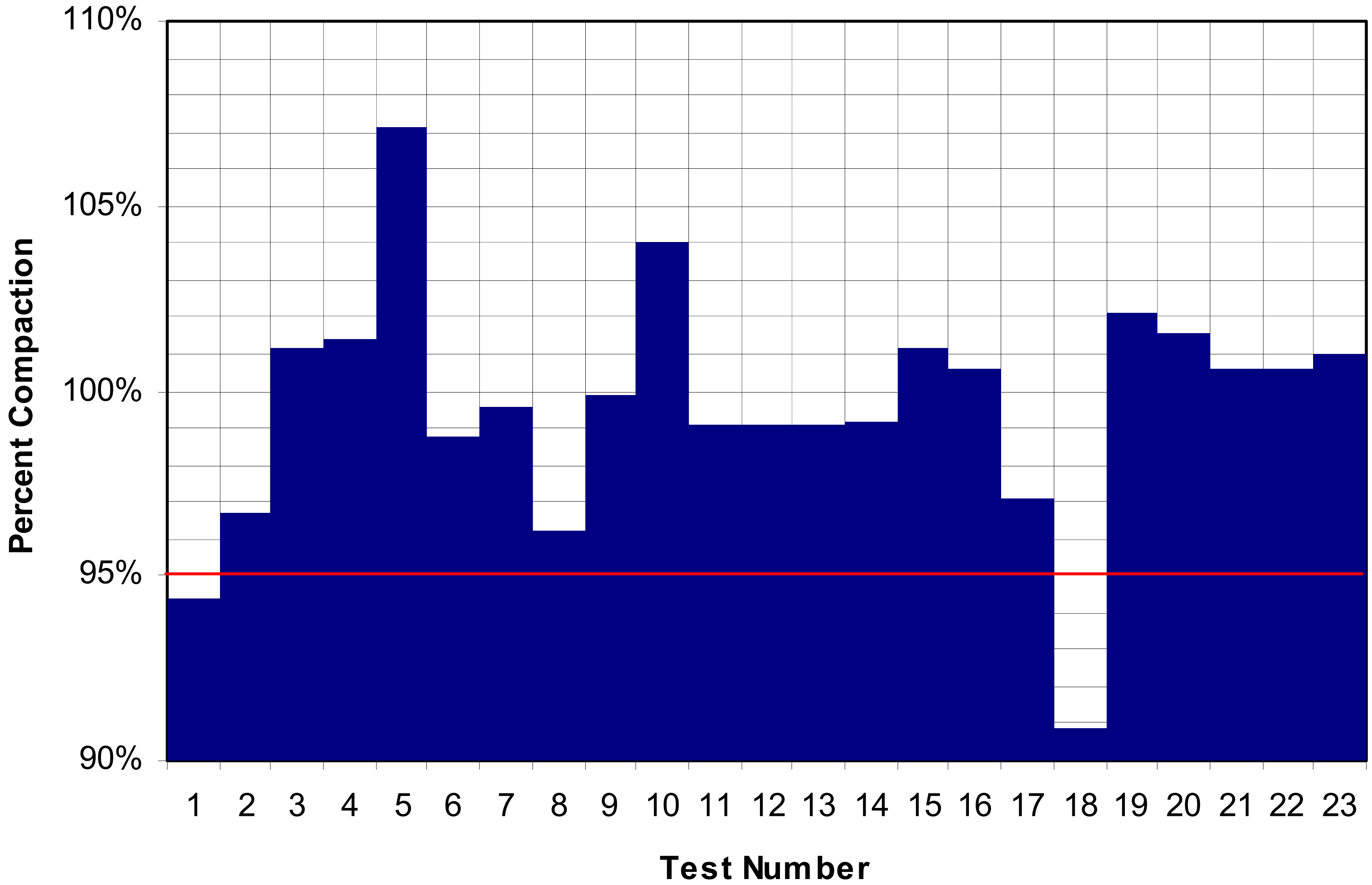


Figure 29

Percent Compaction by Location

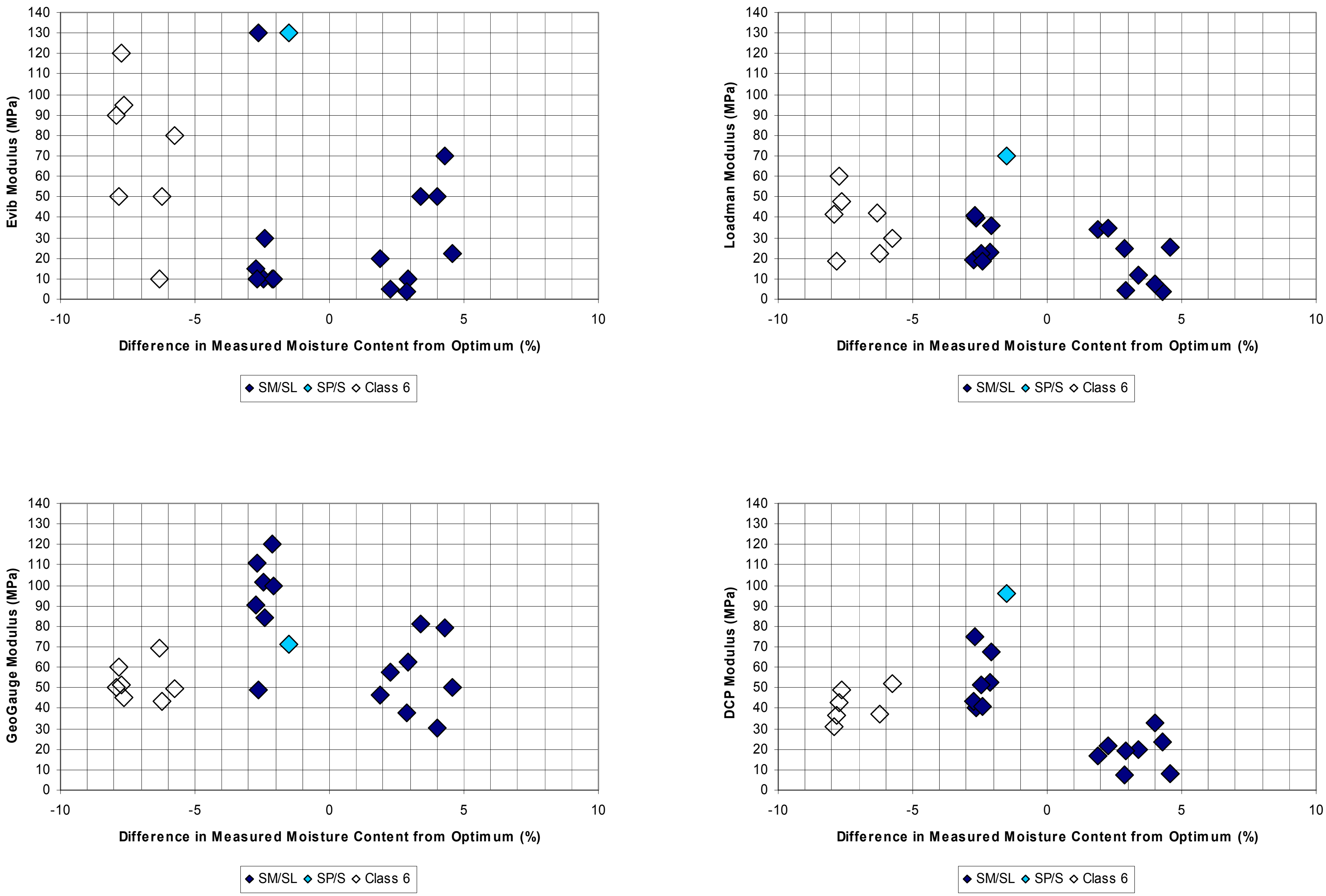


Figure 30

Comparison of In-Place to Optimum Moisture Content

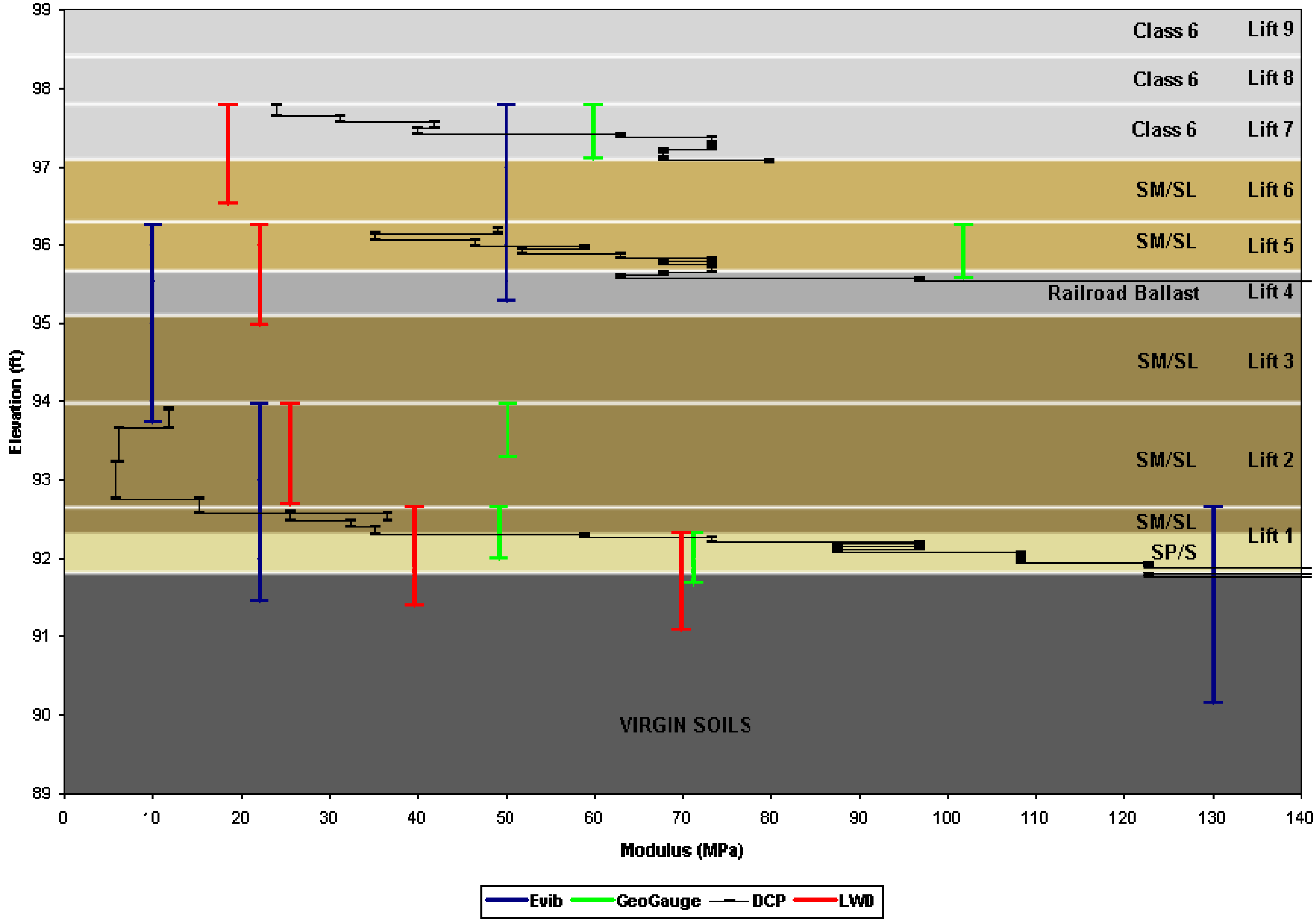


Figure 31

As-Built Section with Selected Modulus Data

Appendix A

Lane	9/27/2004 Lift 1A	9/27/2004 Lift 1B	9/27/2004 Lift 2	9/27/2004 Lift 3	9/27/2004 Lift 4	9/28/2004 Lift 5	9/28/2004 Lift 6	9/29/2004 Lift 7	9/29/2004 Lift 8	9/29/2004 Lift 9	9/30/2004 Lift 10
Lane6					SM, SL, 1	RB[1]	SM, SL, 4	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5
							14,15,16				
						Yes	Yes		Yes		
					Yes	Yes					
Lane5	SM, SL, 1	SM, SL, 1	RB[1]	SM, SL, 1	SM, SL, 1	RB[1]	SM, SL, 4	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5
	1,2			9,10					20,21,22,23		
	Yes	Yes	Yes	Yes		Yes	Yes		Yes		
		Yes	Yes	Yes	Yes	Yes					
Lane4		SM, SL, 1	RB[1]	SM, SL, 1	SM, SL, 1	RB[1]	SM, SL, 4	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5
		Yes	Yes	Yes		Yes	Yes		Yes		
		Yes	Yes	Yes	Yes	Yes					
Lane3		SM, SL, 1		SM, SL, 1	SM, SL, 1	RB[1]	SM, SL, 4	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5
		Yes		Yes		Yes	Yes		Yes		
		Yes		Yes	Yes	Yes					
Lane2		SM, SL, 1		SM, SL, 3/1	SM, SL, 1	RB[1]	SM, SL, 4	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5
		3,4,5,6		7,8			11,12,13				
		Yes		Yes		Yes	Yes		Yes		
		Yes		Yes	Yes						
Lane1									-, CL6[2], 5	-, CL6[2], 5	-, CL6[2], 5
									17,18,19		
									Yes		

Legend

	Date Lift #
Lane#	ASTM Soil Type, MnDOT Soil Type, Proctor Number
	Test Numbers
	Paper Record of Bomag Data
	Electronic Record of Bomag Data

Note: Shading indicates that soil was placed in the coresponding Lane and Lift
1. RB = Railroad Ballast
2. CL6 = Class 6

Figure A.1

Guide

Lane 5

test #1 & #2

clay start

BOMAG VARIOCONTROL

PASS NO. 1 For.
BOMAG BTM05 + BTM-E REV 0073 + EVIB
BW213DH Variocontrol 101 581 45 1068

Settings : Automatic / 45 MN/m2
Evib set-point achieved: 21 %

EVIB max.	=	53 MN/m2
EVIB min.	=	1 MN/m2
Average EVIB	=	20 MN/m2
Change of EVIB	=	--- %
Frequency	=	24.5 Hz
Average speed value	=	1.0 km/h
Track length	=	13.1 m

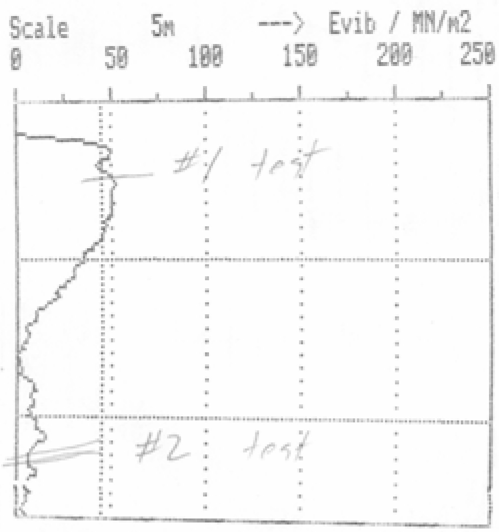


Figure A.2

BOMAG Paper Strips – Lift 1A Lane 5

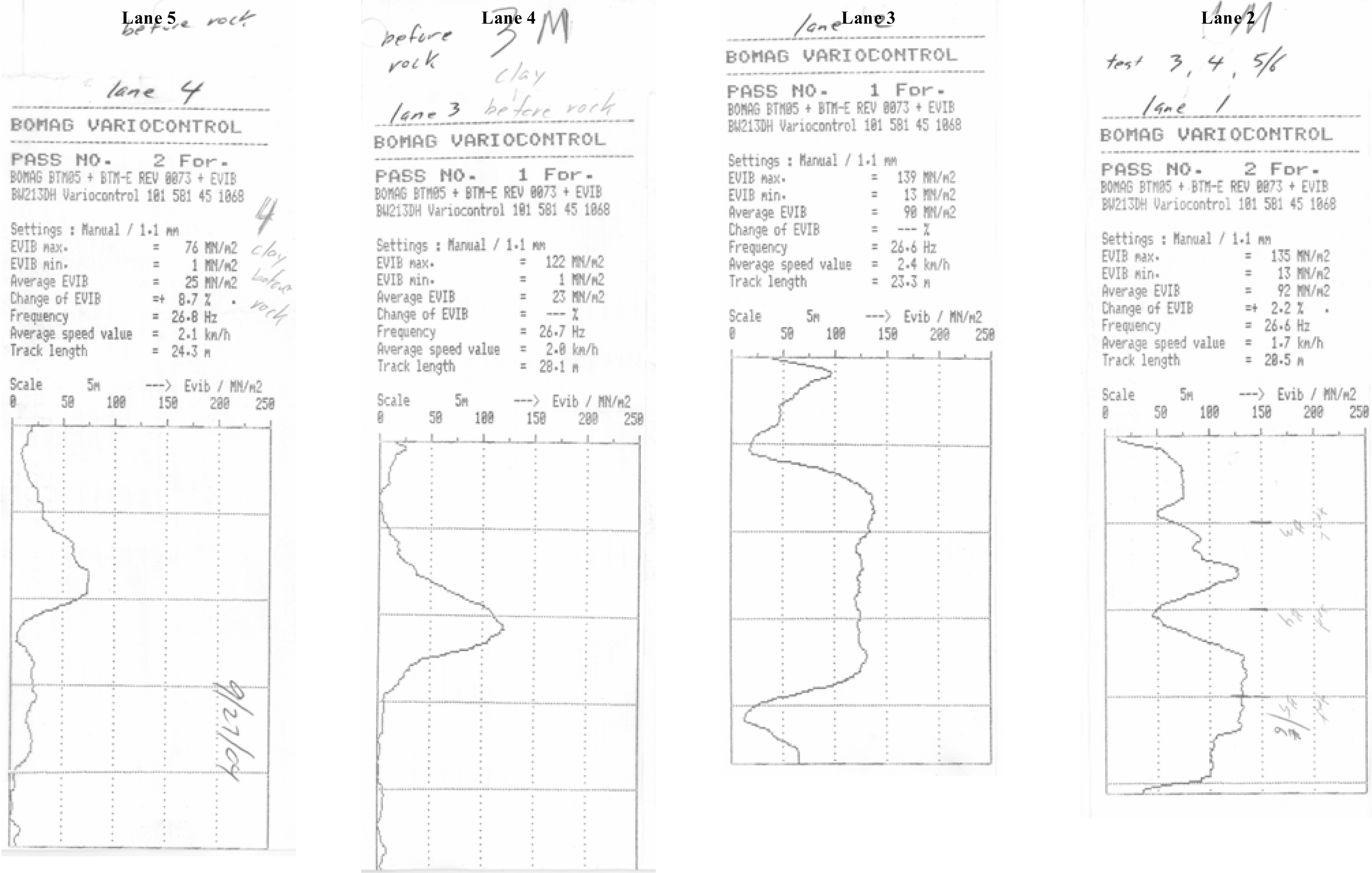
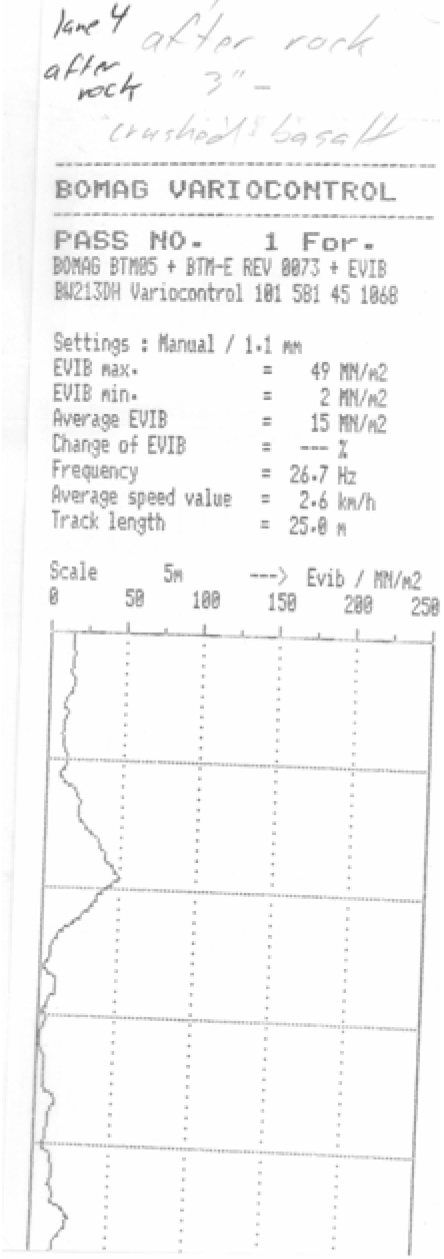


Figure A.3

BOMAG Paper Strips – Lift 1B Lane 2-5

Lane 5



lane 4 after rock

after rock 3" – crushed basalt

BOMAG VARIOCONTROL

PASS NO. 1 For.

BOMAG BTM05 + BTM-E REV 0073 + EVIB

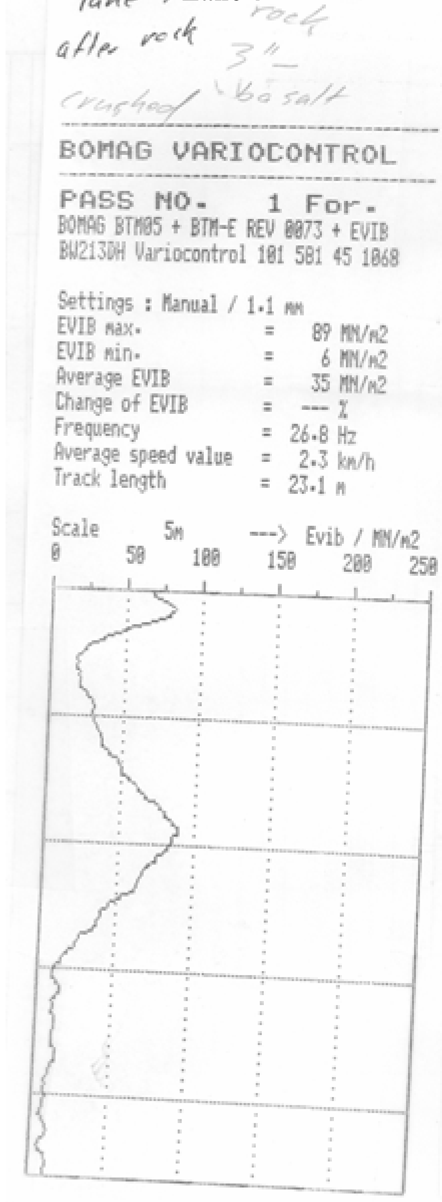
BW213DH Variocontrol 101 581 45 1068

Settings : Manual / 1.1 mm		
EVIB max.	=	49 MN/m2
EVIB min.	=	2 MN/m2
Average EVIB	=	15 MN/m2
Change of EVIB	=	--- %
Frequency	=	26.7 Hz
Average speed value	=	2.6 km/h
Track length	=	25.0 m

Scale 5m ---> Evib / MN/m2

0 50 100 150 200 250

Lane 4



lane 3 after rock

after rock 3" – crushed basalt

BOMAG VARIOCONTROL

PASS NO. 1 For.

BOMAG BTM05 + BTM-E REV 0073 + EVIB

BW213DH Variocontrol 101 581 45 1068

Settings : Manual / 1.1 mm		
EVIB max.	=	89 MN/m2
EVIB min.	=	6 MN/m2
Average EVIB	=	35 MN/m2
Change of EVIB	=	--- %
Frequency	=	26.8 Hz
Average speed value	=	2.3 km/h
Track length	=	23.1 m

Scale 5m ---> Evib / MN/m2

0 50 100 150 200 250

Figure A.4

BOMAG Paper Strips – Lift 2 Lane 4-5

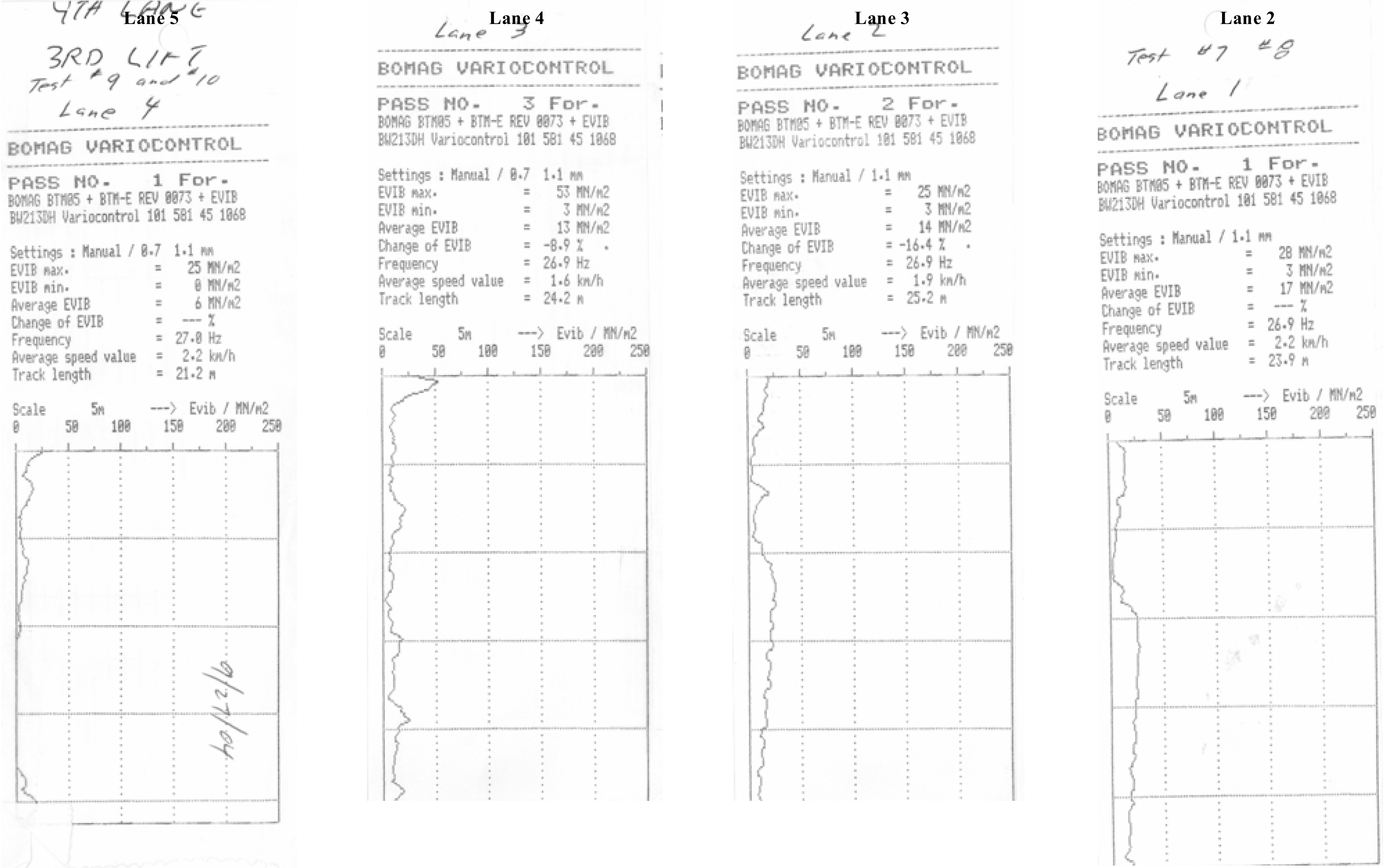


Figure A.5

BOMAG Paper Strips – Lift 3 Lane 2-5

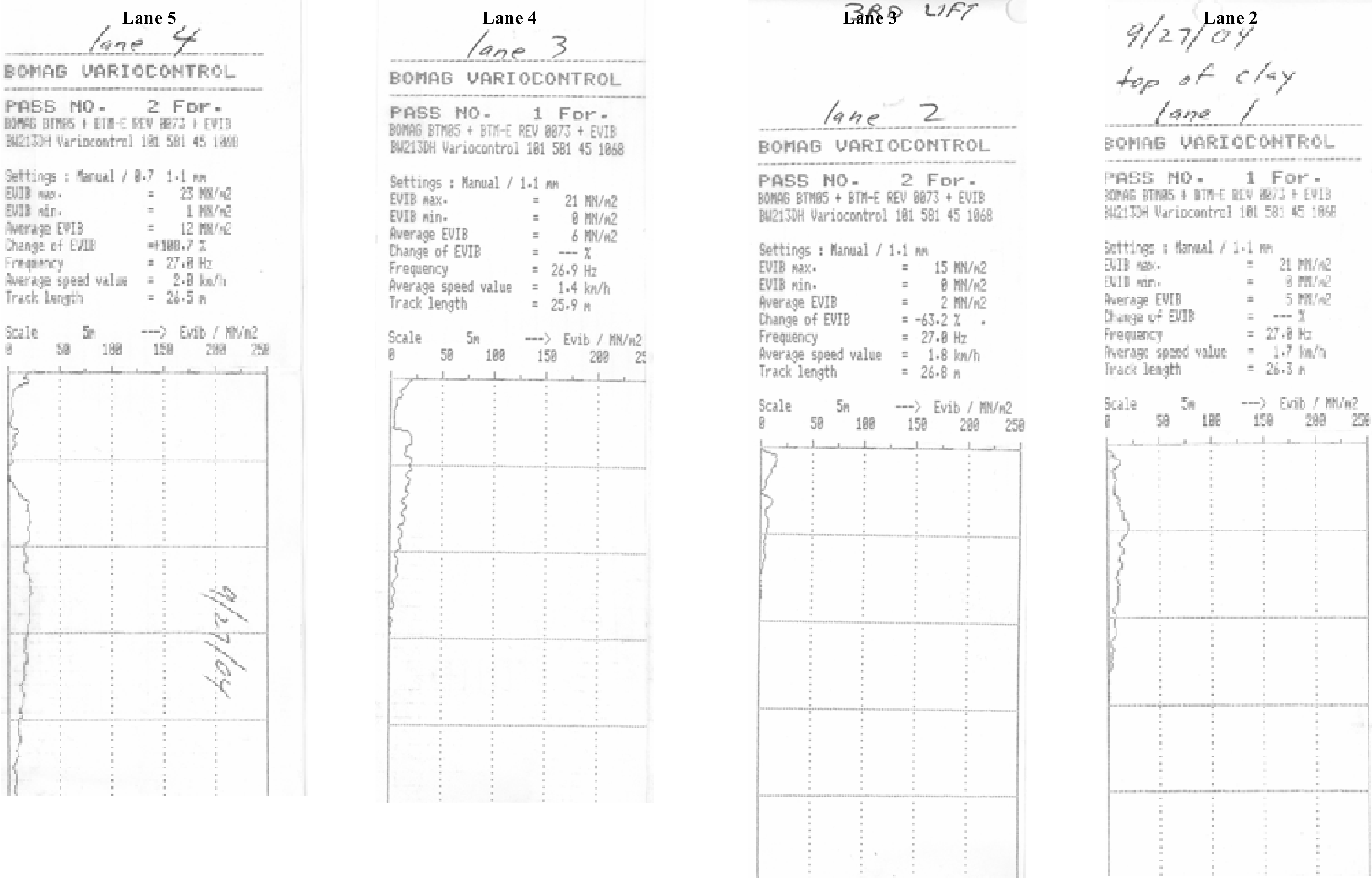


Figure A.6

BOMAG Paper Strips – Lift 4 Lane 2-5

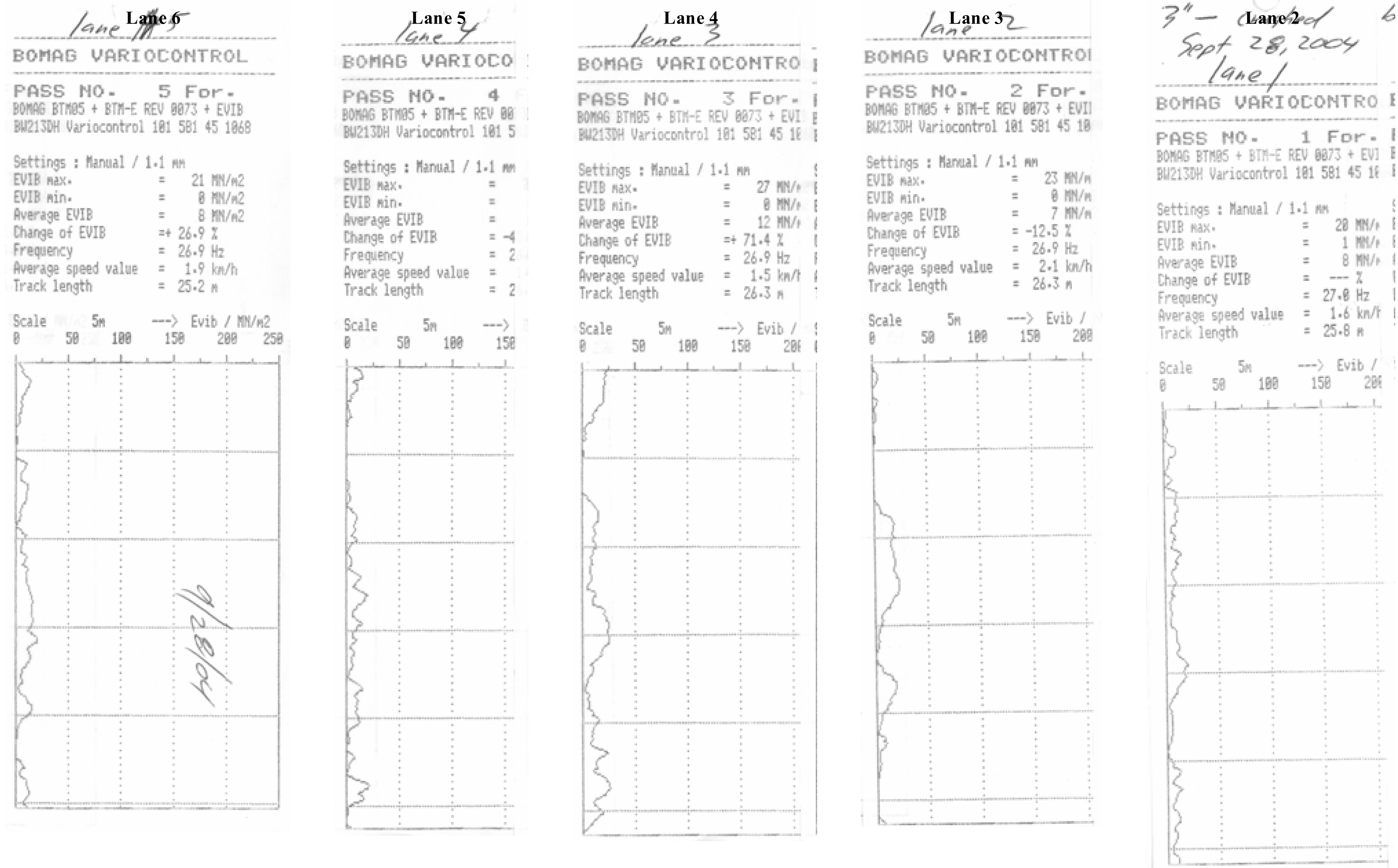


Figure A.7

BOMAG Paper Strips – Lift 5 Lane 2-6

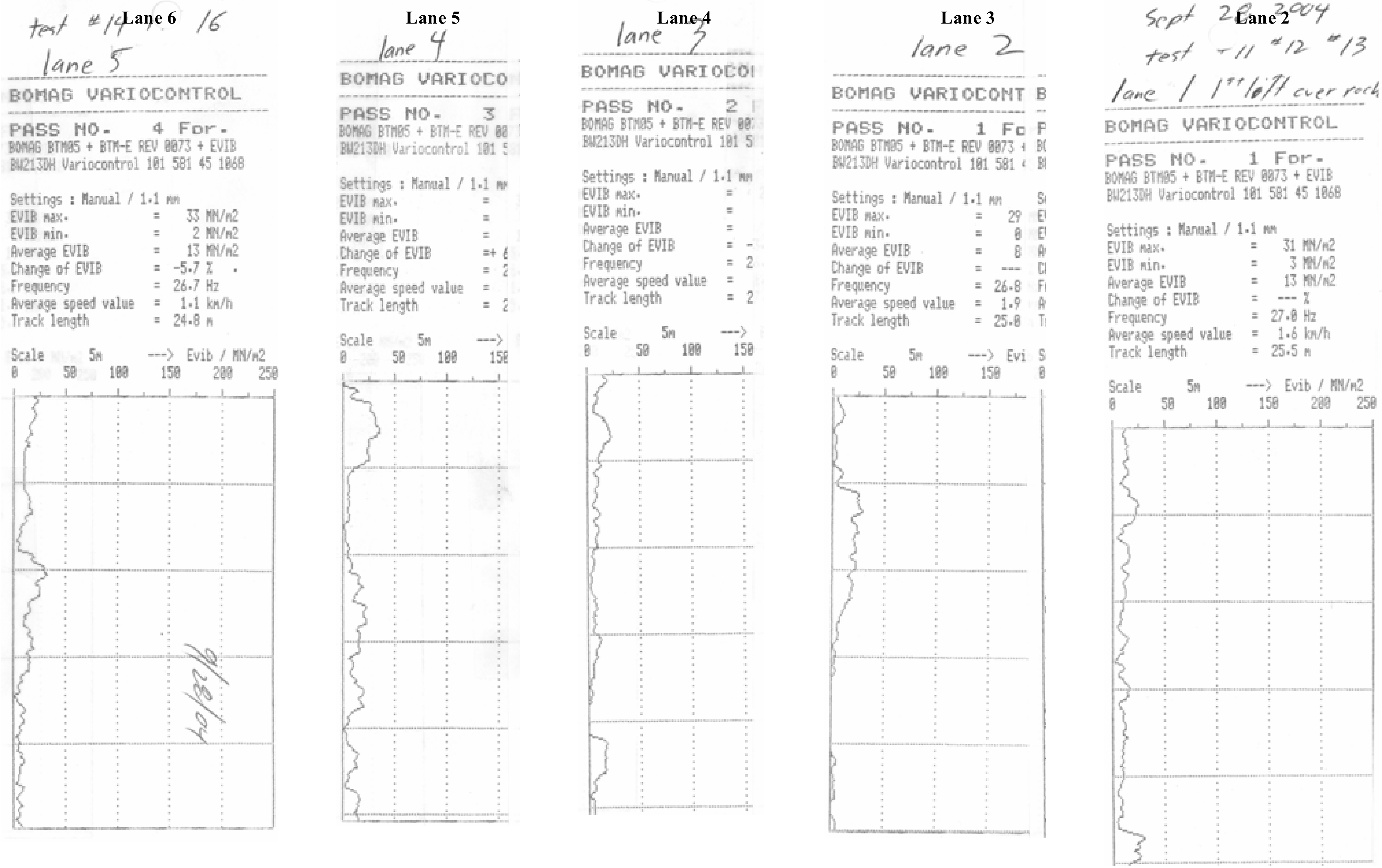


Figure A.8

BOMAG Paper Strips – Lift 6 Lane 2-6

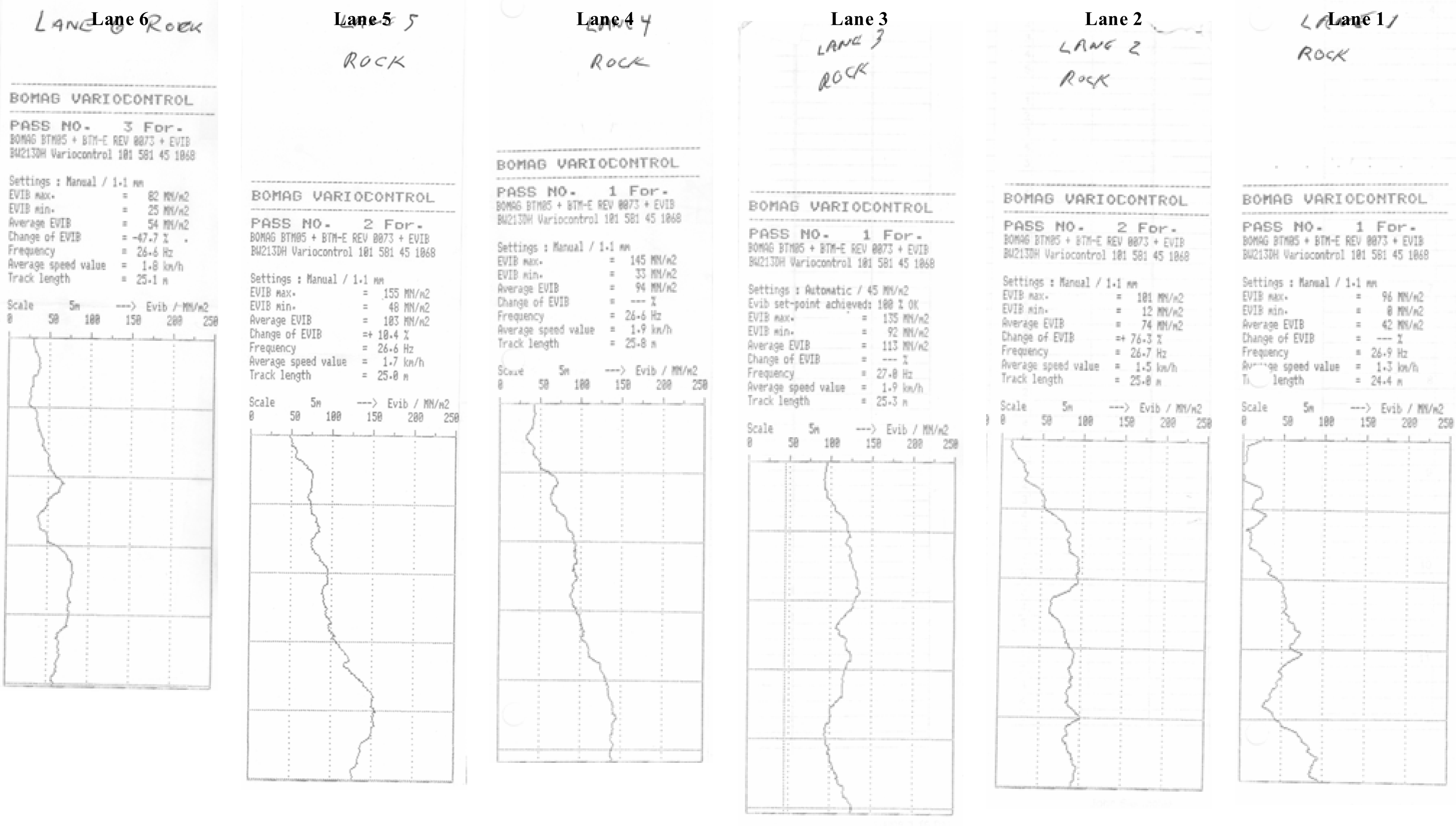


Figure A.9

BOMAG Paper Strips – Lift 8 Lane 1-6

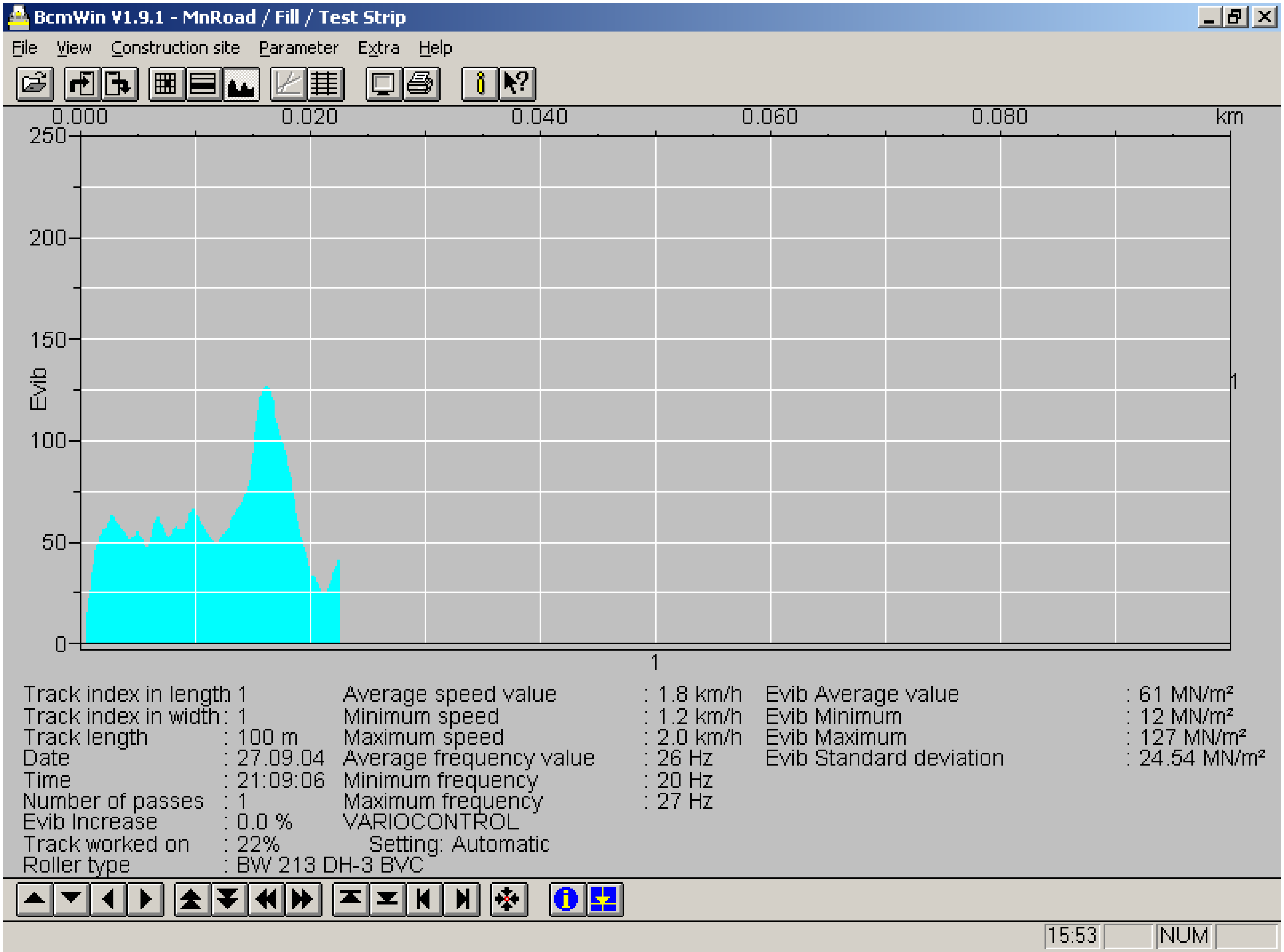


Figure A.10

BOMAG Electronic Record – Lift 1B Lane 2

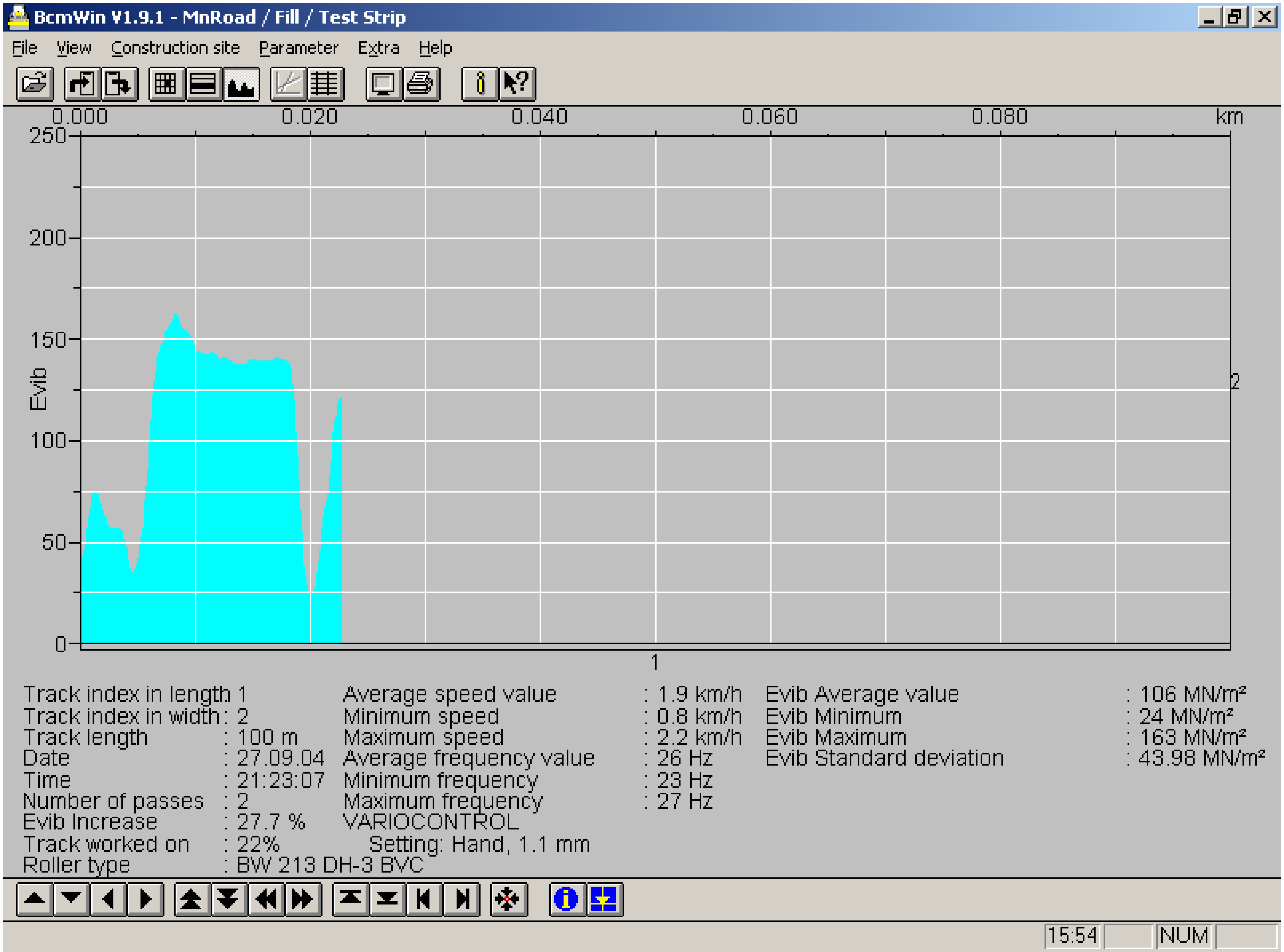


Figure A.11

BOMAG Electronic Record – Lift 1B Lane 3

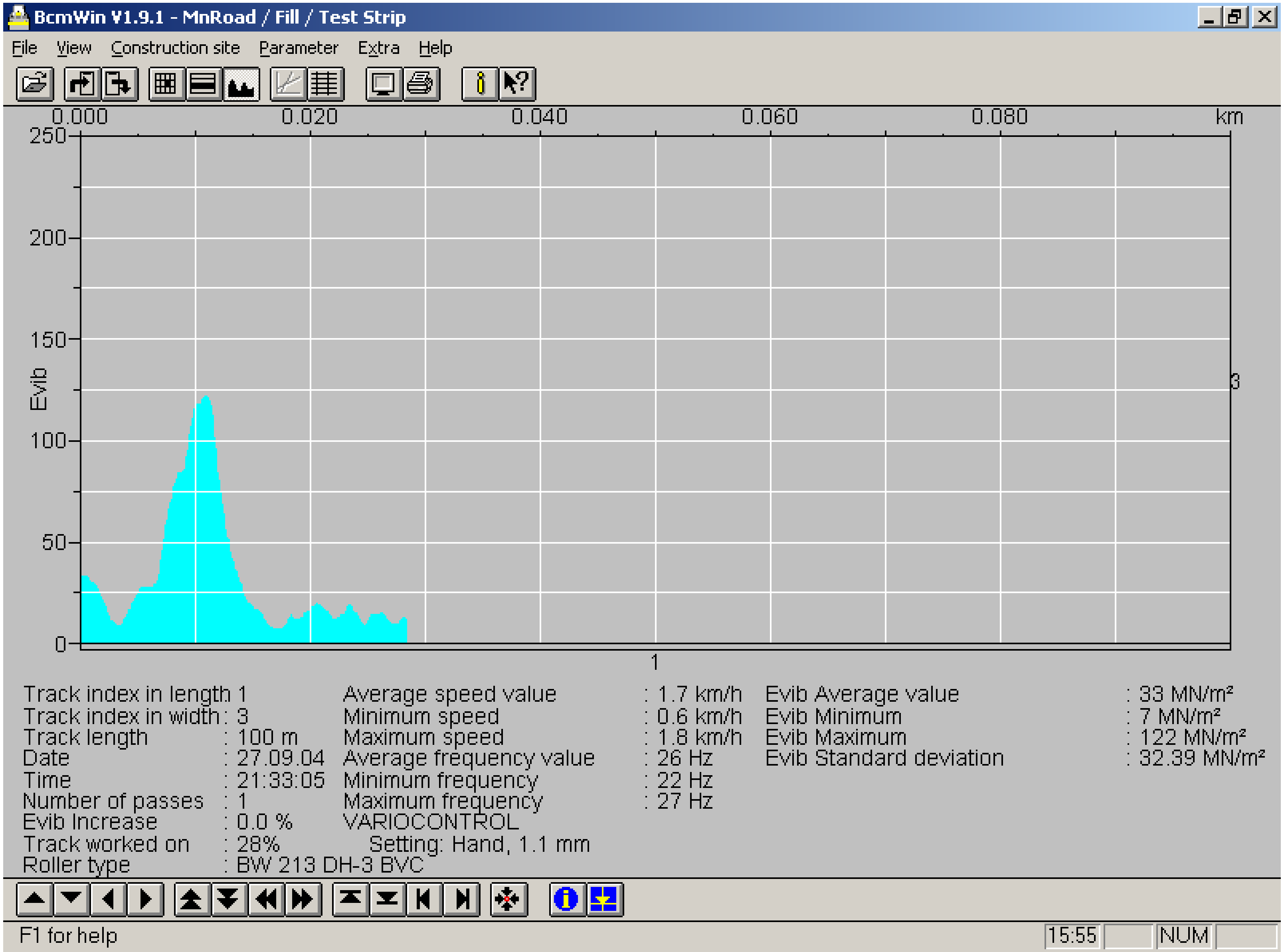


Figure A.12

BOMAG Electronic Record – Lift 1B Lane 4

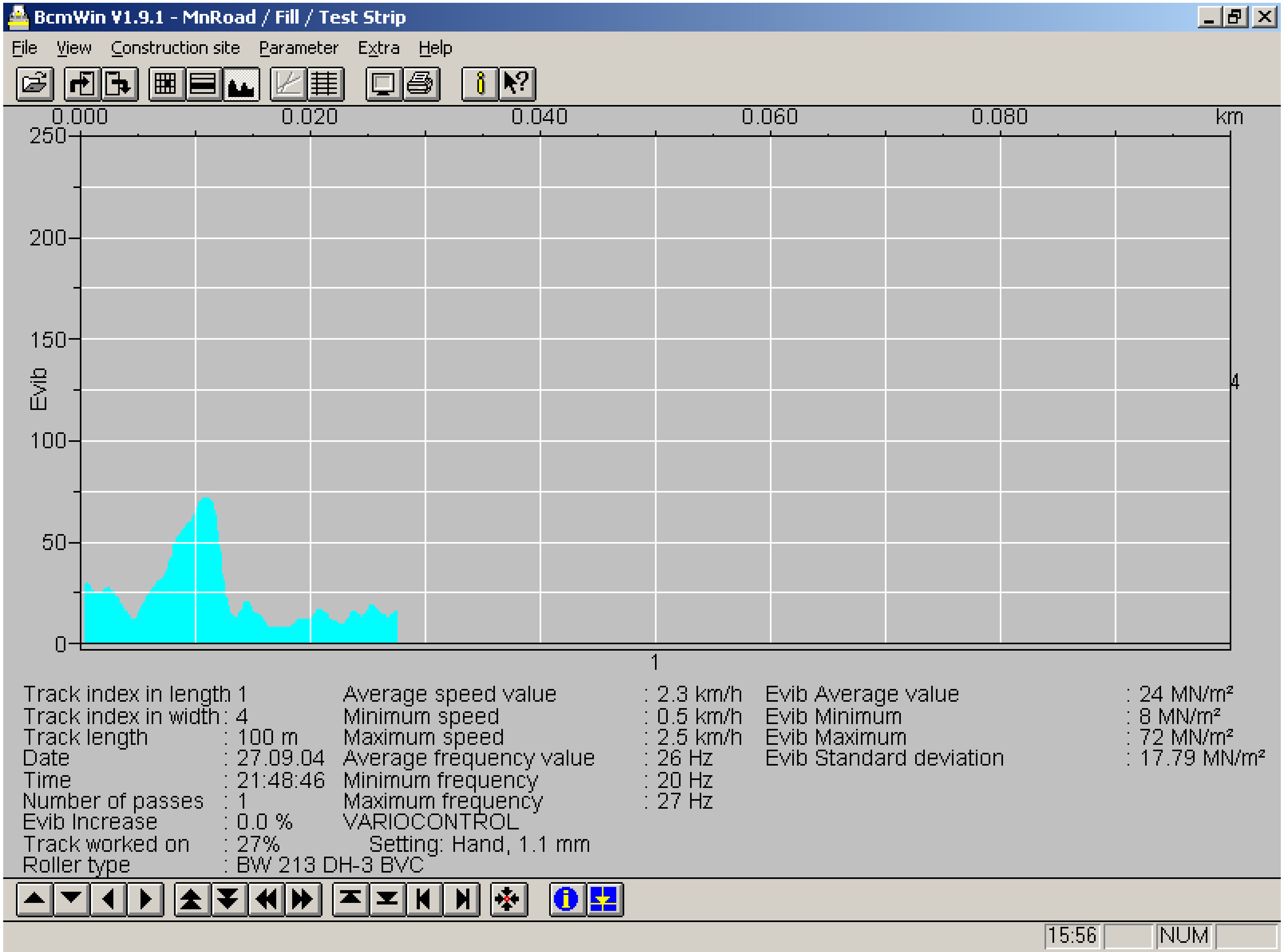


Figure A.13

BOMAG Electronic Record – Lift 1B Lane 5

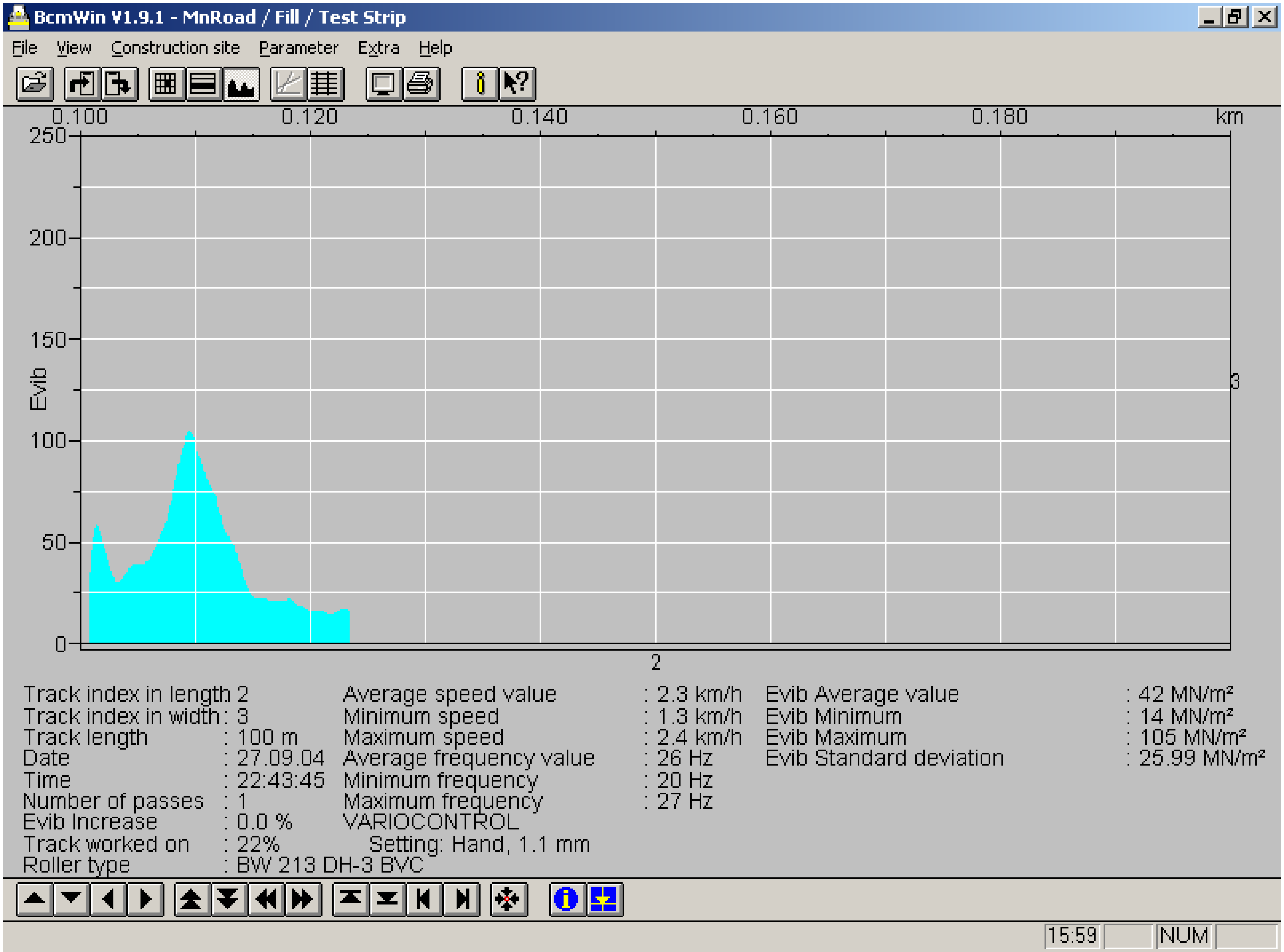


Figure A.14

BOMAG Electronic Record – Lift 2 Lane 4

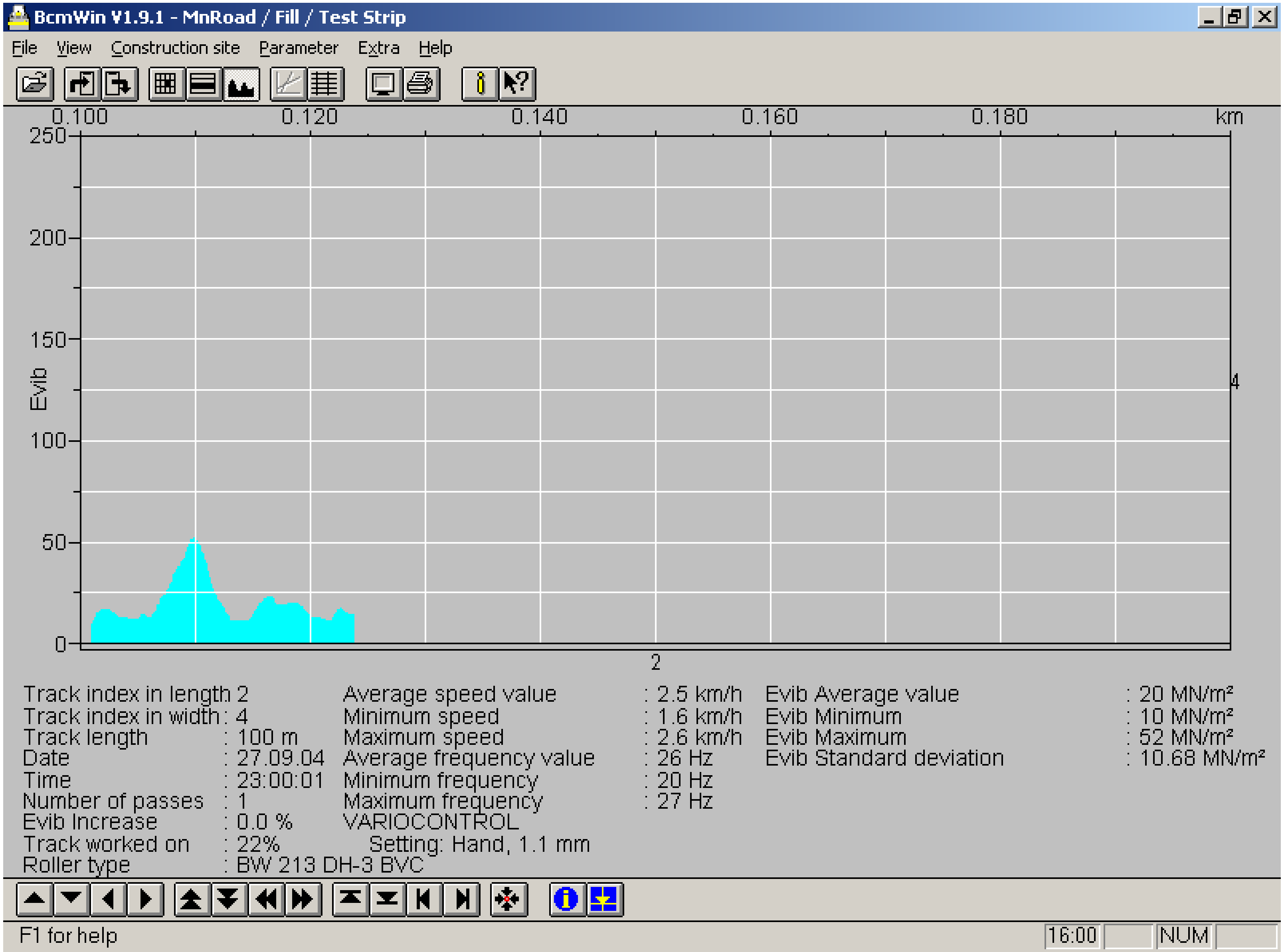


Figure A.15

BOMAG Electronic Record – Lift 2 Lane 5

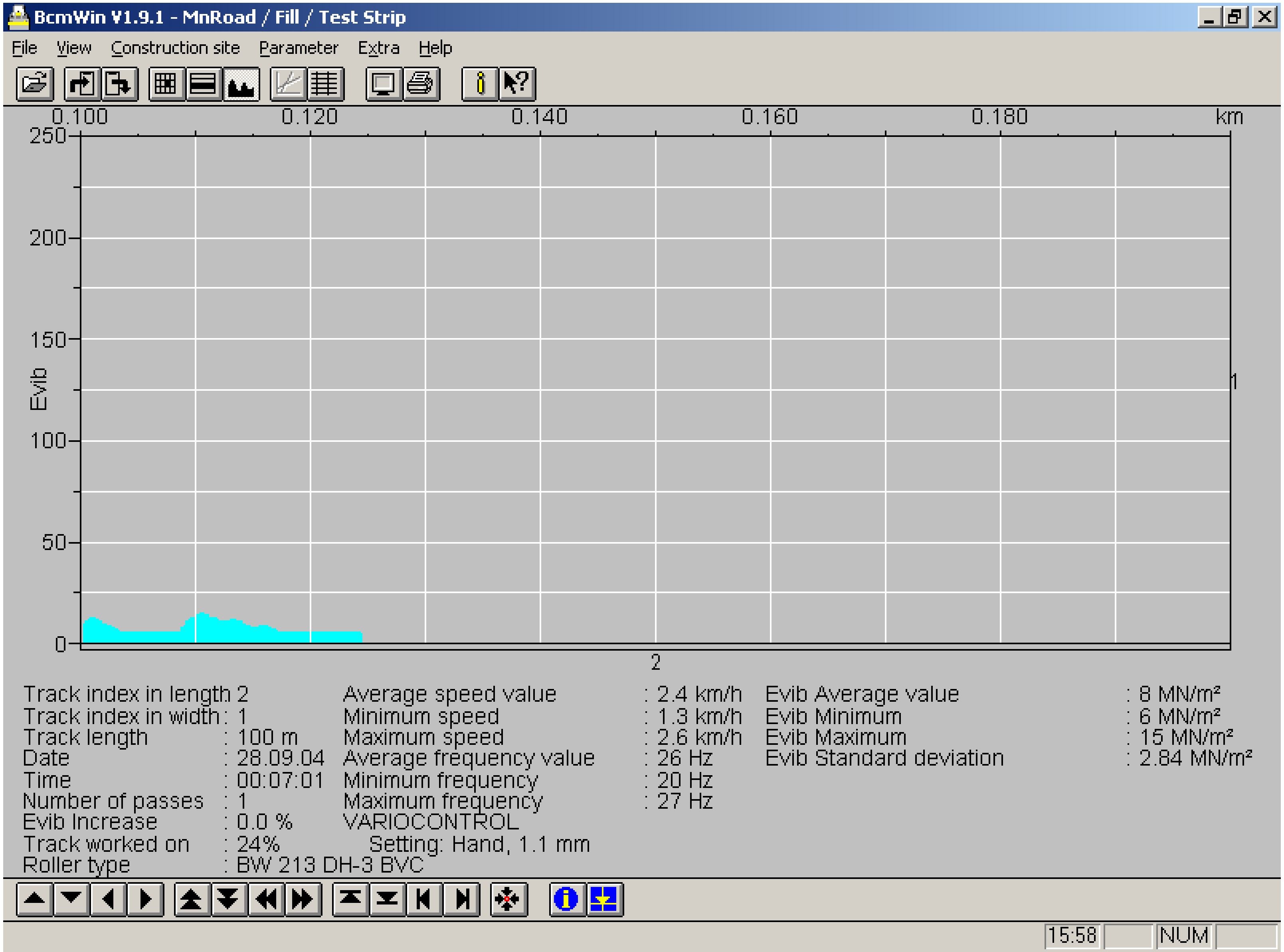


Figure A.16

BOMAG Electronic Record – Lift 3 Lane 2

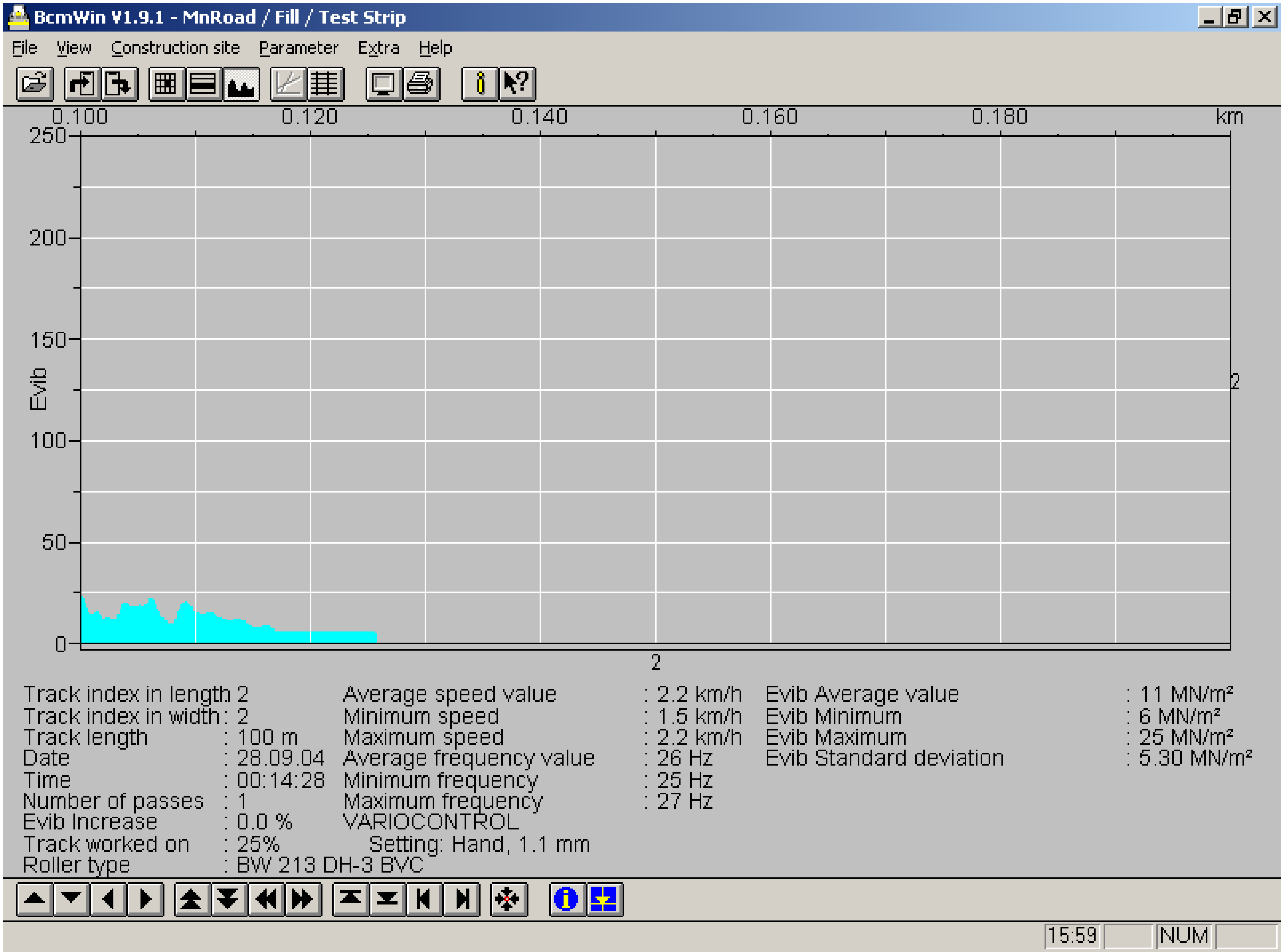


Figure A.17

BOMAG Electronic Record – Lift 3 Lane 3

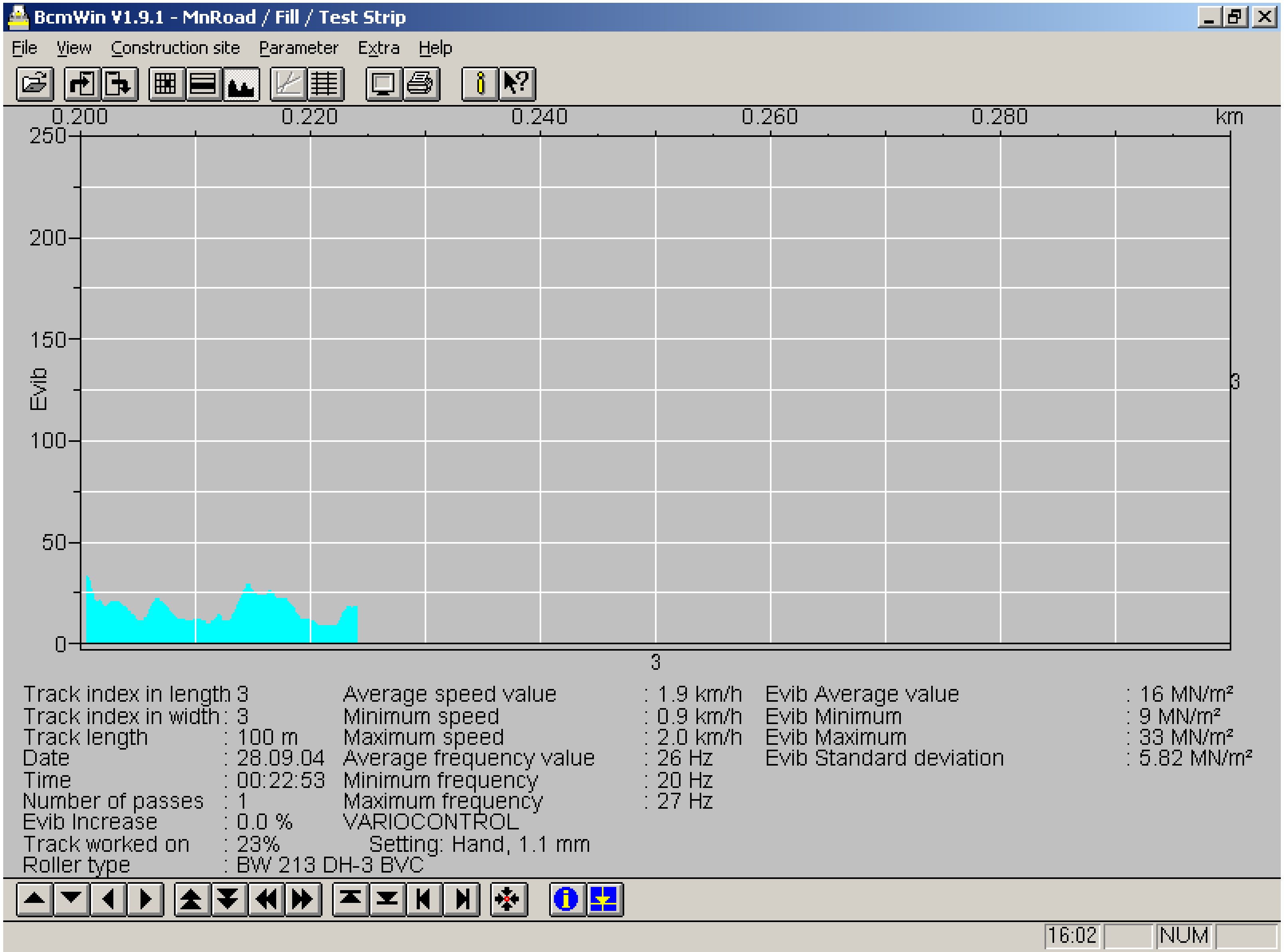


Figure A.18

BOMAG Electronic Record – Lift 3 Lane 4

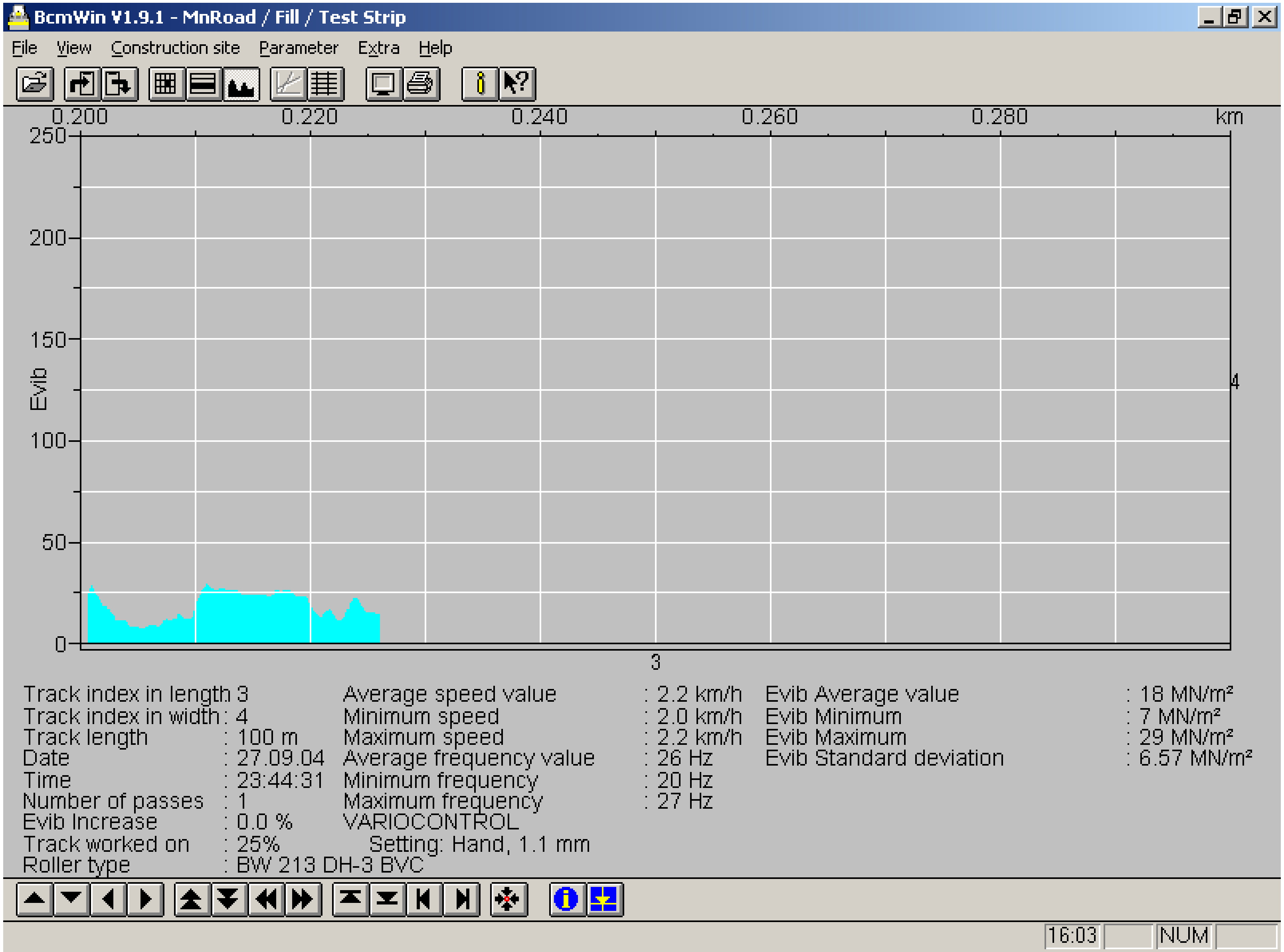


Figure A.19

BOMAG Electronic Record – Lift 3 Lane 5

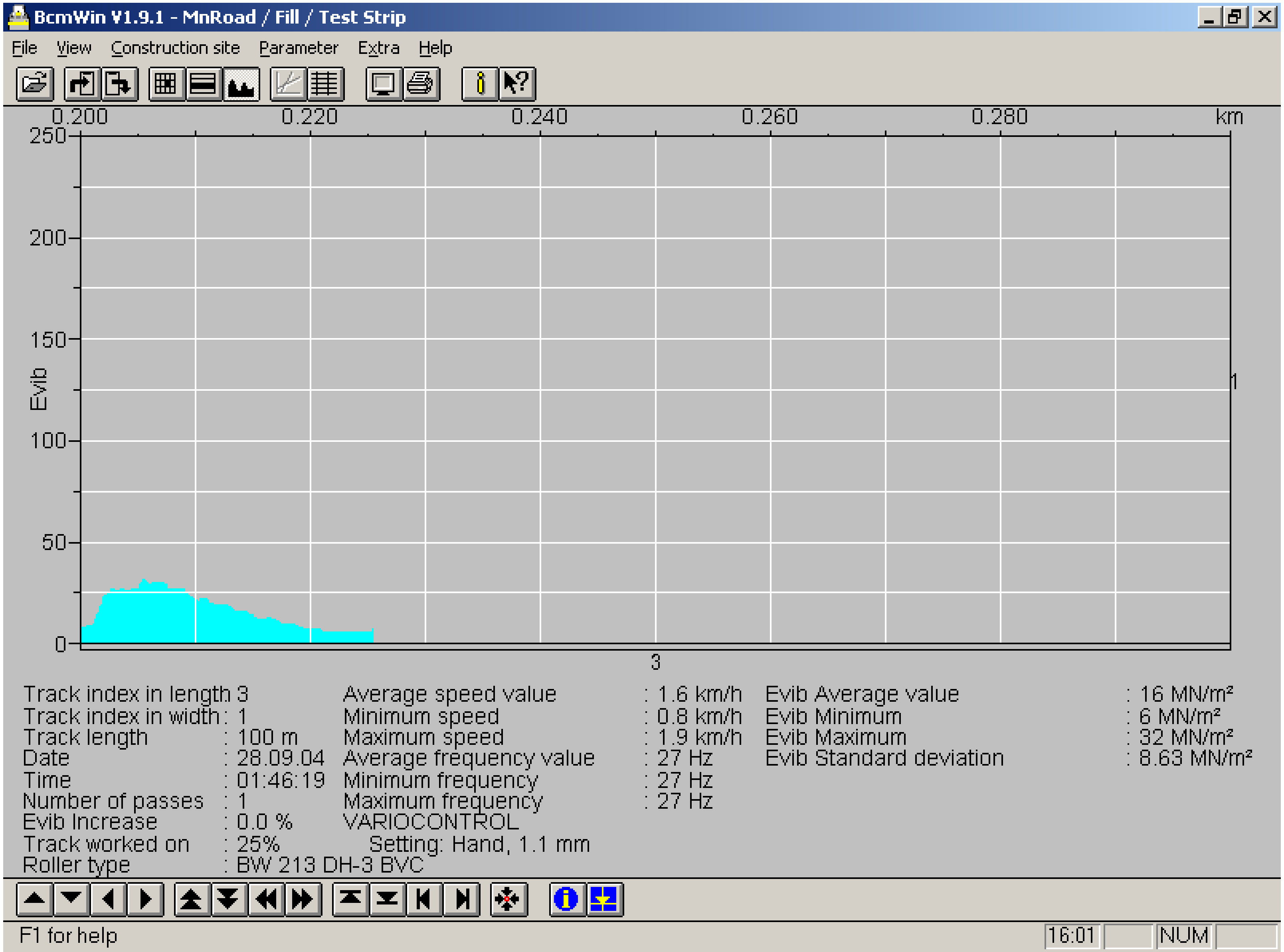


Figure A.20

BOMAG Electronic Record – Lift 4 Lane 2

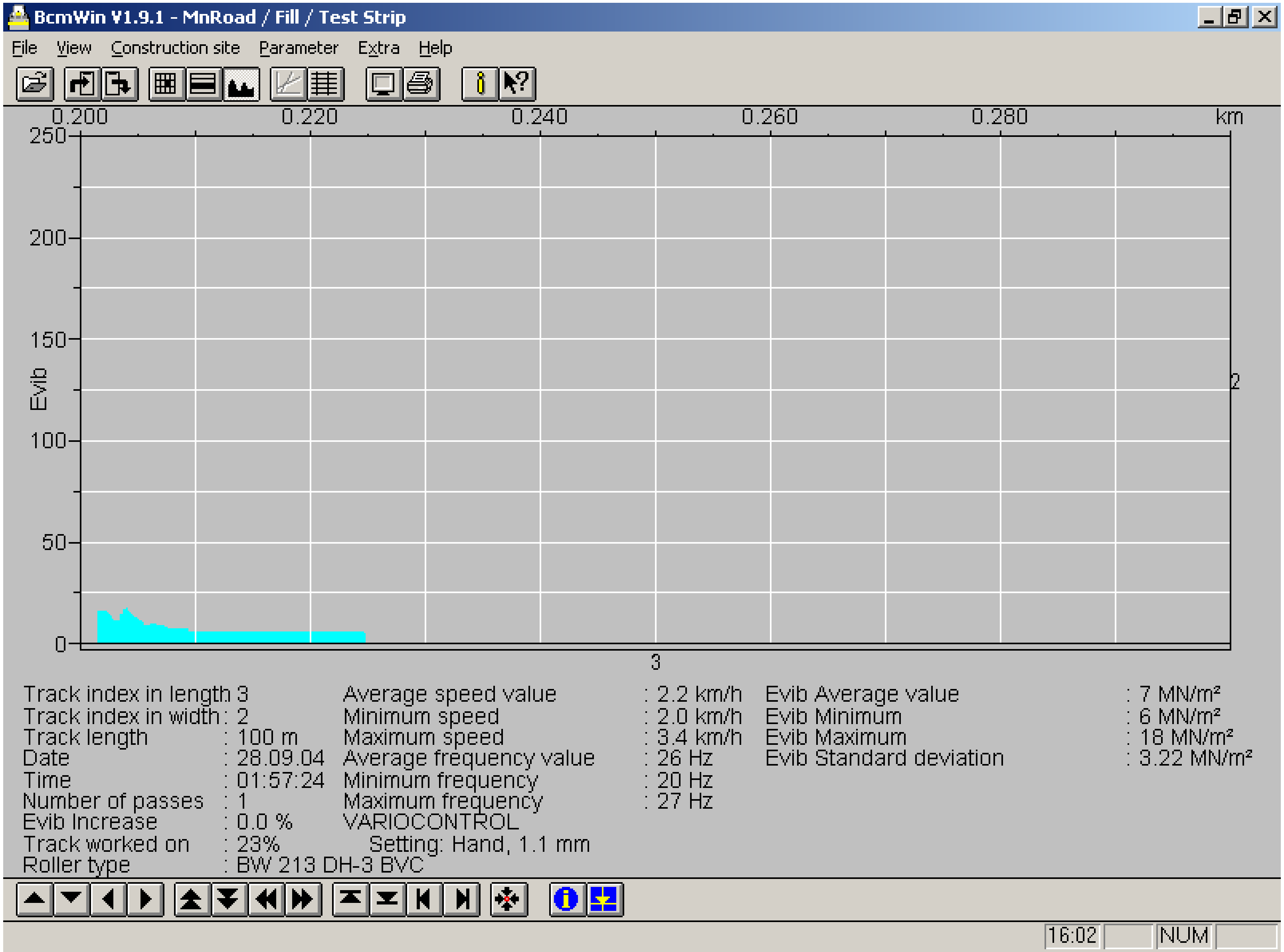


Figure A.21

BOMAG Electronic Record – Lift 4 Lane 3

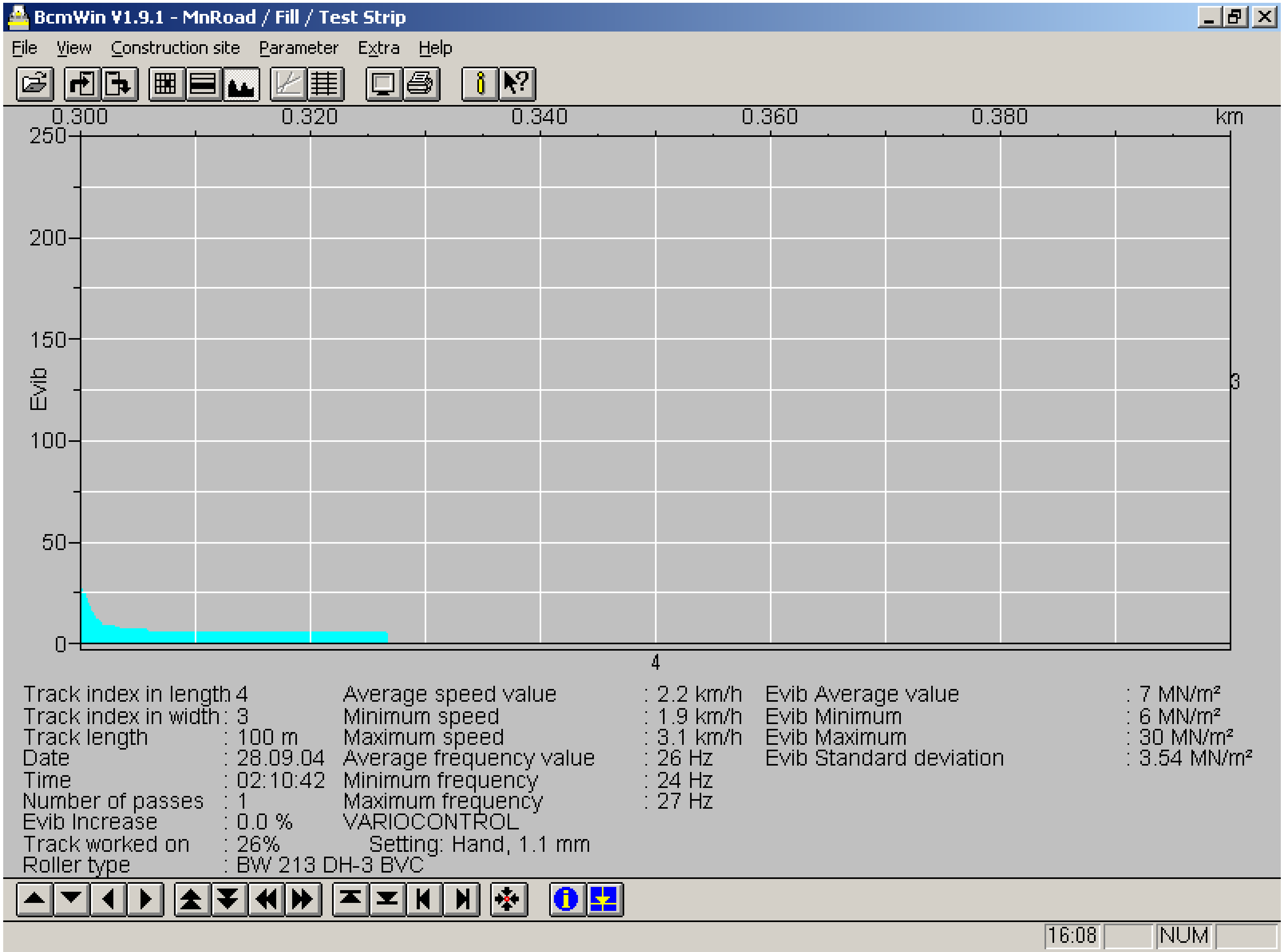


Figure A.22

BOMAG Electronic Record – Lift 4 Lane 4

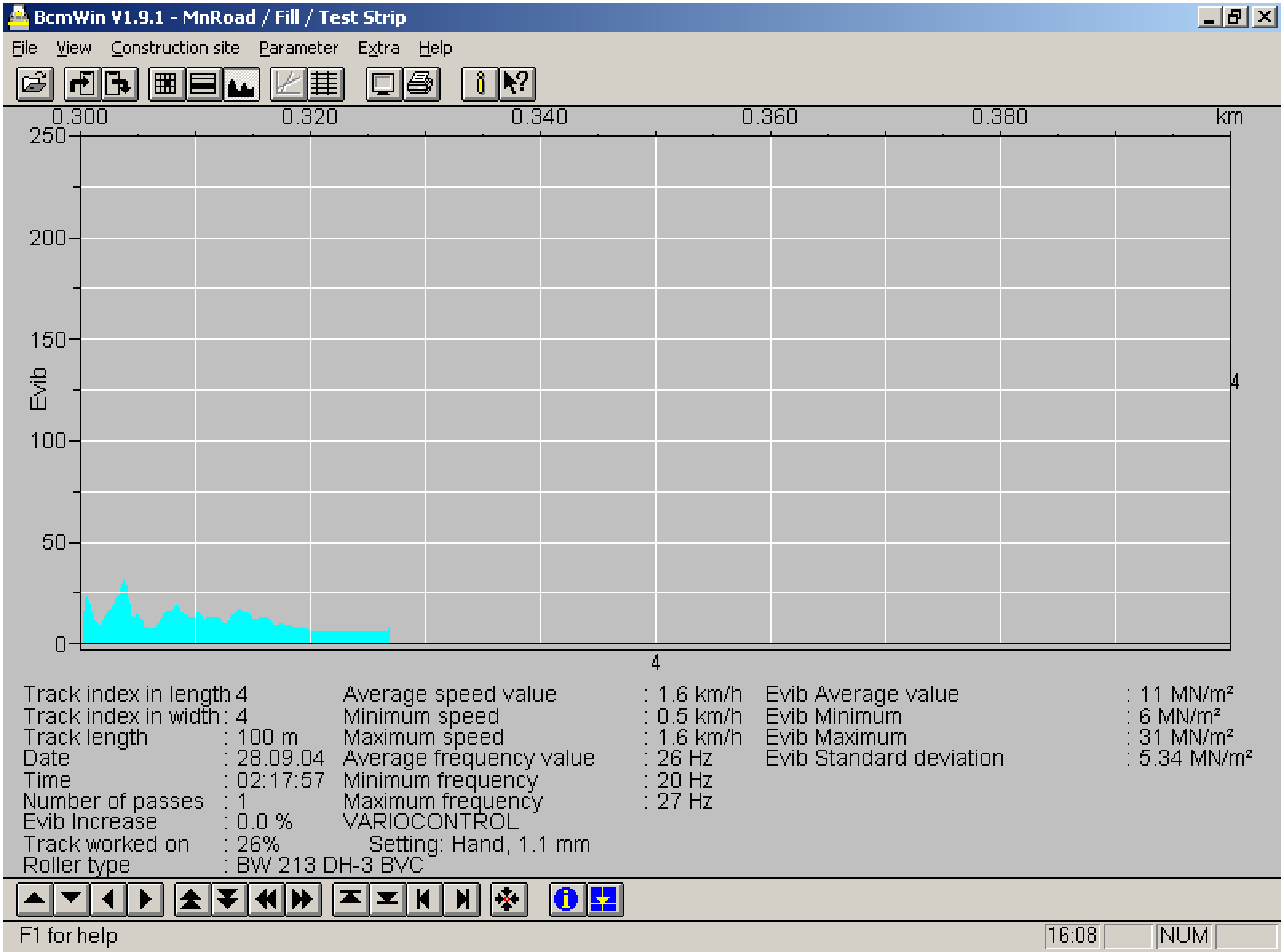


Figure A.23

BOMAG Electronic Record – Lift 4 Lane 5

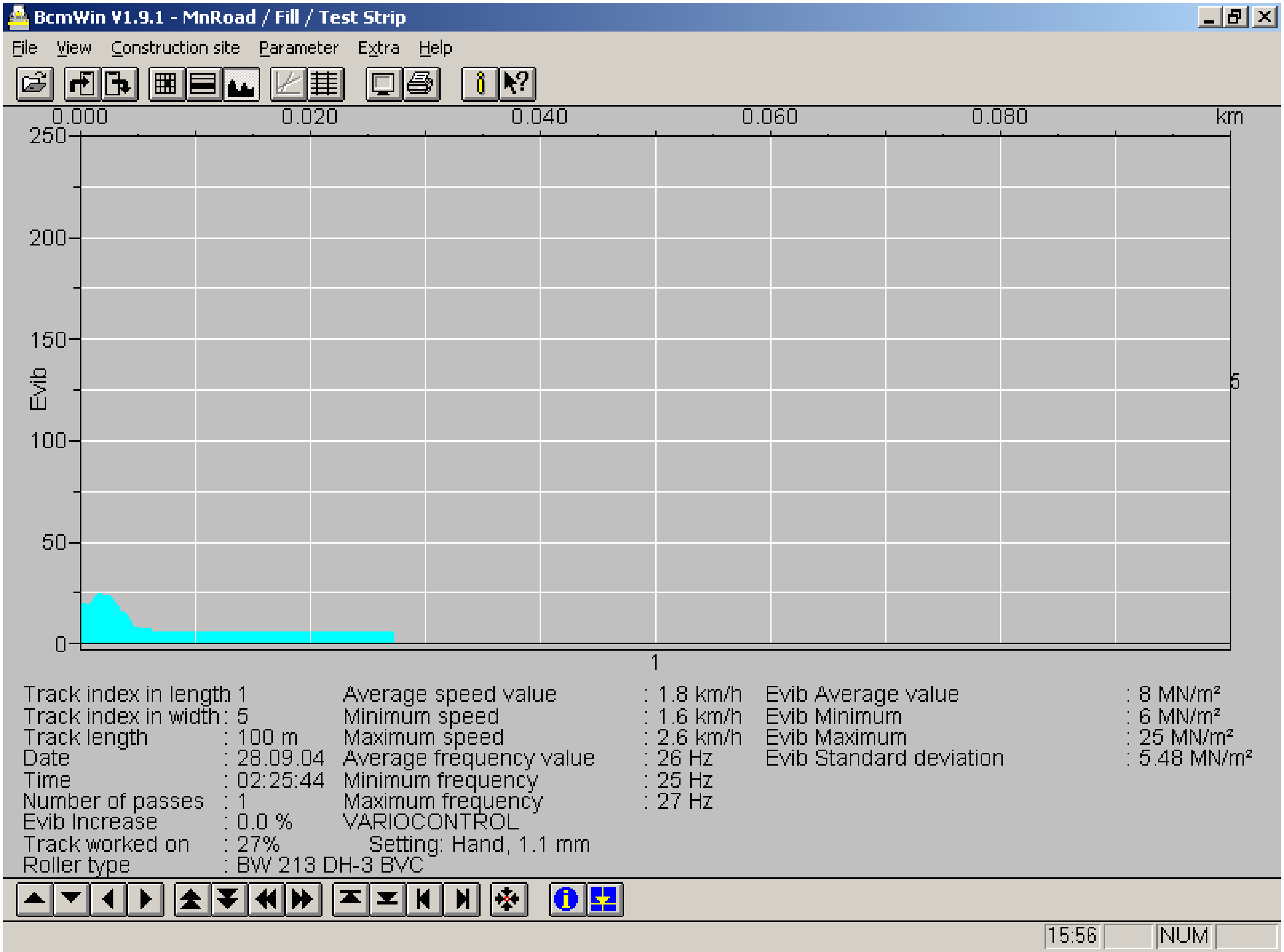


Figure A.24

BOMAG Electronic Record – Lift 4 Lane 6

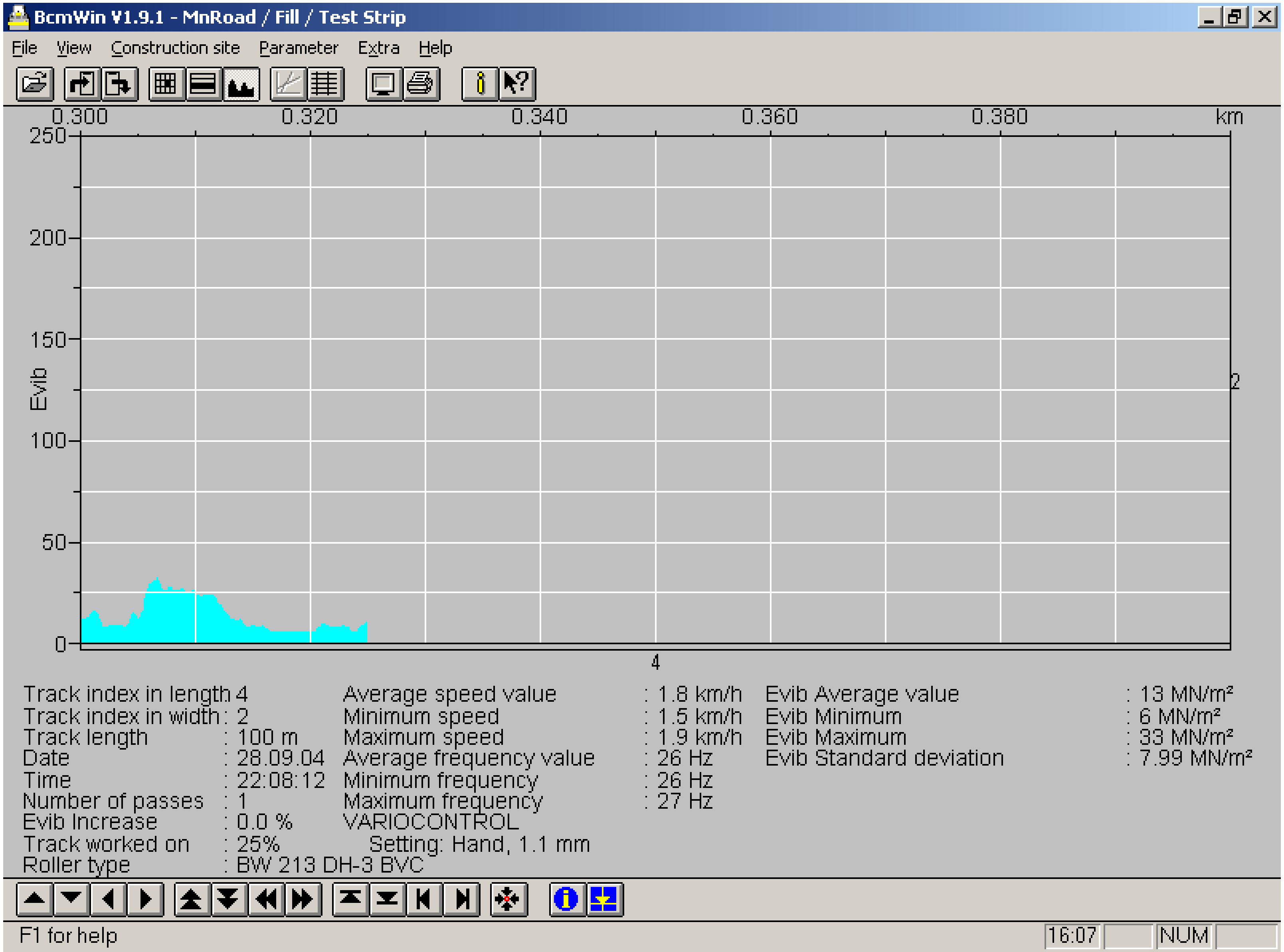


Figure A.25

BOMAG Electronic Record – Lift 5 Lane 3

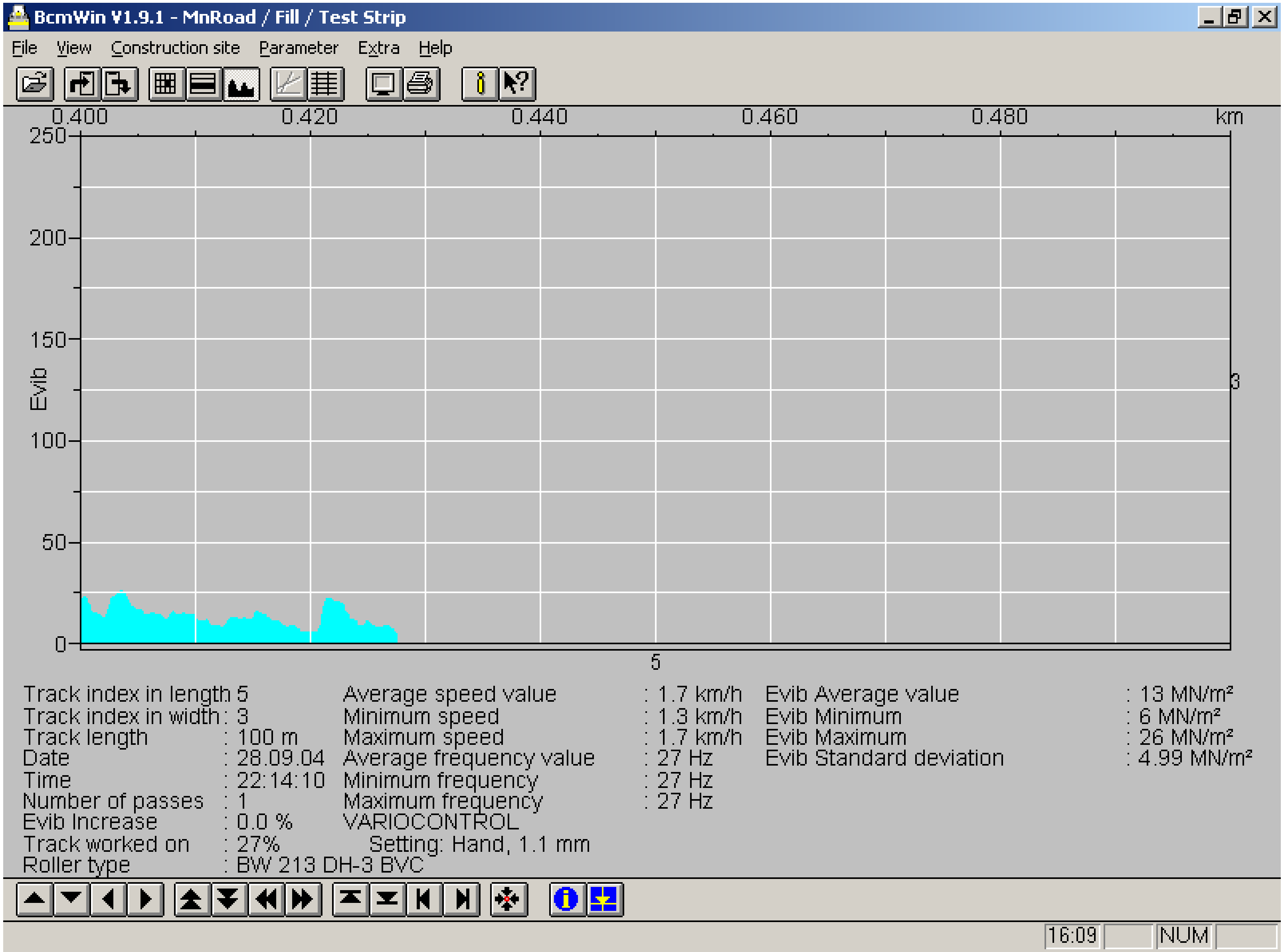


Figure A.26

BOMAG Electronic Record – Lift 5 Lane 4

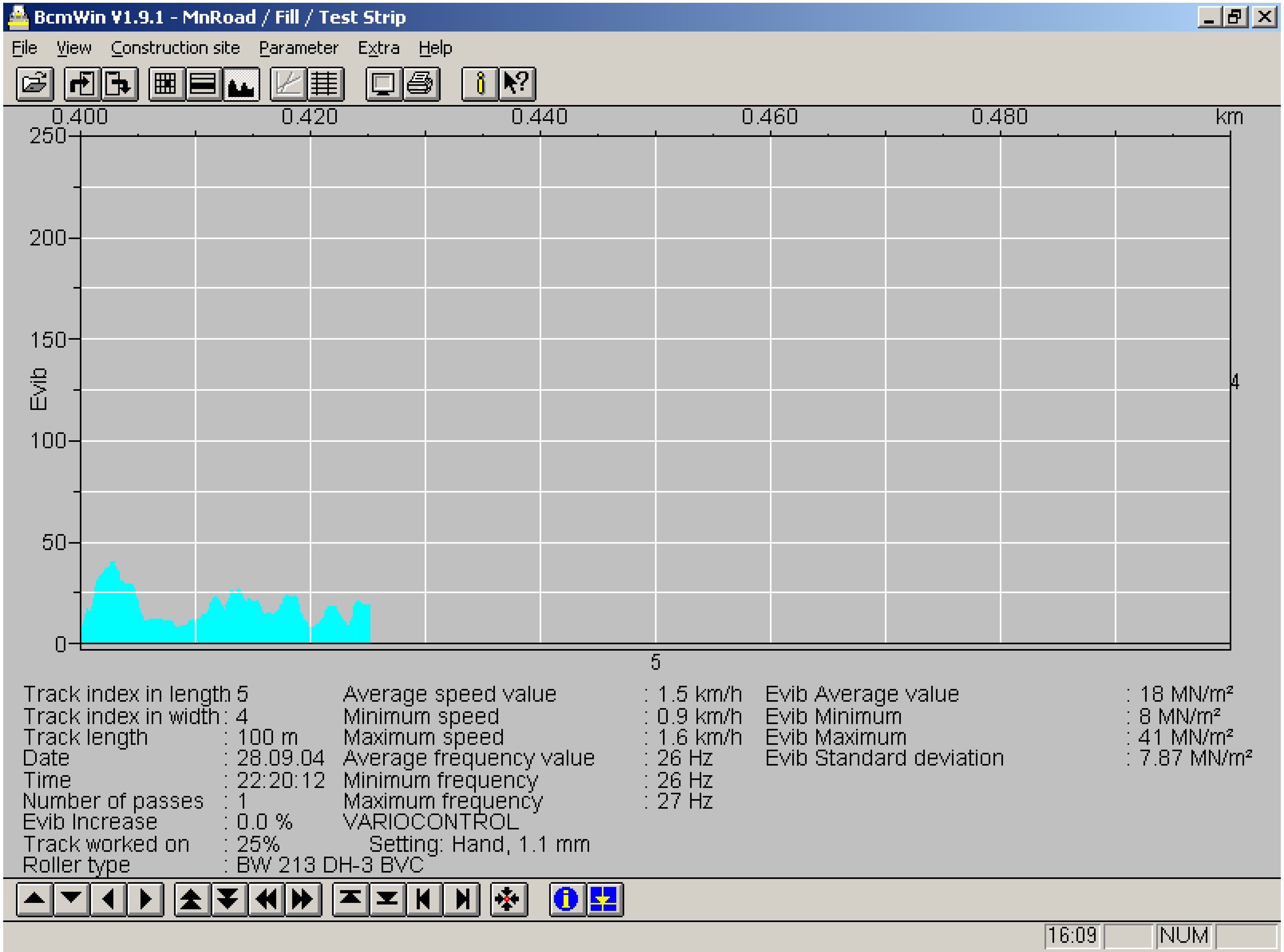


Figure A.27

BOMAG Electronic Record – Lift 5 Lane 5

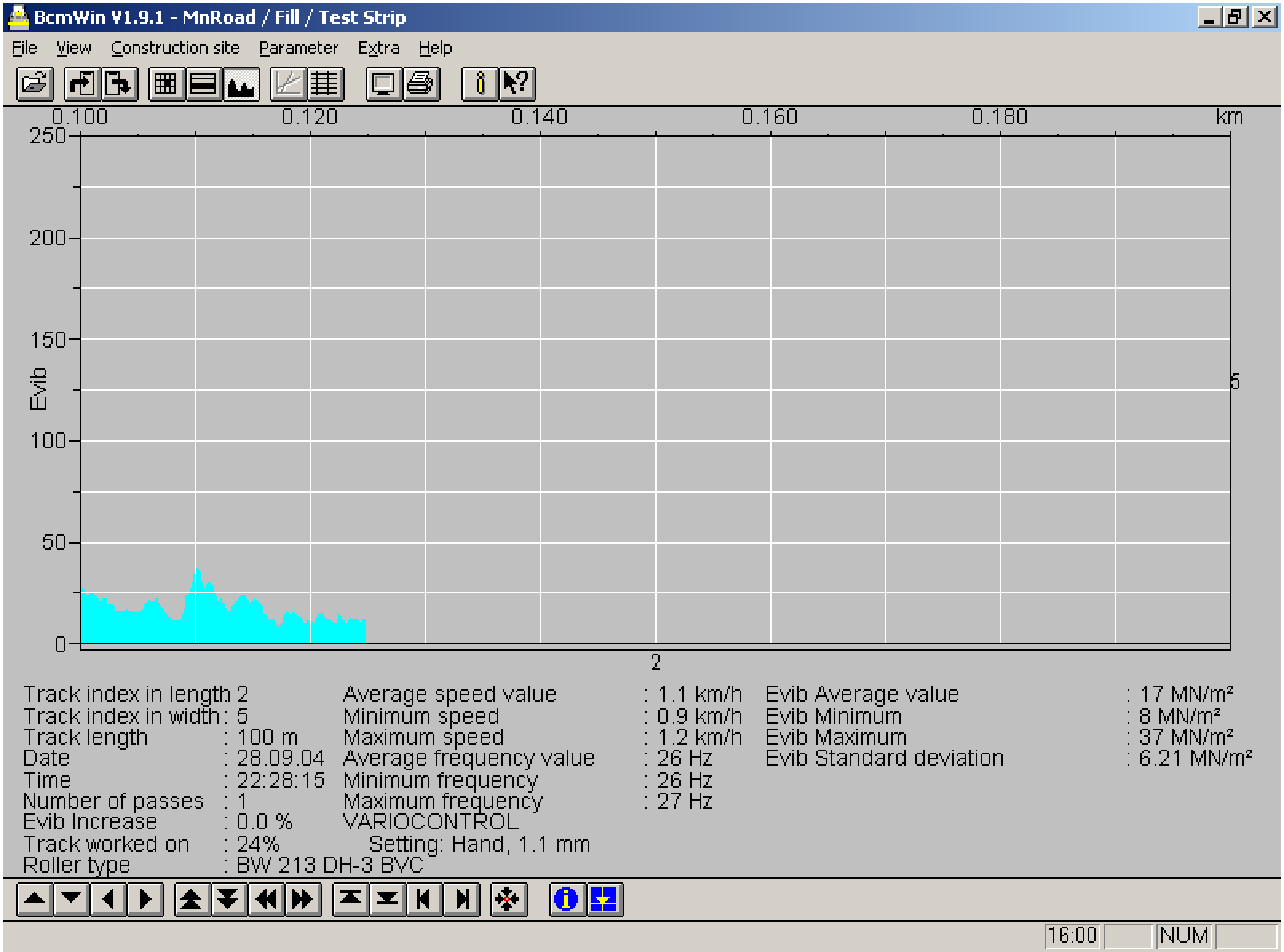


Figure A.28

BOMAG Electronic Record – Lift 5 Lane 6

Appendix B

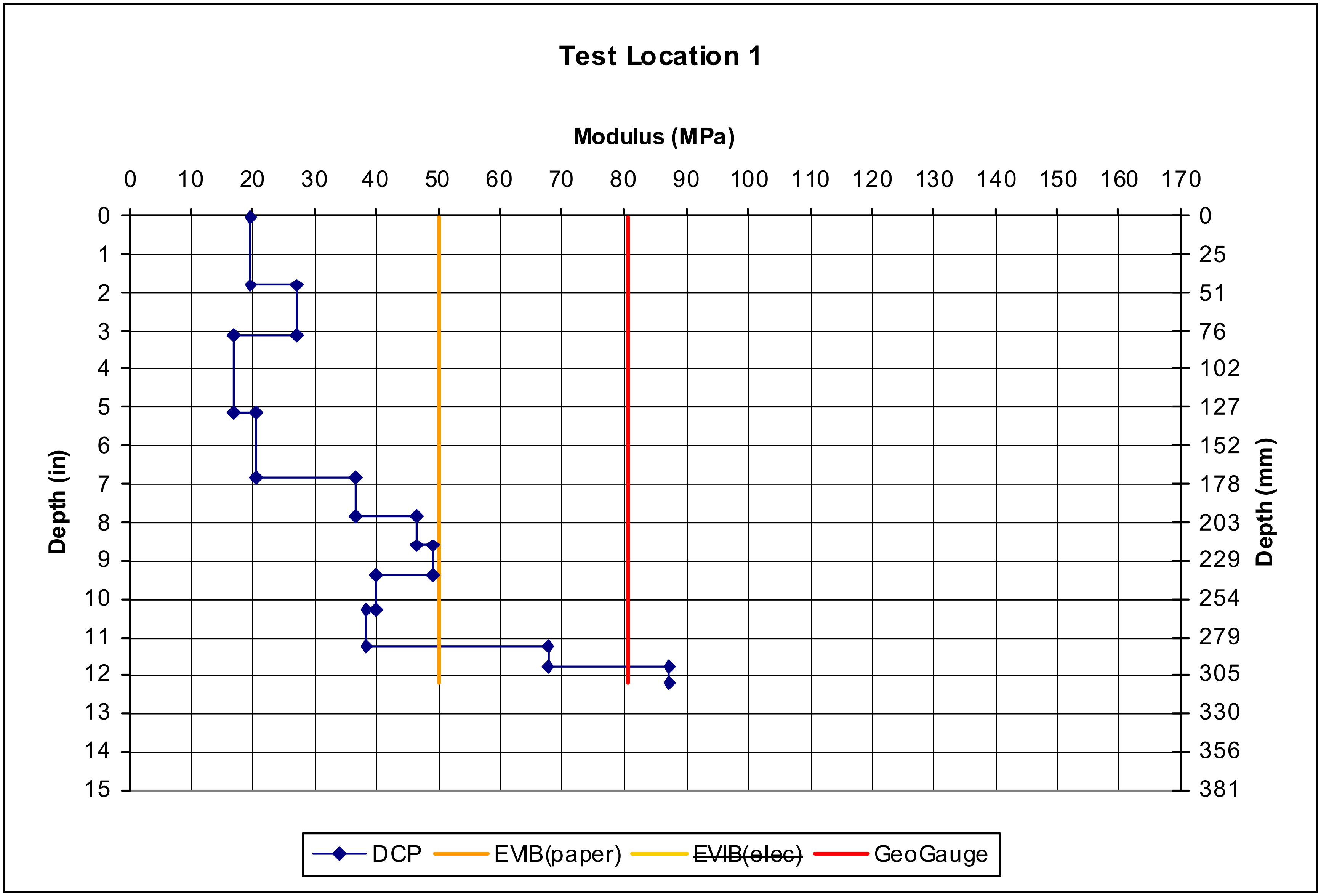


Figure B.1

DCP at Test Location 1

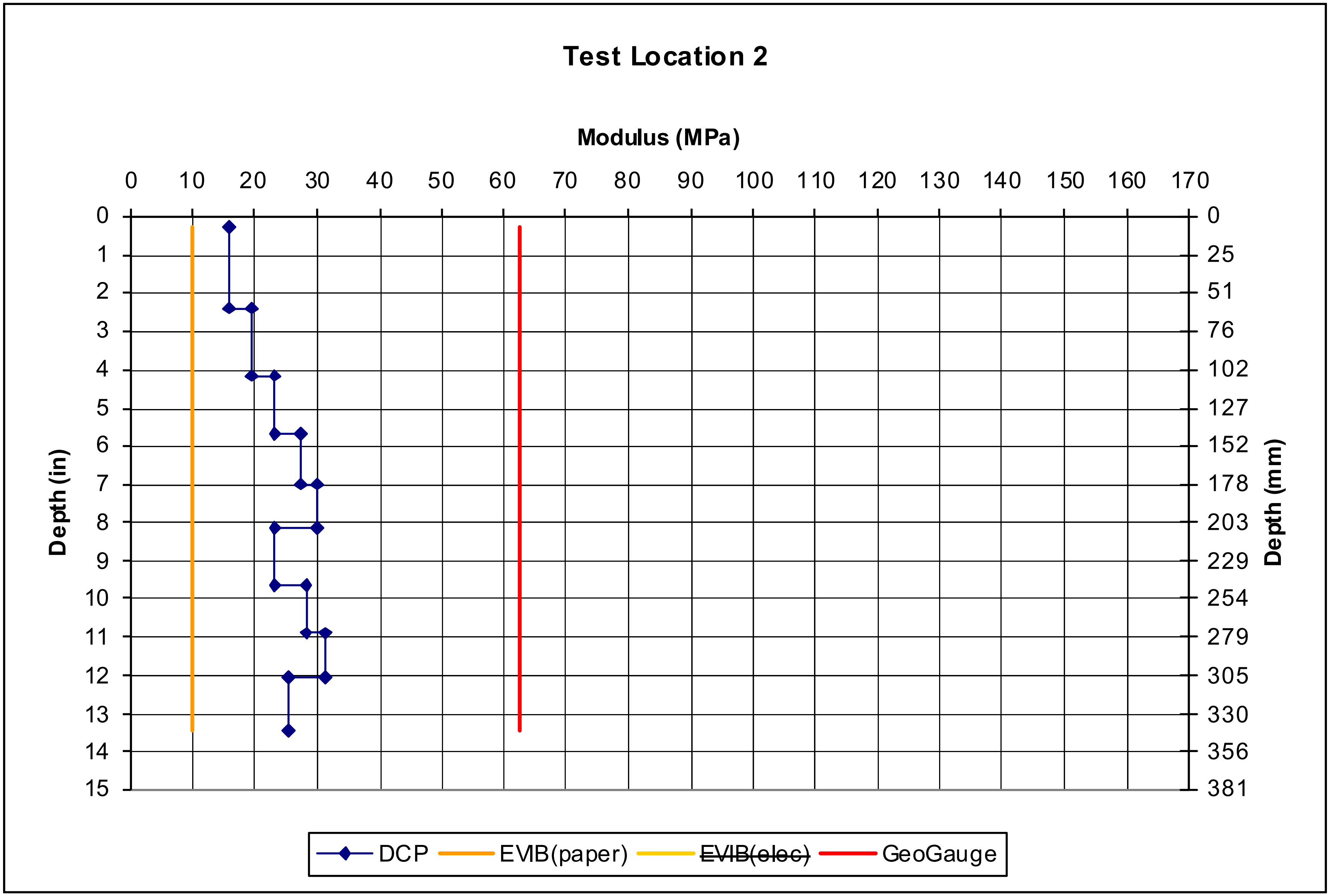


Figure B.2

DCP at Test Location 2

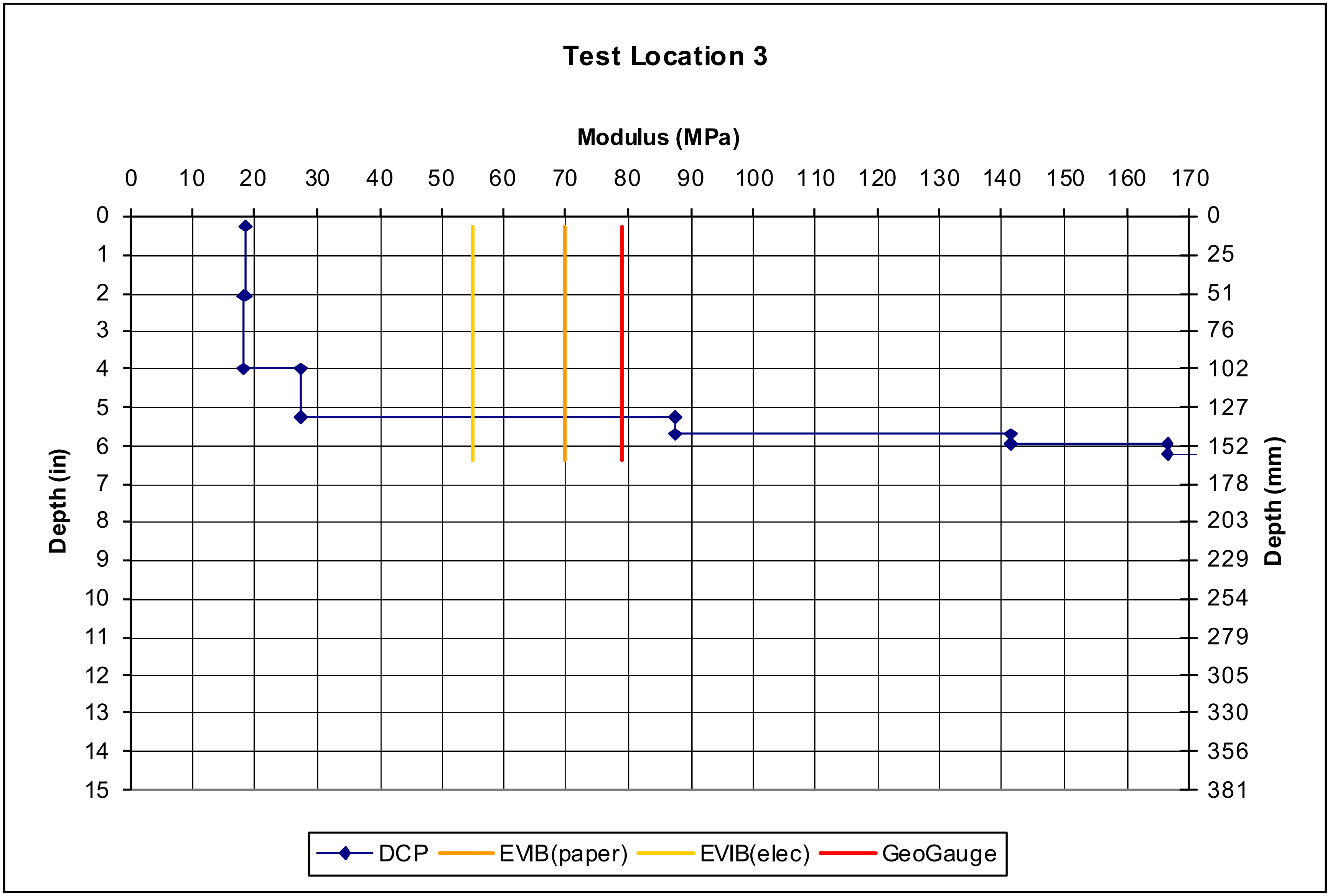


Figure B.3

DCP at Test Location 3

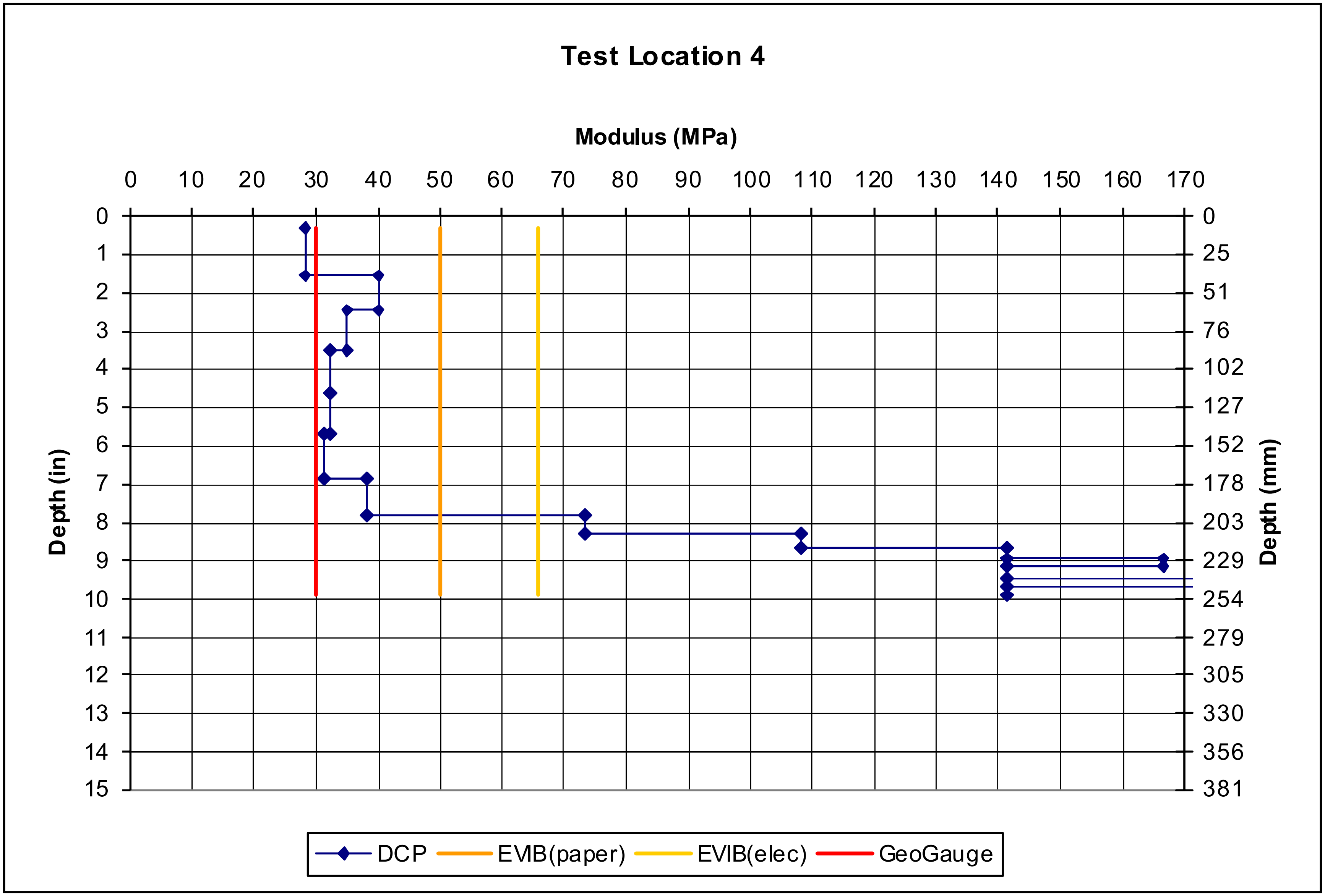


Figure B.4

DCP at Test Location 4

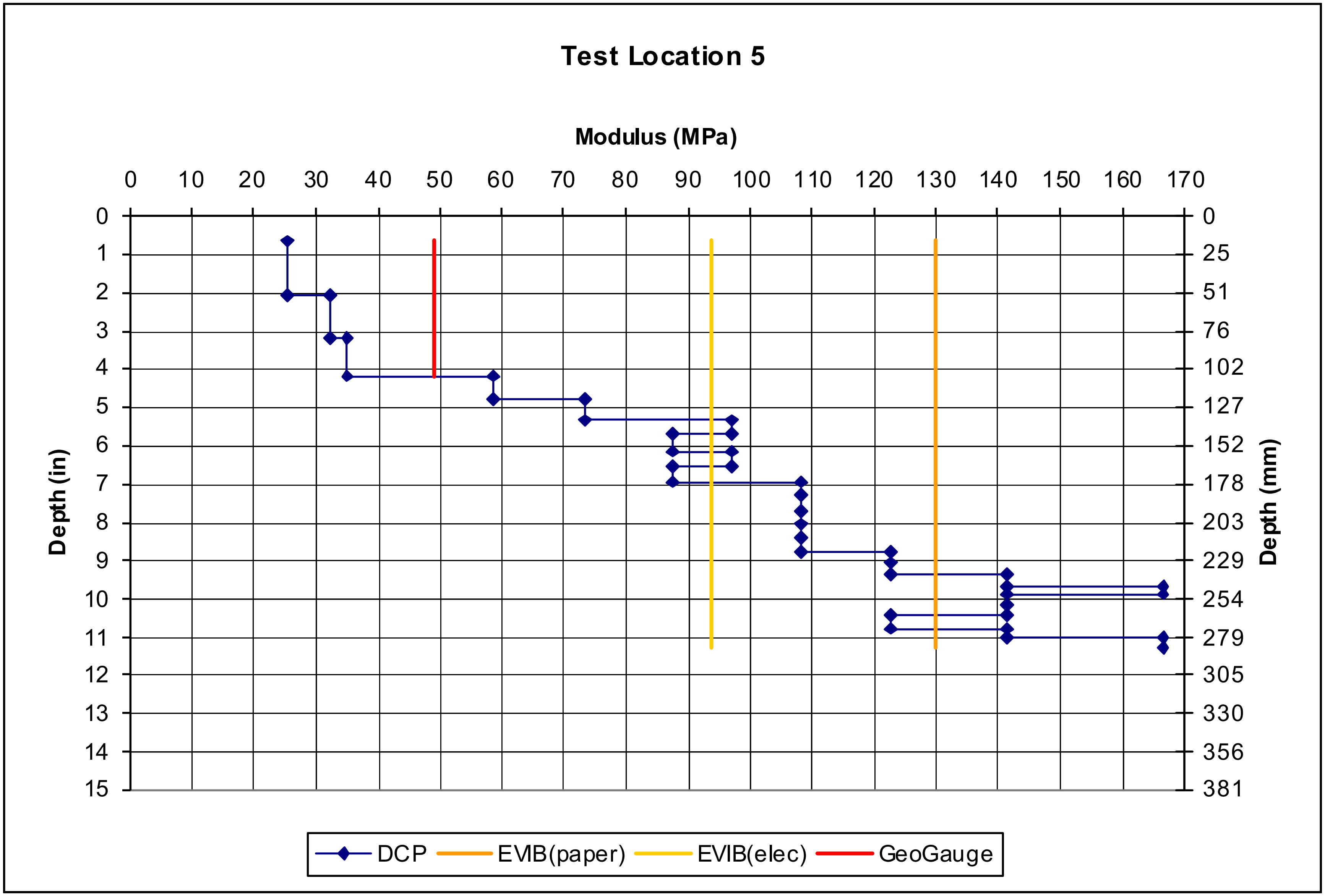


Figure B.5

DCP at Test Location 5

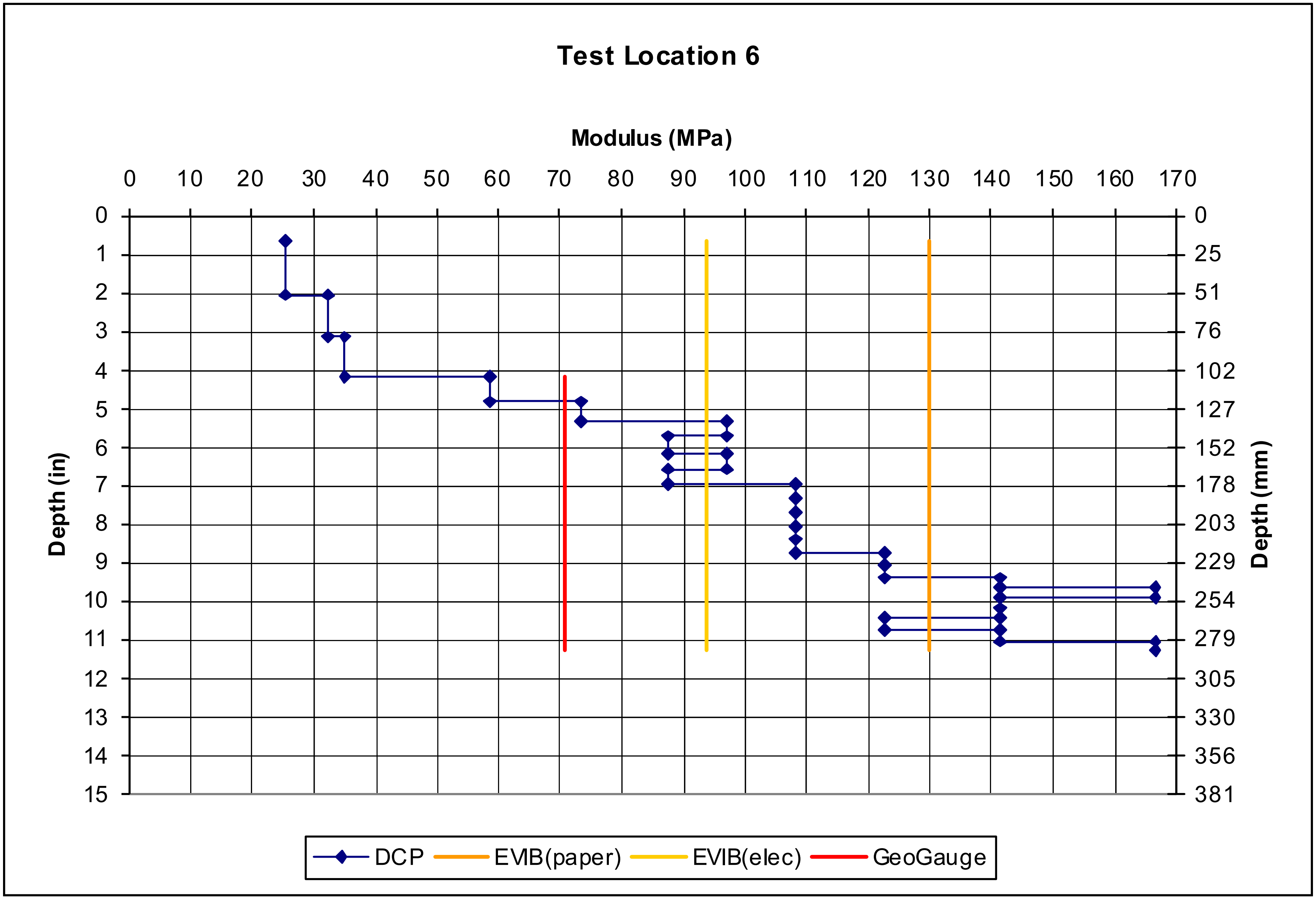


Figure B.6

DCP at Test Location 6

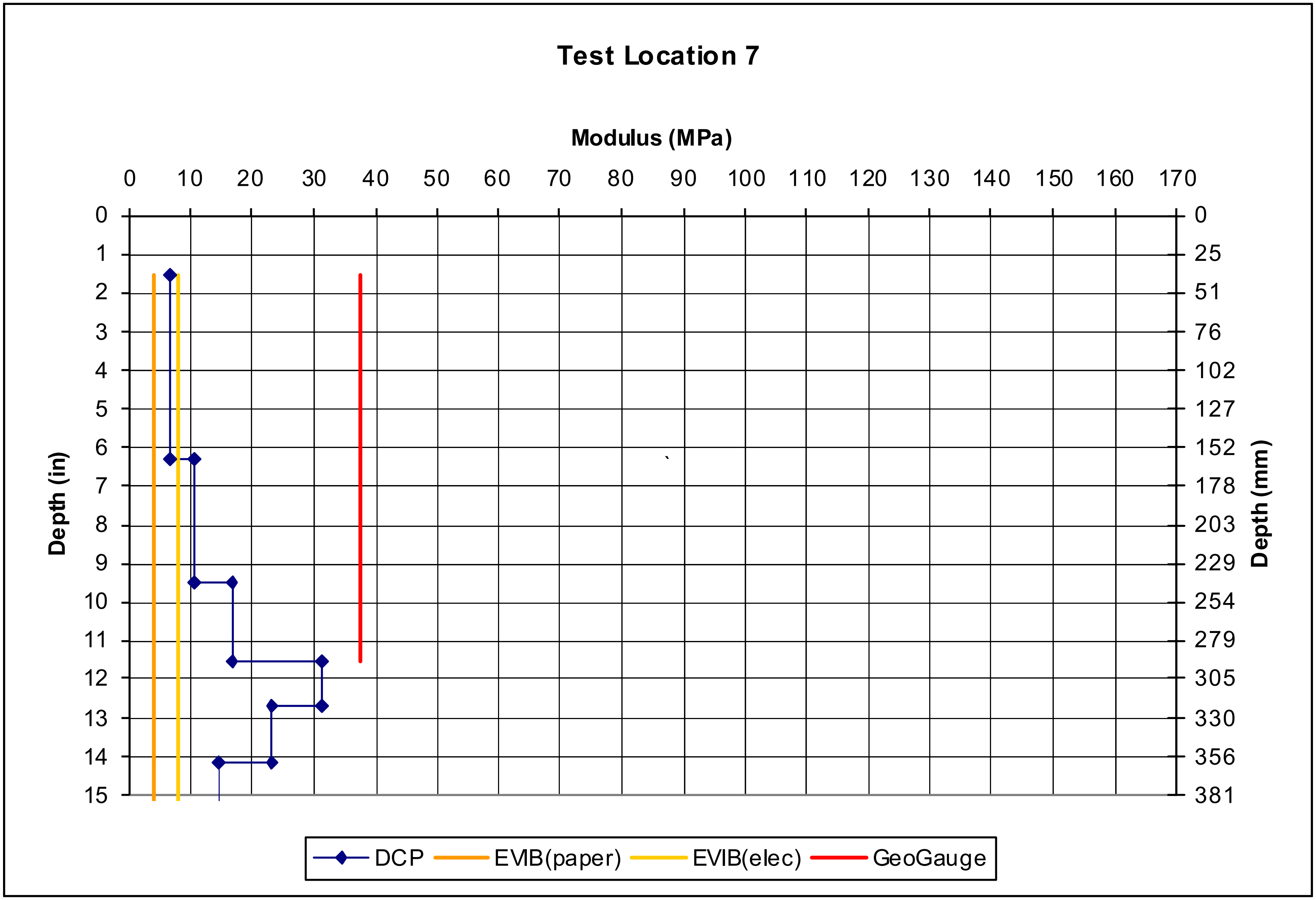


Figure B.7

DCP at Test Location 7

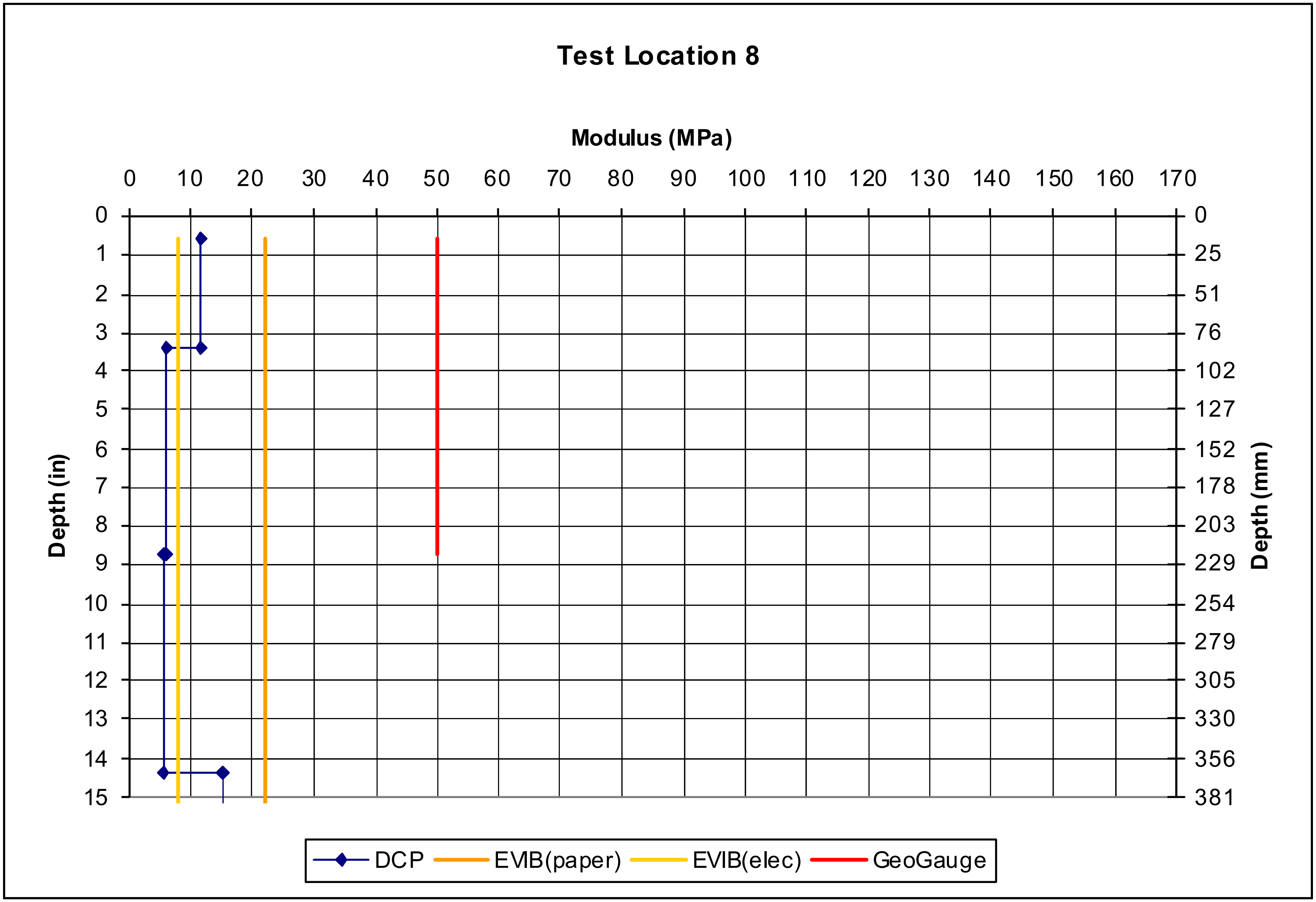


Figure B.8

DCP at Test Location 8

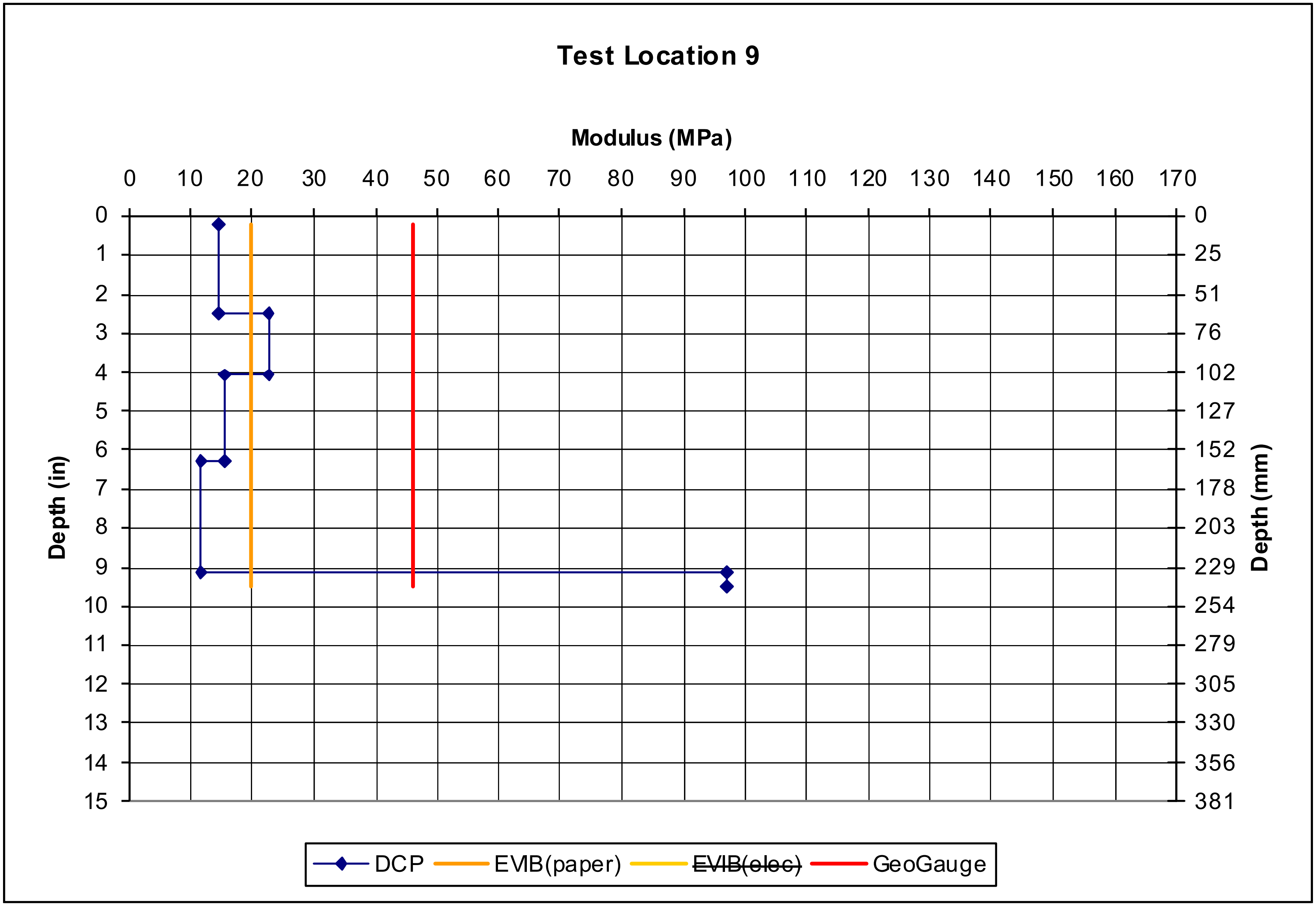


Figure B.9

DCP at Test Location 9

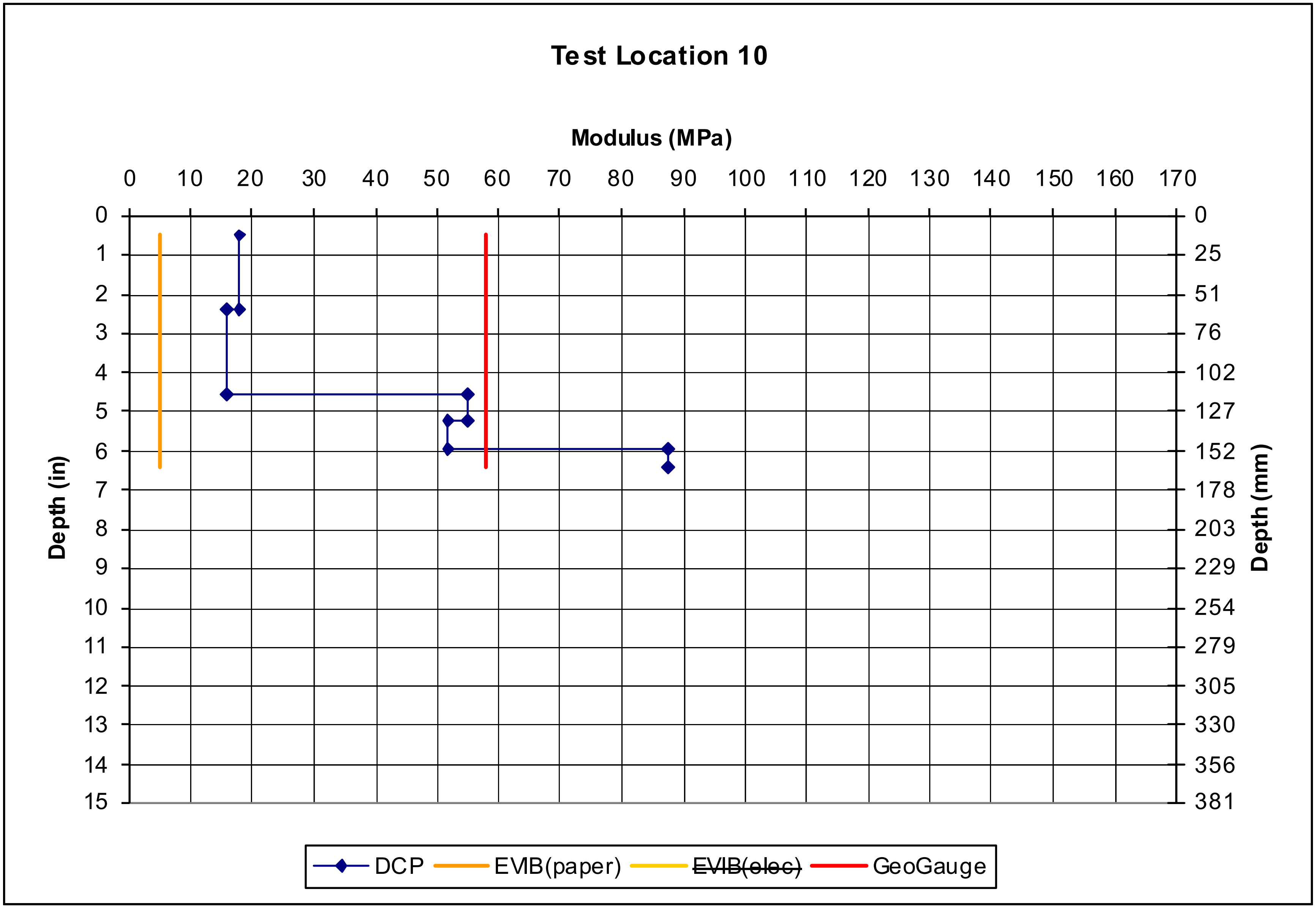
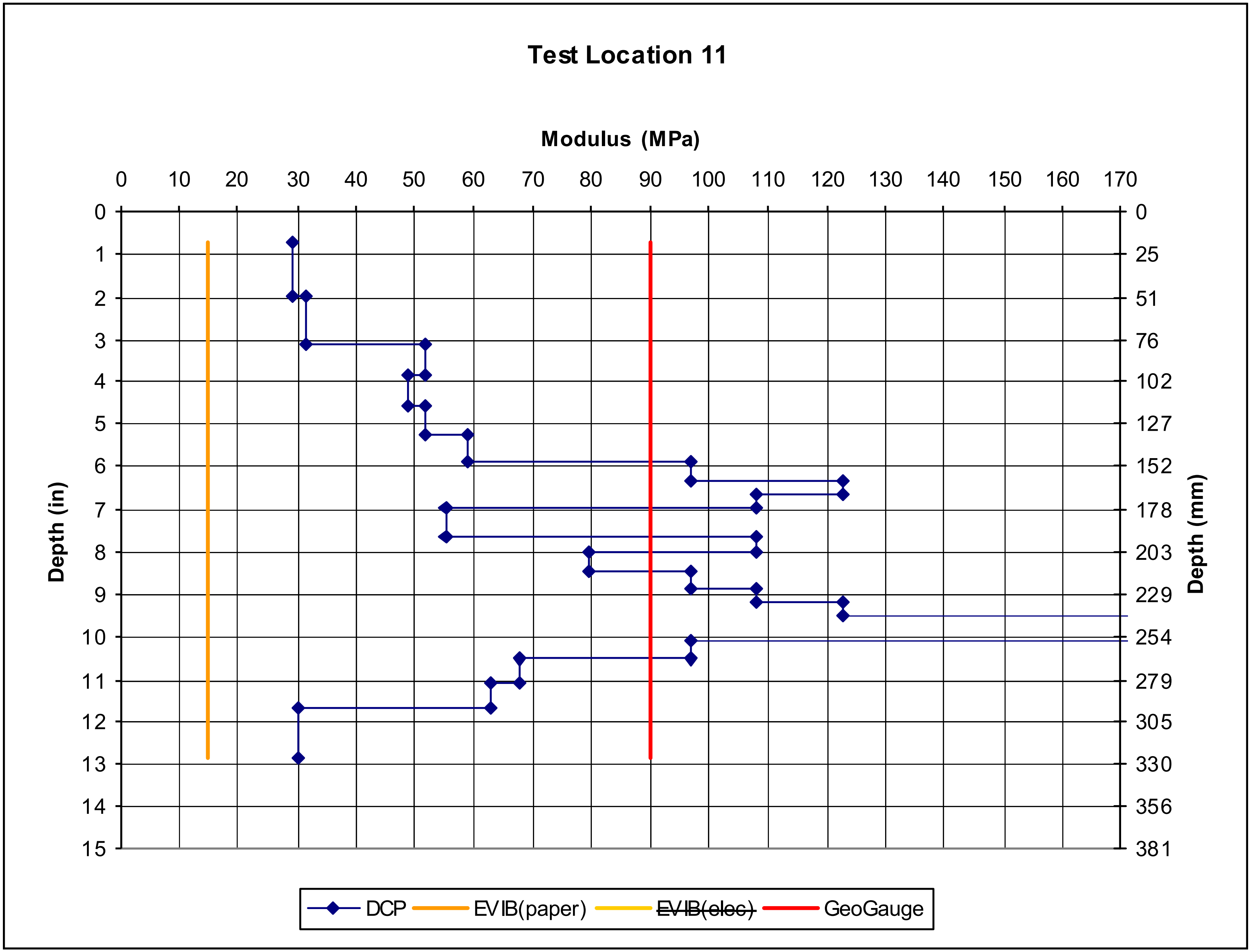
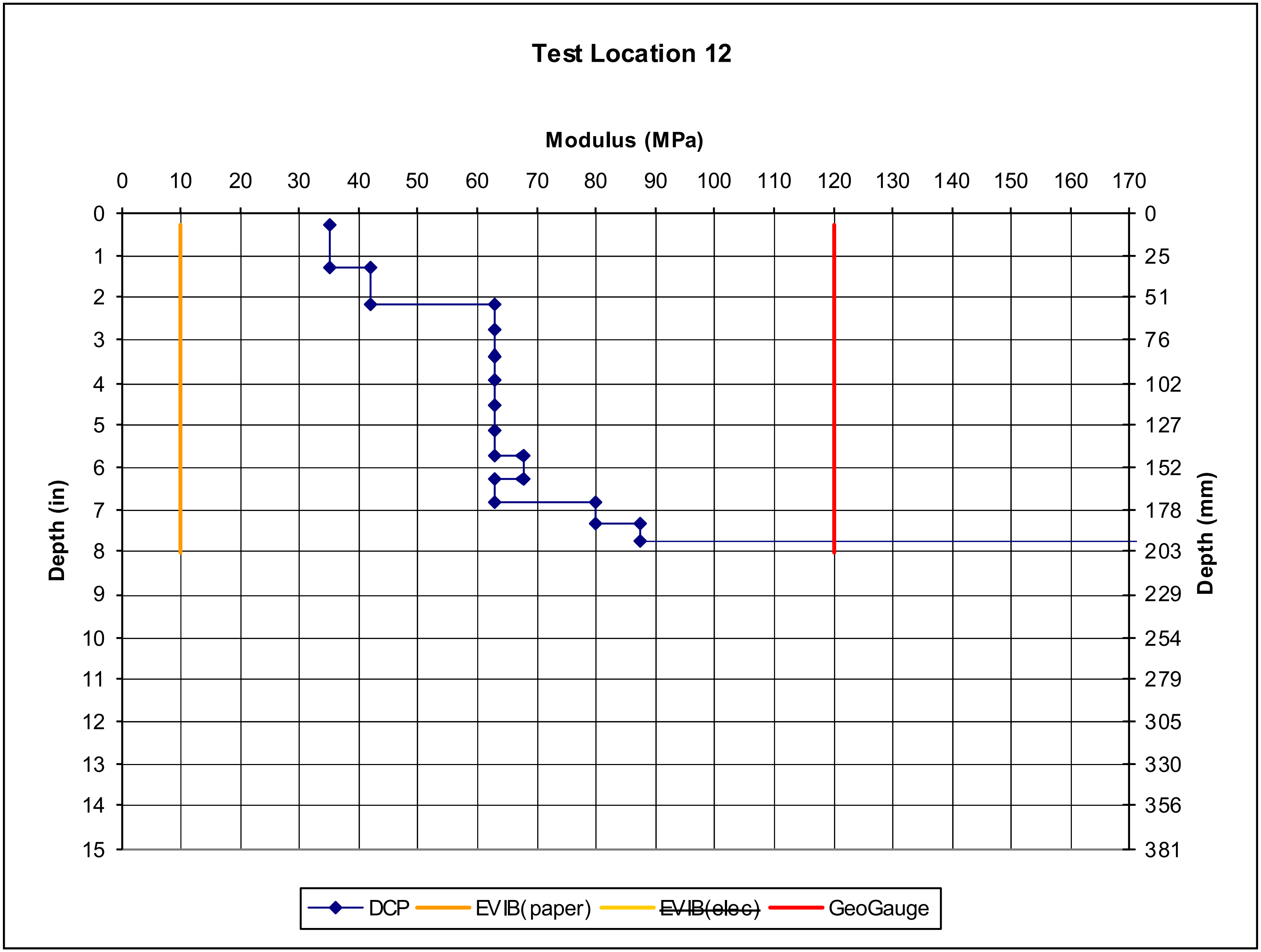


Figure B.10

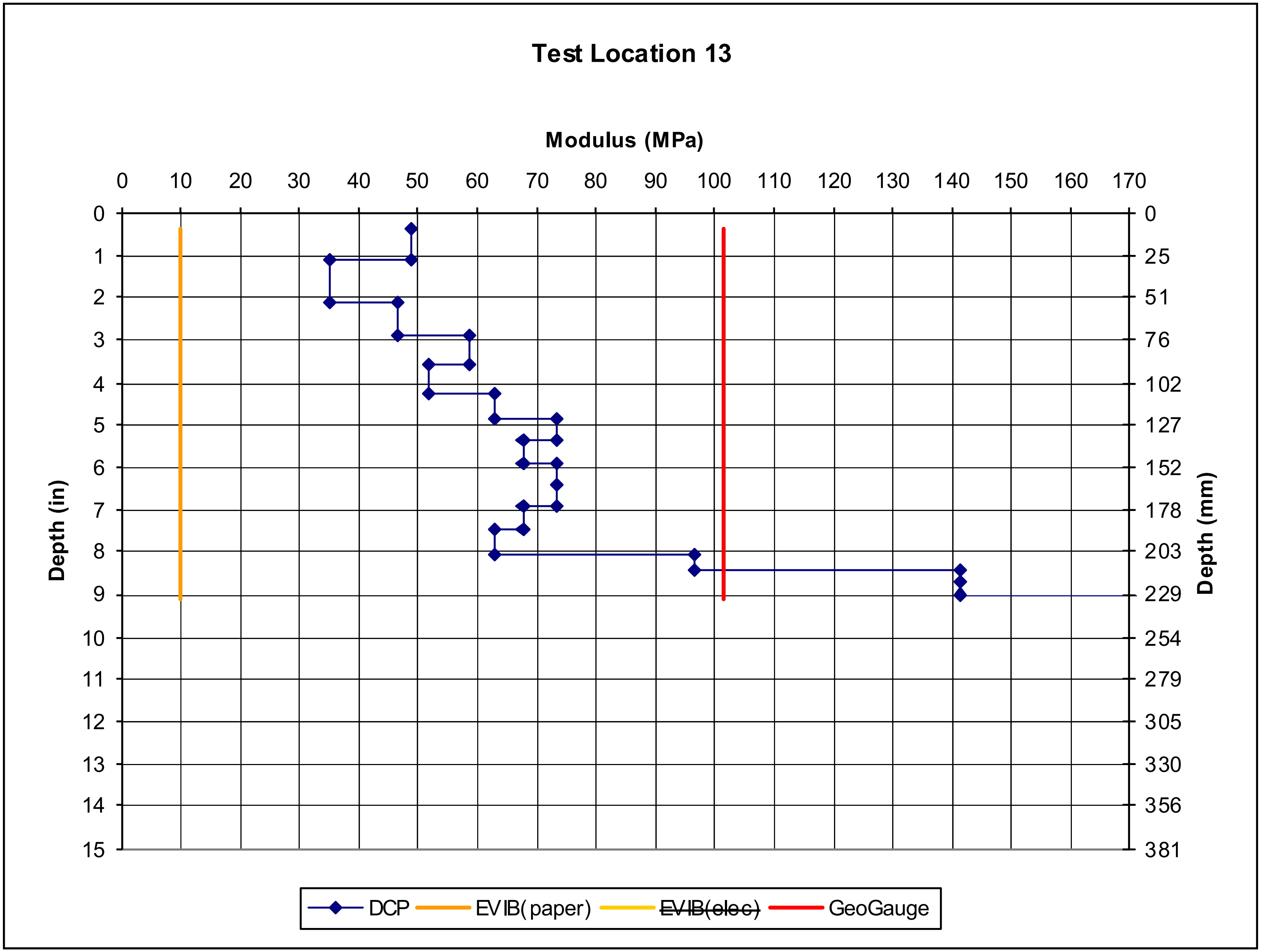
DCP at Test Location 10



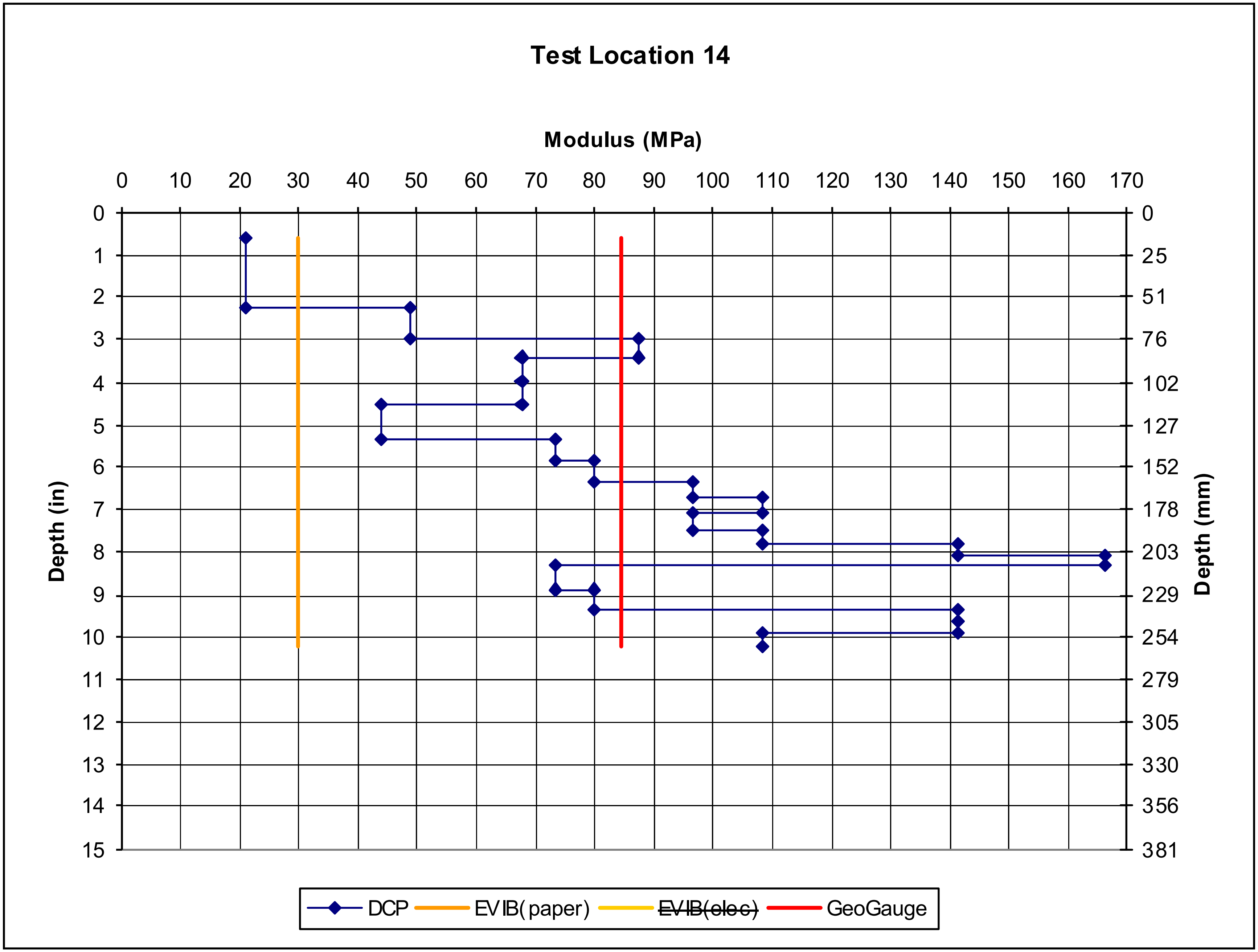
DCP at Test Location 11



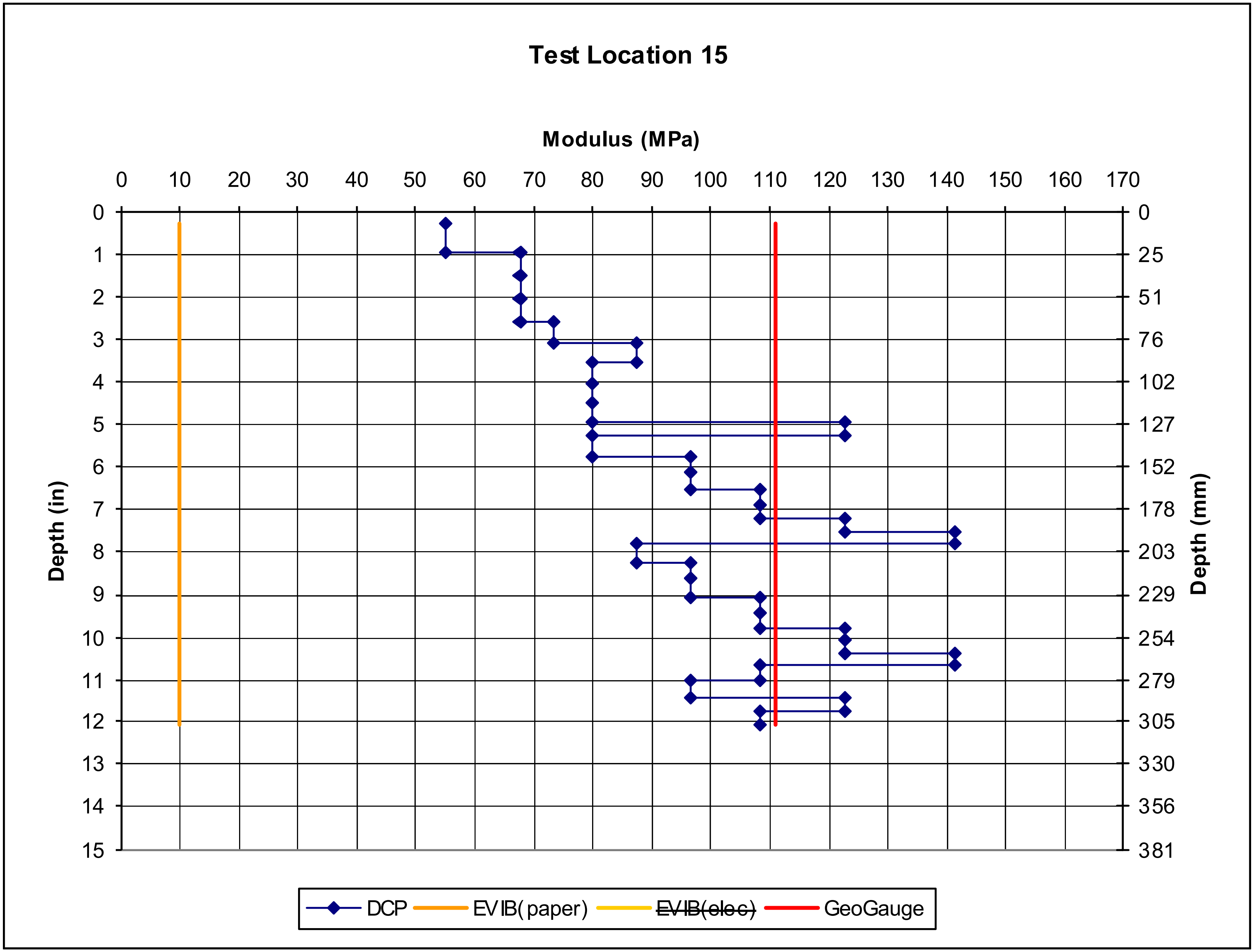
DCP at Test Location 12



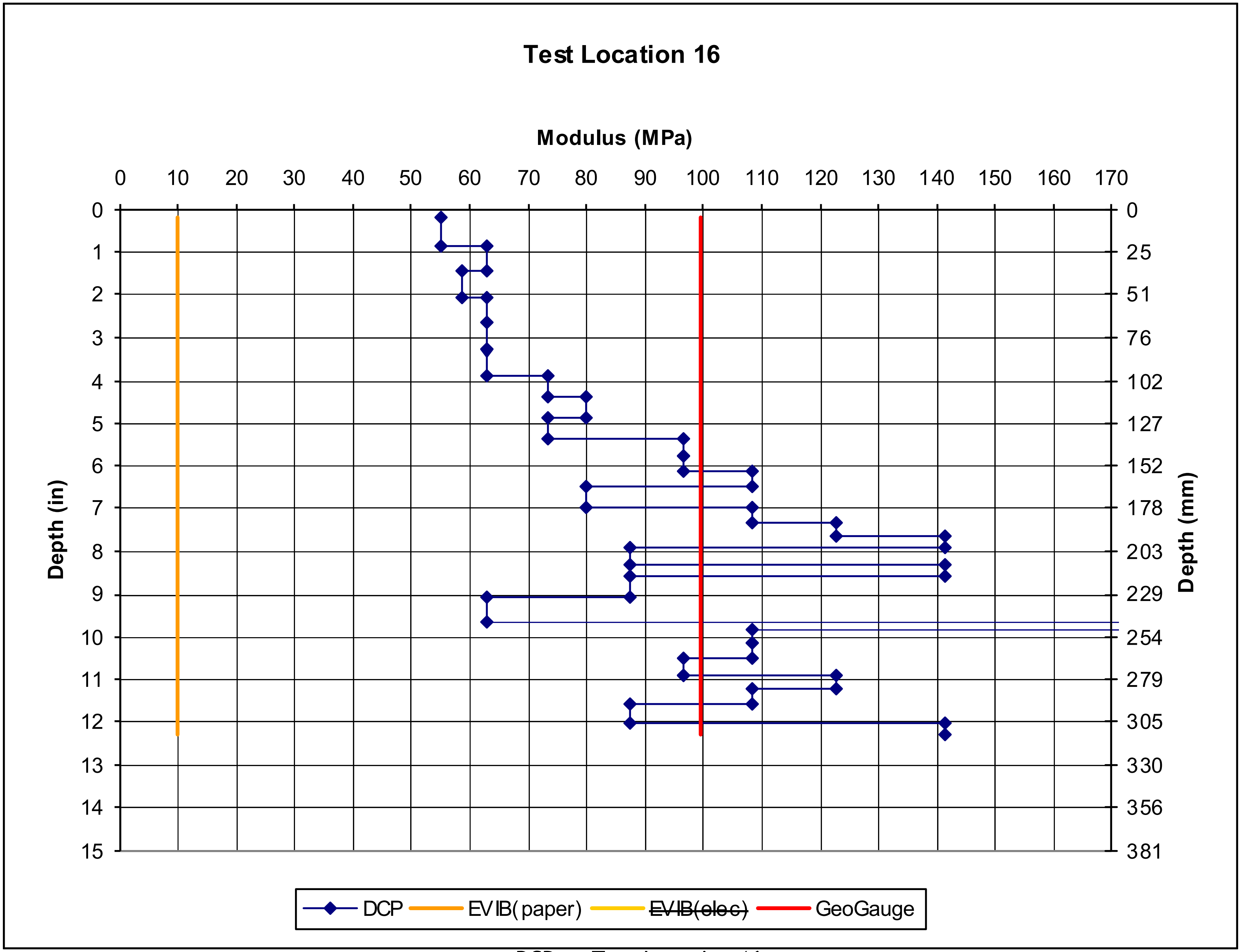
DCP at Test Location 13



DCP at Test Location 14



DCP at Test Location 15



DCP at Test Location 16

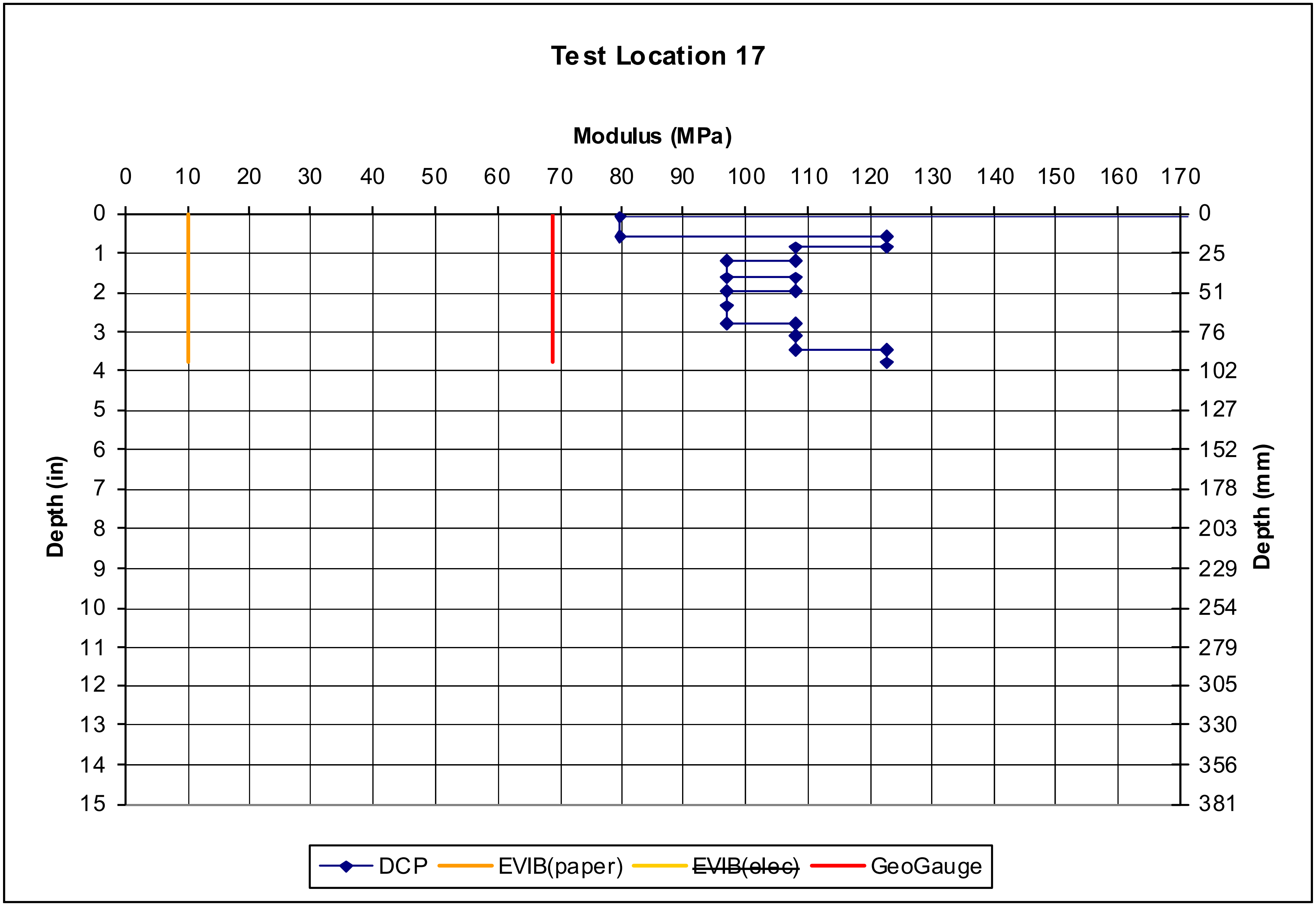
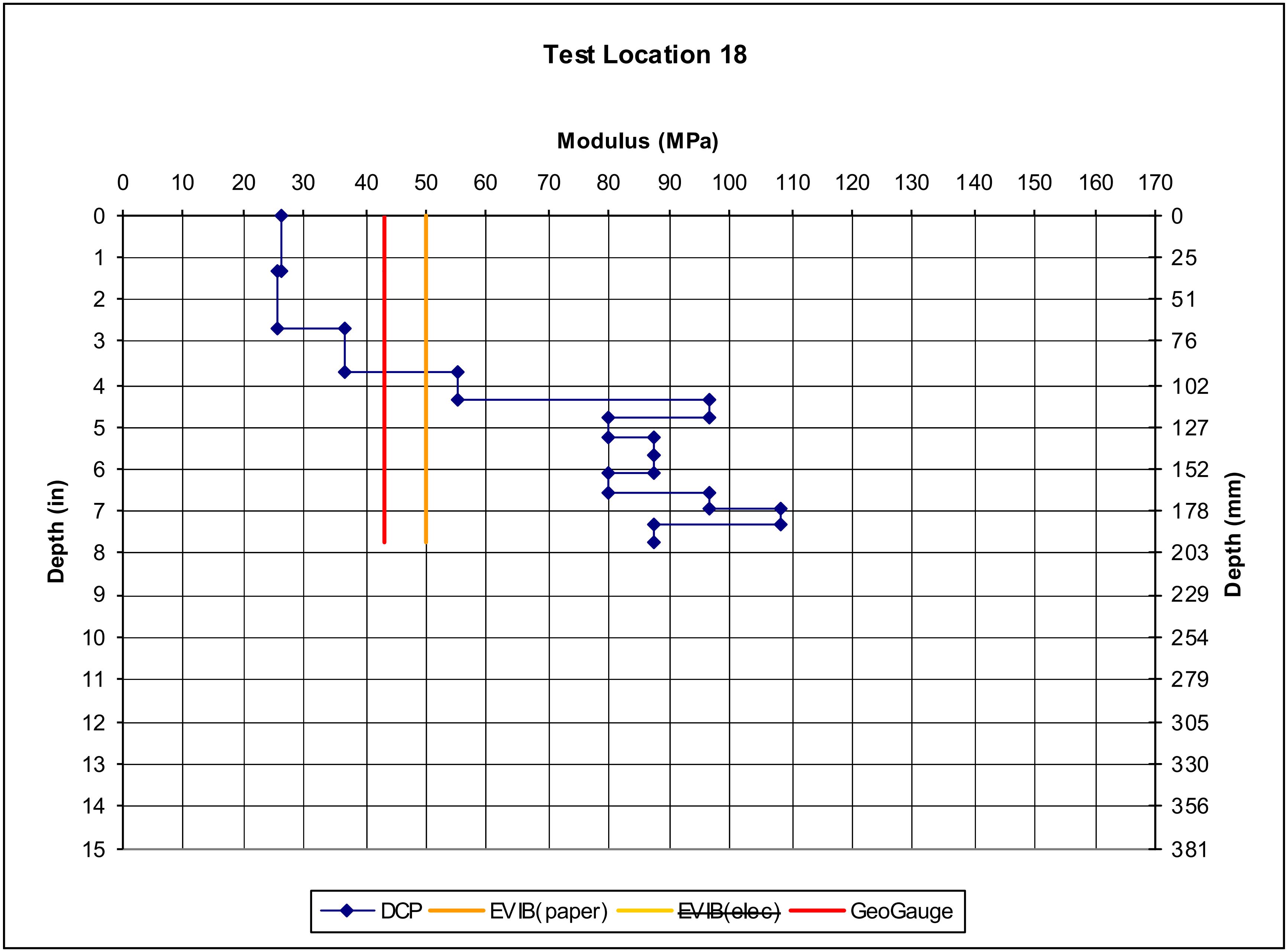
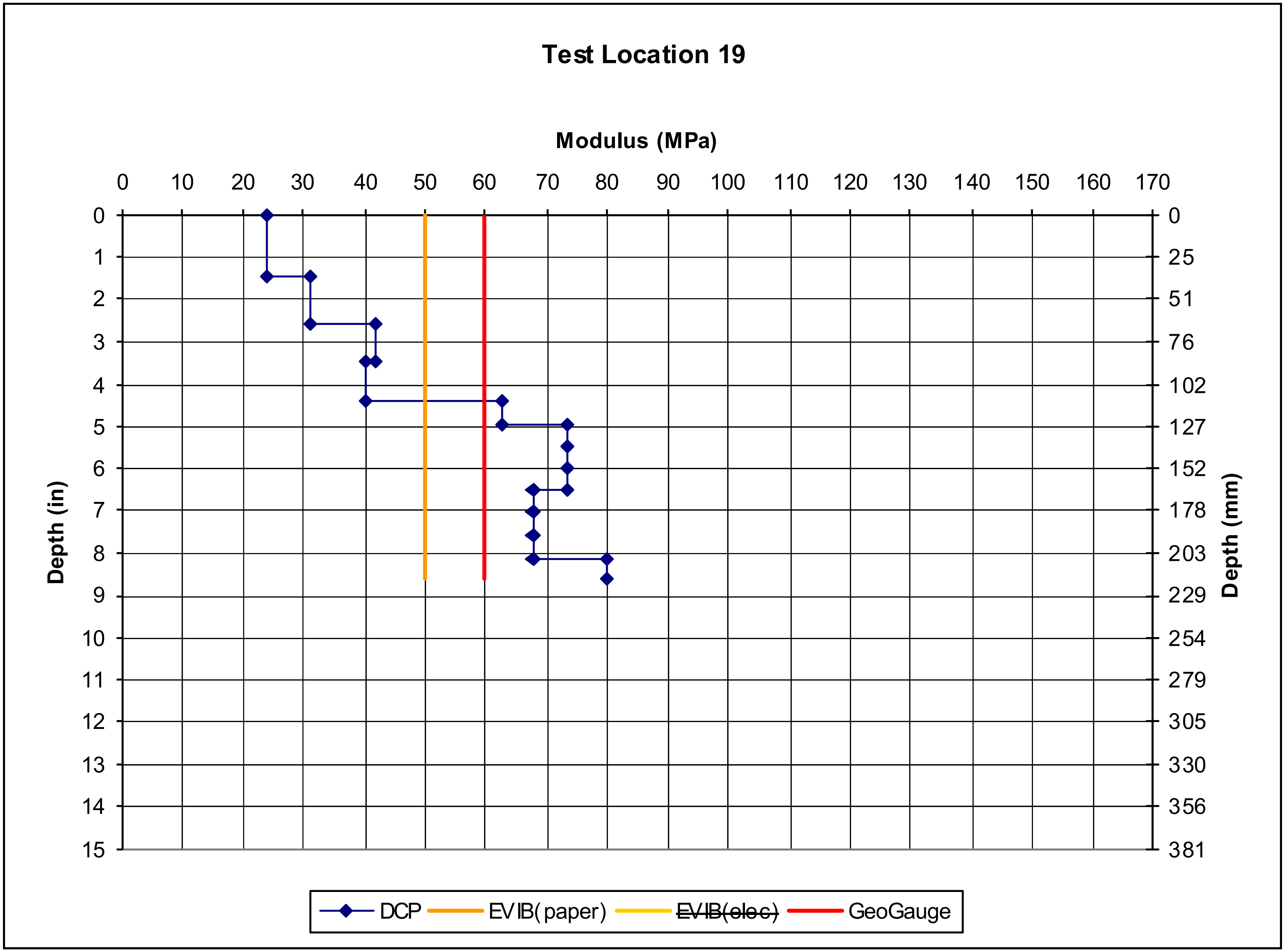


Figure B.17

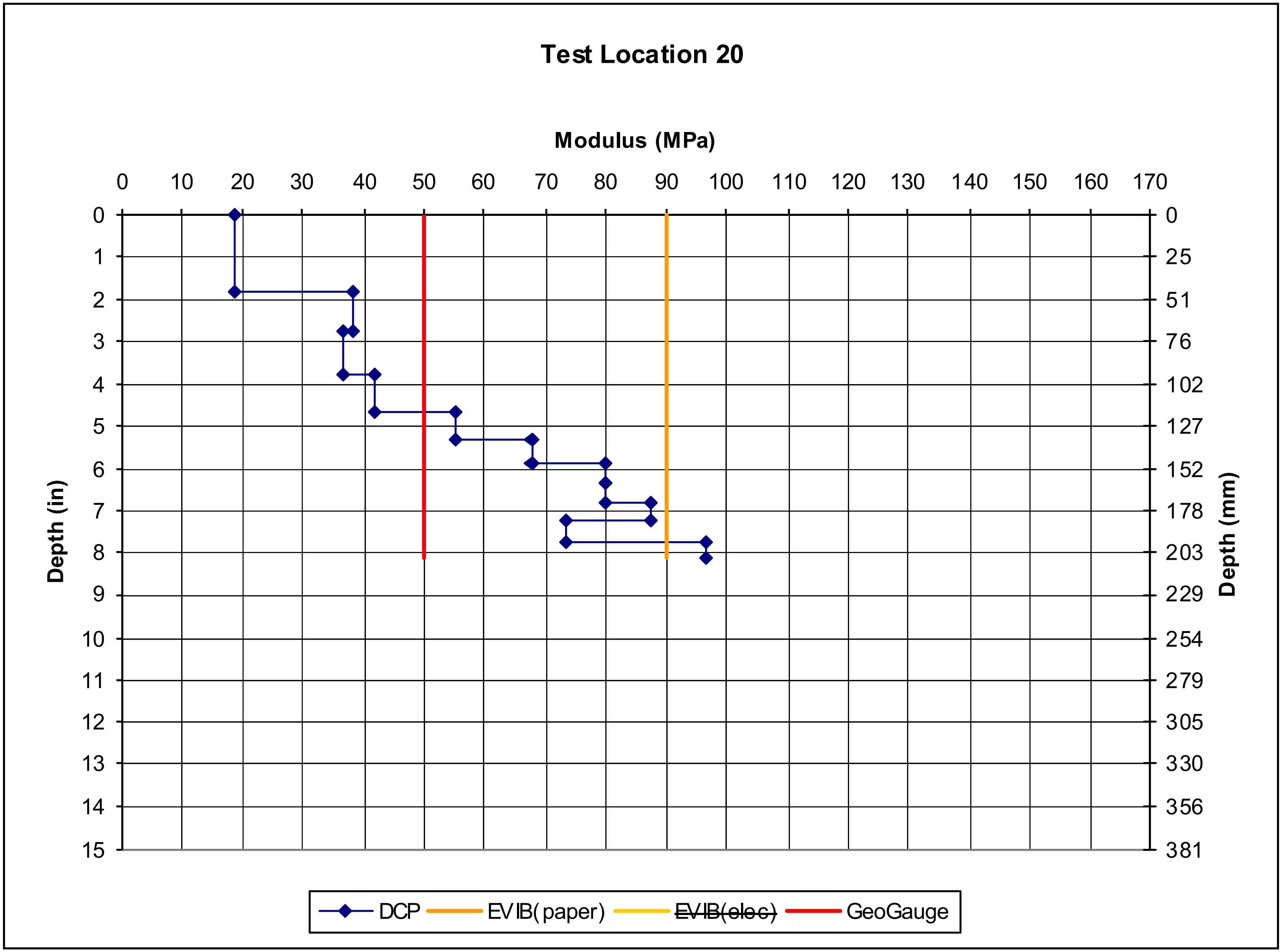
DCP at Test Location 17



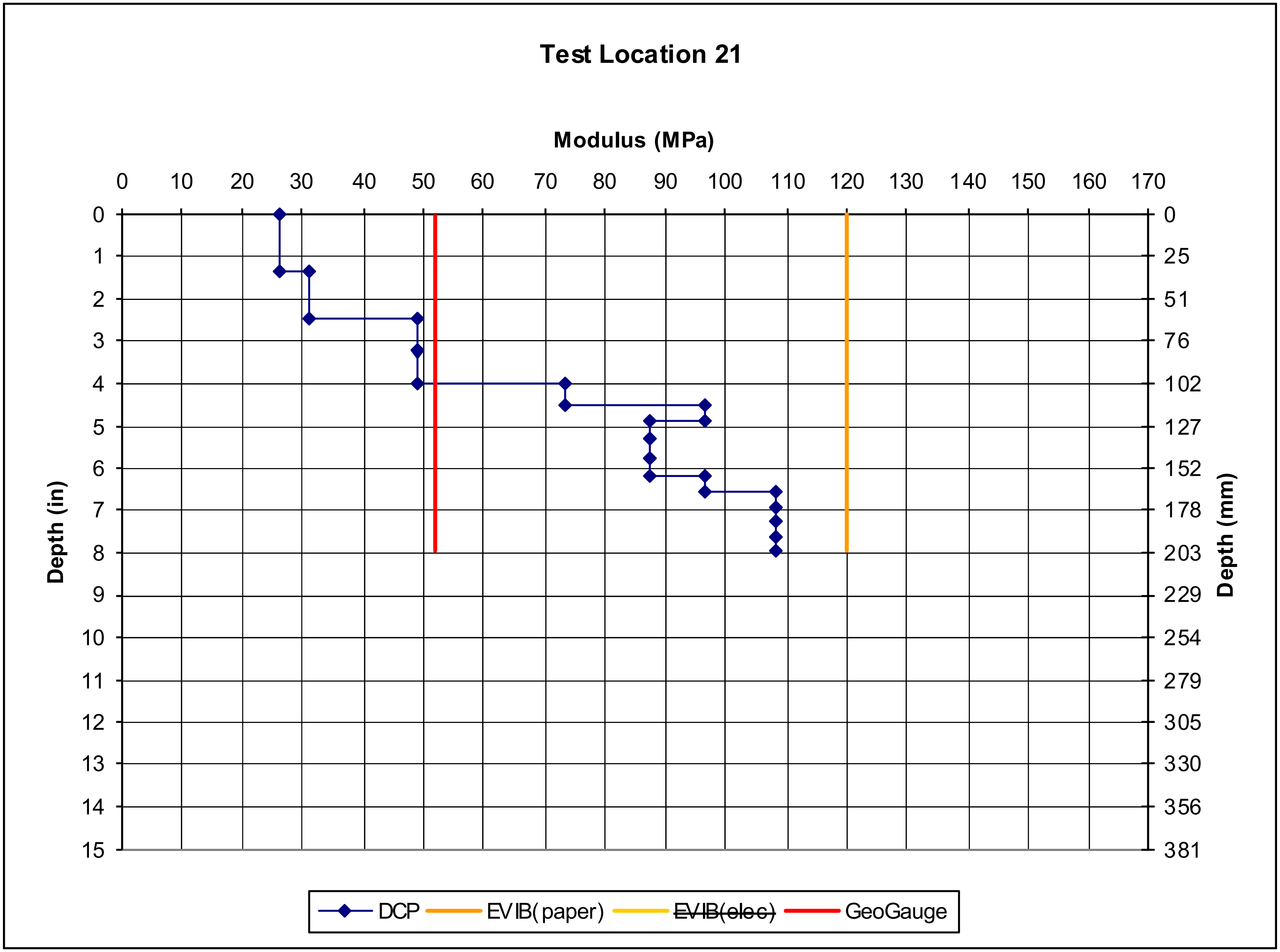
DCP at Test Location 18



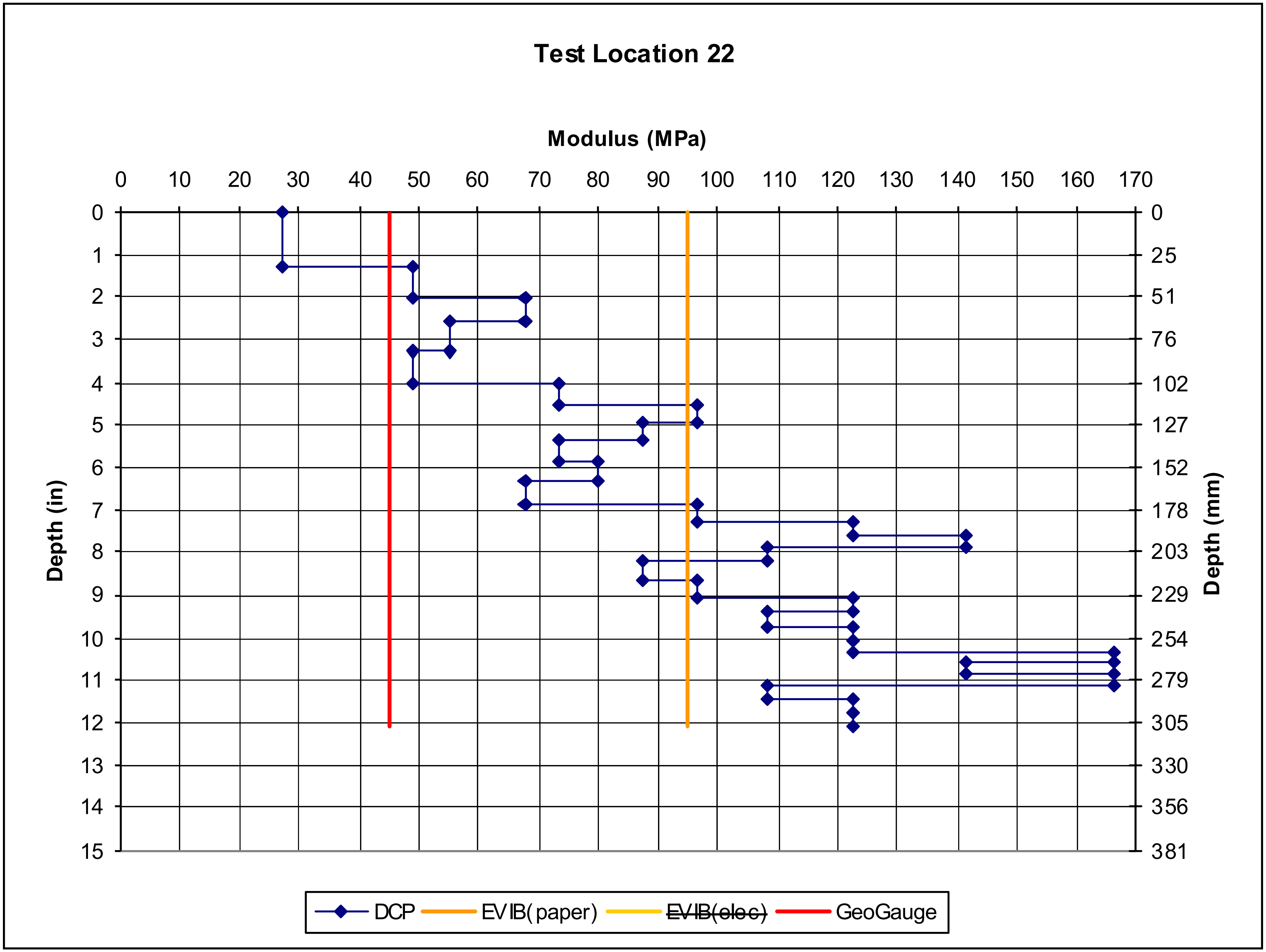
DCP at Test Location 19



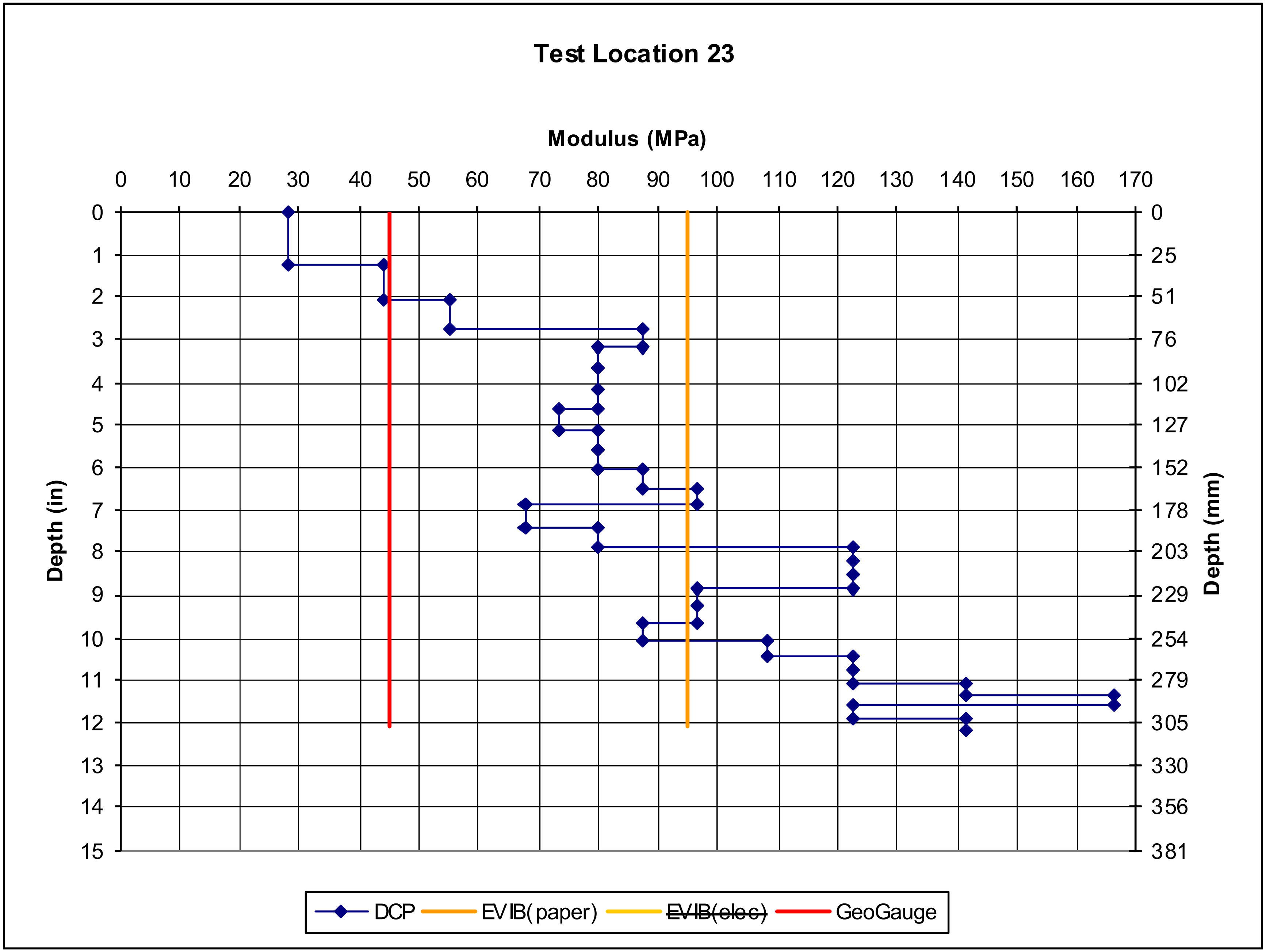
DCP at Test Location 20



DCP at Test Location 21



DCP at Test Location 22



DCP at Test Location 23

Appendix C

BRAUN
INTERTEC

Braun Intertec Corporation
1017 109th Avenue NE
Blaine, MN 55434

Phone: 651.487.7070
Fax: 763.754.2750
Web: braunintertec.com

Report of Field Compaction Tests

Date: October 7, 2004

Project: SP-04-06582

Client:
Lee Peterson
CNA Consulting Engineers
2800 University Avenue Southeast
Minneapolis, MN 55414

Project Description:
MN Roads Test Compactor
Albertville, MN

Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
1	9/27/2004	N	P-1/SM	9.3	122.7	13.7	112.5	92	95	B
2	9/27/2004	N	P-1/SM	9.3	122.7	11.5	117.9	96	95	A
3	9/27/2004	N	P-1/SM	9.3	122.7	12.1	116.6	95	95	A
4	9/27/2004	N	P-1/SM	9.3	122.7	13.4	116.4	95	95	A
4A	9/27/2004	SC	P-1/SM	9.3	122.7	13.0	120.4	98	95	A
5	9/27/2004	N	P-1/SM	9.3	122.7	12.8	117.6	96	95	A
6	9/27/2004	N	P-1/SM	9.3	122.7	12.0	117.0	95	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
1	North Lane, Northwest Corner, Station 20'W, Offset 42'N	93.64
2	North Lane, Northwest Corner, Station 20'W, Offset 42'N	93.64
3	North Lane, Northwest Corner, Station 20'W, Offset 42'N	93.64
4	North Lane, Northwest Corner, Station 20'W, Offset 42'N	93.64
4A	**Sand Cone:** North Lane, Northwest Corner, Station 20'W, Offset 42'N	93.64
5	North Lane, Northeast Corner, Station 15'E, Offset 42'N	92.55
6	North Lane, Northeast Corner, Station 15'E, Offset 42'N	92.55

Elevation Reference: Provided by CNA

Note 1: Nuclear Method performed using a Troxler 3430 type nuclear density meter.

Note 2: Soils at tests 5 through 8 appeared to contain a little more sand than soils at previous test locations.

Braun Intertec Corporation

Perry Elstrom
Project Manager

BRAUN INTERTEC

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Web: braunintertec.com

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2800 University Avenue Southeast
Minneapolis, MN 55414

Project Description:
MN Roads Test Compactor
Albertville, MN

Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
7	9/27/2004	N	P-1/SM	9.3	122.7	12.2	119.6	98	95	A
8	9/27/2004	N	P-1/SM	9.3	122.7	11.9	120.4	98	95	A
9	9/27/2004	N	P-1/SM	9.3	122.7	14.2	120.9	99	95	A
10	9/27/2004	N	P-1/SM	9.3	122.7	14.1	120.5	98	95	A
11	9/27/2004	N	P-1/SM	9.3	122.7	13.7	124.0	101	95	A
12	9/27/2004	N	P-1/SM	9.3	122.7	12.4	131.0	107	95	A
13	9/27/2004	N	P-1/SM	9.3	122.7	13.9	124.8	102	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
7	North Lane, Northeast Corner, Station 15'E, Offset 42'N	92.55
8	North Lane, Northeast Corner, Station 15'E, Offset 42'N	92.55
9	South Lane, Southwest Corner, Station 30'W, Offset 20'N	92.87
10	South Lane, Southwest Corner, Station 30'W, Offset 20'N	92.87
11	South Lane, Southwest Corner, Station 30'W, Offset 20'N	92.87
12	South Lane, Southwest Corner, Station 30'W, Offset 20'N	92.87
13	South Lane, Middle, Station 15'W, Offset 20'N	92.94

Elevation Reference: Provided by CNA

Note: For test 9 through 12, a large rock was encountered below the tested location.

Braun Intertec Corporation

Perry Elstrom
Project Manager

BRAUN INTERTEC

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Report of Field Compaction Tests

Date: October 7, 2004

Project: SP-04-06582

Client:
Lee Peterson
CNA Consulting Engineers
2800 University Avenue Southeast
Minneapolis, MN 55414

Project Description:
MN Roads Test Compactor
Albertville, MN

Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
14	9/27/2004	N	P-1/SM	9.3	122.7	12.9	125.0	102	95	A
15	9/27/2004	N	P-1/SM	9.3	122.7	12.7	124.7	102	95	A
16	9/27/2004	N	P-1/SM	9.3	122.7	13.7	123.0	100	95	A
17	9/27/2004	N	P-2/SP	8.0	130.2	7.6	128.4	99	95	A
18	9/27/2004	N	P-2/SP	8.0	130.2	6.5	130.6	100	95	A
18A	9/27/2004	SC	P-2/SP	8.0	130.2	6.0	136.8	105	95	A
19	9/27/2004	N	P-2/SP	8.0	130.2	6.5	132.2	102	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
14	South Lane, Middle, Station 15'W, Offset 20'N	92.94
15	South Lane, Middle, Station 15'W, Offset 20'N	92.94
16	South Lane, Middle, Station 15'W, Offset 20'N	92.94
17	South Lane, Southeast Corner, Station 0'E/W, Offset 20'N	92.66
18	South Lane, Southeast Corner, Station 0'E/W, Offset 20'N	92.66
18A	**Sand Cone:** South Lane, Southeast Corner, Station 0'E/W, Offset 20'N	92.66
19	South Lane, Southeast Corner, Station 0'E/W, Offset 20'N	92.66

Elevation Reference: Provided by CNA

Note: For tests 17 through 20, the soils from the surface to the depth of about 3 inches consisted of type "P-1" soils. The soils for the balance of the test depth consisted of type "P-2" soils.

Braun Intertec Corporation

Perry Elstrom
Project Manager

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INTERTEC

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Date: October 7, 2004

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CNA Consulting Engineers
2800 University Avenue Southeast
Minneapolis, MN 55414

Project Description:
MN Roads Test Compactor
Albertville, MN

Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
20	9/27/2004	N	P-2/SP	8.0	130.2	6.1	134.6	103	95	A
21	9/27/2004	N	P-2/SP	8.0	130.2	6.5	128.6	99	95	A
21A	9/27/2004	SC	P-2/SP	8.0	130.2	7.1	124.3	95	95	A
22	9/27/2004	N	P-3/SM	11.0	119.2	14.0	119.8	101	95	A
22A	9/27/2004	SC	P-3/SM	11.0	119.2	14.4	121.9	94	95	B
23	9/27/2004	N	P-3/SM	11.0	119.2	13.7	118.8	100	95	A
24	9/27/2004	N	P-3/SM	11.0	119.2	14.4	117.5	99	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
20	South Lane, Southeast Corner, Station 0'E/W, Offset 20'N	92.66
21	South Lane, Southeast Corner, Station 0'E/W, Offset 20'N (taken in sand 4" below tests 18-20)	92.33
21A	**Sand Cone:** South Lane, SE Corner, Sta. 0'E/W, Offset 20'N (taken in sand 4" below tests 18-20)	92.33
22	South Lane, Southwest Corner, Station 25'W, Offset 17'N	---
22A	**Sand Cone:** South Lane, Southwest Corner, Station 25'W, Offset 17'N	---
23	South Lane, Southwest Corner, Station 25'W, Offset 17'N	---
24	South Lane, Southwest Corner, Station 25'W, Offset 17'N	---

Elevation Reference: Provided by CNA

Braun Intertec Corporation

Perry Elstrom
Project Manager

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Report of Field Compaction Tests

Date: October 7, 2004

Project: SP-04-06582

Client:
Lee Peterson
CNA Consulting Engineers
2800 University Avenue Southeast
Minneapolis, MN 55414

Project Description:
MN Roads Test Compactor
Albertville, MN

Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
25	9/27/2004	N	P-3/SM	11.0	119.2	13.4	118.6	100	95	A
26	9/27/2004	N	P-1/SM	9.3	122.7	14.6	117.0	95	95	A
27	9/27/2004	N	P-1/SM	9.3	122.7	14.1	117.8	96	95	A
28	9/27/2004	N	P-1/SM	9.3	122.7	13.7	118.2	96	95	A
29	9/27/2004	N	P-1/SM	9.3	122.7	13.1	119.1	97	95	A
30	9/27/2004	N	P-1/SM	9.3	122.7	11.1	123.5	101	95	A
31	9/27/2004	N	P-1/SM	9.3	122.7	11.9	121.3	99	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
25	South Lane, Southwest Corner, Station 25'W, Offset 17'N	---
26	South Lane, Southeast Corner, Station 0'E/W, Offset 17'N	93.96
27	South Lane, Southeast Corner, Station 0'E/W, Offset 17'N	93.96
28	South Lane, Southeast Corner, Station 0'E/W, Offset 17'N	93.96
29	South Lane, Southeast Corner, Station 0'E/W, Offset 17'N	93.96
30	North Lane, Northeast Corner, Station 15'E, Offset 41'N	93.73
31	North Lane, Northeast Corner, Station 15'E, Offset 41'N	93.73

Elevation Reference: Provided by CNA

Note: Soils at tests 30 through 37 appeared to contain a little more gravel than previous "P-1" soils.

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Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
32	9/27/2004	N	P-1/SM	9.3	122.7	10.8	122.2	100	95	A
33	9/27/2004	N	P-1/SM	9.3	122.7	11.0	123.3	100	95	A
34	9/27/2004	N	P-1/SM	9.3	122.7	11.1	128.6	105	95	A
35	9/27/2004	N	P-1/SM	9.3	122.7	11.4	128.1	104	95	A
36	9/27/2004	N	P-1/SM	9.3	122.7	11.4	128.5	105	95	A
37	9/27/2004	N	P-1/SM	9.3	122.7	12.3	125.3	102	95	A
38	9/28/2004	N	P-4/SM	9.9	128.3	6.9	126.0	98	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
32	North Lane, Northeast Corner, Station 15'E, Offset 41'N	93.73
33	North Lane, Northeast Corner, Station 15'E, Offset 41'N	93.73
34	North Lane, Northwest Corner, Station 20'W, Offset 41'N	93.72
35	North Lane, Northwest Corner, Station 20'W, Offset 41'N	93.72
36	North Lane, Northwest Corner, Station 20'W, Offset 41'N	93.72
37	North Lane, Northwest Corner, Station 20'W, Offset 41'N	93.72
38	South Lane, Southwest Corner, Station 30'W, Offset 15'N	---

Elevation Reference: Provided by CNA

Note 1: Soils at tests 30 through 37 appeared to contain a little more gravel than previous "P-1" soils.

Note 2: Soils at tests 38 through 41 consisted of 10-inches of "P-4" type soils over "P-1" type soils. The top 8-inches were tested.

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Test	Date	Type	Soil ID and Classification	Optimum Moisture (%)	Max. Lab Dry Density (Std. Proc.) (pcf)	Inplace Moisture (%)	Inplace Dry Density (pcf)	Relative Compaction (%)	Specified Minimum Compaction (%)	Comments
39	9/28/2004	N	P-4/SM	9.9	128.3	6.9	129.8	101	95	A
40	9/28/2004	N	P-4/SM	9.9	128.3	7.5	125.6	98	95	A
40A	9/28/2004	SC	P-4/SM	9.9	128.3	7.5	128.1	100	95	A
41	9/28/2004	N	P-4/SM	9.9	128.3	7.3	127.2	99	95	A
42	9/28/2004	N	P-4/SM	9.9	128.3	7.8	126.2	98	95	A
43	9/28/2004	N	P-4/SM	9.9	128.3	7.6	127.8	100	95	A
44	9/28/2004	N	P-4/SM	9.9	128.3	7.8	127.3	99	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
39	South Lane, Southwest Corner, Station 30'W, Offset 15'N	---
40	South Lane, Southwest Corner, Station 30'W, Offset 15'N	---
40A	**Sand Cone:** South Lane, Southwest Corner, Station 30'W, Offset 15'N	---
41	South Lane, Southwest Corner, Station 30'W, Offset 15'N	---
42	South Lane, Middle, Station 15'W, 15'N Offset	---
43	South Lane, Middle, Station 15'W, 15'N Offset	---
44	South Lane, Middle, Station 15'W, 15'N Offset	---

Elevation Reference: Provided by CNA

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45	9/28/2004	N	P-4/SM	9.9	128.3	8.0	127.1	99	95	A
46	9/28/2004	N	P-4/SM	9.9	128.3	7.5	125.8	98	95	A
47	9/28/2004	N	P-4/SM	9.9	128.3	7.7	127.2	99	95	A
48	9/28/2004	N	P-4/SM	9.9	128.3	7.4	128.0	100	95	A
49	9/28/2004	N	P-4/SM	9.9	128.3	7.2	127.5	99	95	A
50	9/28/2004	N	P-4/SM	9.9	128.3	7.6	125.5	98	95	A
51	9/28/2004	N	P-4/SM	9.9	128.3	7.2	128.3	100	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
45	South Lane, Middle, Station 15'W, Offset 15'N	---
46	South Lane, Southeast Corner, Station 0'E/W, Offset 15'N	---
47	South Lane, Southeast Corner, Station 0'E/W, Offset 15'N	---
48	South Lane, Southeast Corner, Station 0'E/W, Offset 15'N	---
49	South Lane, Southeast Corner, Station 0'E/W, Offset 15'N	---
50	North Lane, Northwest Corner, Station 0'E/W, Offset 42'N	96.09
51	North Lane, Northwest Corner, Station 0'E/W, Offset 42'N	96.09

Elevation Reference: Provided by CNA

Note: Soils at test area 50 through 53 appeared to contain occasional clay lumps.

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52	9/28/2004	N	P-4/SM	9.9	128.3	7.2	128.9	100	95	A
53	9/28/2004	N	P-4/SM	9.9	128.3	7.9	126.4	99	95	A
54	9/28/2004	N	P-4/SM	9.9	128.3	7.5	127.9	100	95	A
55	9/28/2004	N	P-4/SM	9.9	128.3	7.3	129.1	101	95	A
56	9/28/2004	N	P-4/SM	9.9	128.3	7.1	131.1	102	95	A
57	9/28/2004	N	P-4/SM	9.9	128.3	7.0	131.0	102	95	A
57A	9/28/2004	SC	P-4/SM	9.9	128.3	7.9	131.9	103	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
52	North Lane, Northwest Corner, Station 20'W, Offset 42'N	96.09
53	North Lane, Northwest Corner, Station 20'W, Offset 42'N	96.09
54	North Lane, Middle, Station 0'E/W, Station 42'N	96.01
55	North Lane, Middle, Station 0'E/W, Station 42'N	96.01
56	North Lane, Middle, Station 0'E/W, Station 42'N	96.01
57	North Lane, Middle, Station 0'E/W, Station 42'N	96.01
57A	**Sand Cone:** North Lane, Middle, Station 0'E/W, Station 42'N	96.01

Elevation Reference: Provided by CNA

Note: Soils at test area 50 through 53 appeared to contain occasional clay lumps.

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58	9/28/2004	N	P-4/SM	9.9	128.3	7.9	127.6	99	95	A
59	9/28/2004	N	P-4/SM	9.9	128.3	8.1	128.2	100	95	A
60	9/28/2004	N	P-4/SM	9.9	128.3	7.7	129.8	101	95	A
61	9/28/2004	N	P-4/SM	9.9	128.3	7.6	130.6	102	95	A
62	9/29/2004	N	P-5/Class 6	10.7	131.9	4.2	128.5	97	95	A
63	9/29/2004	N	P-5/Class 6	10.7	131.9	4.2	129.5	98	95	A
64	9/29/2004	N	P-5/Class 6	10.7	131.9	4.7	126.2	96	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
58	North Lane, Northeast Corner, Station 15'E, Offset 42'N	96.00
59	North Lane, Northeast Corner, Station 15'E, Offset 42'N	96.00
60	North Lane, Northeast Corner, Station 15'E, Offset 42'N	96.00
61	North Lane, Northeast Corner, Station 15'E, Offset 42'N	96.00
62	South Lane, Southwest Corner, Station 30'W, Offset 17'N	97.87
63	South Lane, Southwest Corner, Station 30'W, Offset 17'N	97.87
64	South Lane, Southwest Corner, Station 30'W, Offset 17'N	97.87

Elevation Reference: Provided by CNA

Note: Soils at tests 62 through 65 consisted of 4-inches of "P-5" type material over "P-4" type soils. The top 4-inches were tested.

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65	9/29/2004	N	P-5/Class 6	10.7	131.9	4.5	128.1	97	95	A
66	9/29/2004	N	P-5/Class 6	10.7	131.9	4.7	120.7	92	95	B
67	9/29/2004	N	P-5/Class 6	10.7	131.9	4.4	120.1	91	95	B
68	9/29/2004	N	P-5/Class 6	10.7	131.9	4.3	118.9	90	95	B
69	9/29/2004	N	P-5/Class 6	10.7	131.9	4.4	119.6	91	95	B
70	9/29/2004	N	P-5/Class 6	10.7	131.9	2.9	135.2	103	95	A
71	9/29/2004	N	P-5/Class 6	10.7	131.9	2.8	136.0	103	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
65	South Lane, Southwest Corner, Station 30'W, Offset 17'N	97.87
66	South Lane, Middle, Station 15'W, Offset 17'N	97.77
67	South Lane, Middle, Station 15'W, Offset 17'N	97.77
68	South Lane, Middle, Station 15'W, Offset 17'N	97.77
69	South Lane, Middle, Station 15'W, Offset 17'N	97.77
70	South Lane, Southeast Corner, Station 0'E/W, Offset 17'N	97.77
71	South Lane, Southeast Corner, Station 0'E/W, Offset 17'N	97.77

Elevation Reference: Provided by CNA

Note: Soils at tests 62-65 contained 4-inches of "P-5" type material over "P-4" type soil. The top 4-inches were tested. Soils at tests 66-69 consisted of 6-inches of "P-5" type material over "P-4" type soils. The top 6-inches were tested. Soils at tests 70-73 consisted of 10-inches of "P-5" type material over "P-4" type soils. The top 10-inches were tested.

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72	9/29/2004	N	P-5/Class 6	10.7	131.9	3.0	132.7	101	95	A
73	9/29/2004	N	P-5/Class 6	10.7	131.9	2.8	134.7	102	95	A
74	9/29/2004	N	P-5/Class 6	10.7	131.9	2.7	134.7	102	95	A
75	9/29/2004	N	P-5/Class 6	10.7	131.9	2.9	133.0	101	95	A
76	9/29/2004	N	P-5/Class 6	10.7	131.9	2.7	133.2	101	95	A
77	9/29/2004	N	P-5/Class 6	10.7	131.9	2.8	134.9	102	95	A
78	9/29/2004	N	P-5/Class 6	10.7	131.9	2.8	134.4	102	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
72	South Lane, Southwest Corner, Station 0'E/W, Offset 17'N	97.77
73	South Lane, Southwest Corner, Station 0'E/W, Offset 17'N	97.77
74	North Lane, Southwest Corner, Station 20'W, Offset 42'N	97.35
75	North Lane, Southwest Corner, Station 20'W, Offset 42'N	97.35
76	North Lane, Southwest Corner, Station 20'W, Offset 42'N	97.35
77	North Lane, Southwest Corner, Station 20'W, Offset 42'N	97.35
78	North Lane, Northeast Corner, Station 0'E/W, Offset 42'N (Centerline of Test Area Across from Box)	

Elevation Reference: Provided by CNA

Note: Soils at tests 70 through 73 consisted of 10-inches of "P-5" type material over "P-4" type soil. The top 10-inches were tested.

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79	7/29/2004	N	P-5/Class 6	10.7	131.9	3.0	131.9	100	95	A
80	7/29/2004	N	P-5/Class 6	10.7	131.9	3.1	130.1	99	95	A
81	7/29/2004	N	P-5/Class 6	10.7	131.9	2.9	134.5	102	95	A
82	7/29/2004	N	P-5/Class 6	10.7	131.9	3.3	131.3	100	95	A
83	7/29/2004	N	P-5/Class 6	10.7	131.9	3.2	131.7	100	95	A
84	7/29/2004	N	P-5/Class 6	10.7	131.9	2.9	134.0	102	95	A
84A	7/29/2004	SC	P-5/Class 6	10.7	131.9	4.1	140.6	107	95	A

Type Key: N = Nuclear, ASTM D 2922
SC= Sand Cone, ASTM D 1556

Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
79	North Lane, Northeast Corner, Station 0'E/W, Offset 42'N (Centerline of Test Area Across from Box)	97.32
80	North Lane, Northeast Corner, Station 0'E/W, Offset 42'N (Centerline of Test Area Across from Box)	97.32
81	North Lane, Northeast Corner, Station 0'E/W, Offset 42'N (Centerline of Test Area Across from Box)	97.32
82	North Lane, Middle, Station 10'W, Offset 42'N (Location of First Plate Road Test)	97.45
83	North Lane, Middle, Station 10'W, Offset 42'N (Location of First Plate Road Test)	97.45
84	North Lane, Middle, Station 10'W, Offset 42'N (Location of First Plate Road Test)	97.45
84A	**Sand Cone:** North Lane, Middle, Station 10'W, Offset 42'N (Location of First Plate Load Test)	97.45

Elevation Reference:

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85	9/29/2004	N	P-5/Class 6	10.7	131.9	2.8	133.6	101	95	A
86	9/29/2004	N	P-5/Class 6	10.7	131.9	4.7	130.8	99	95	A
87	9/29/2004	N	P-5/Class 6	10.7	131.9	4.9	134.1	102	95	A
88	9/29/2004	N	P-5/Class 6	10.7	131.9	5.1	133.5	101	95	A
88A	9/29/2004	SC	P-5/Class 6	10.7	131.9	4.5	144.2	109	95	A
89	9/29/2004	N	P-5/Class 6	10.7	131.9	5.0	134.3	102	95	A

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Comments: A = Test results comply with specifications.
B = Test results do not comply with specifications.

Test	Test Location	Elevation
85	North Lane, Middle, Station 10'W, Offset 42'N (Location of First Plate Load Test)	97.45
86	North Lane, Northwest Corner, Station 25'W, Offset 42'N (Location of Second Plate Load Test)	97.35
87	North Lane, Northwest Corner, Station 25'W, Offset 42'N (Location of Second Plate Load Test)	97.35
88	North Lane, Northwest Corner, Station 25'W, Offset 42'N (Location of Second Plate Load Test)	97.35
88A	**Sand Cone:** North Lane, NW Corner, Sta. 25'W, Offset 42'N (Location of Second Plate Load Test)	97.35
89	North Lane, Northwest Corner, Station 25'W, Offset 42'N (Location of Second Plate Load Test)	97.35

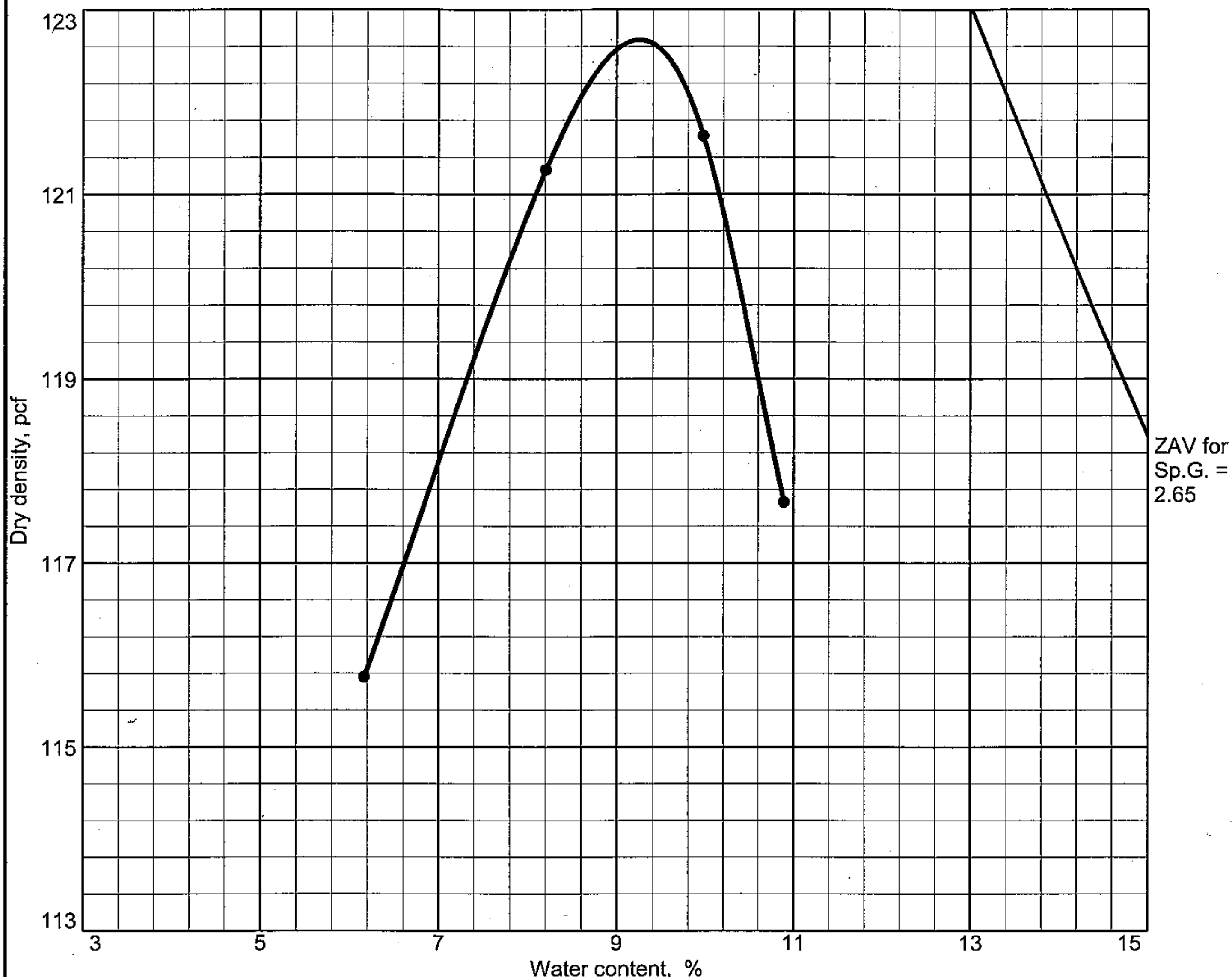
Elevation Reference:

c:

Braun Intertec Corporation

Perry Elstrom
Project Manager

Moisture-Density Relationship Test



Test specification: ASTM D 698-91 Procedure A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > No.4	% < No.200
	USCS	AASHTO						
				2.65				

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 122.7 pcf Optimum moisture = 9.3 %	SM, Silty Sand, mostly fine grained, brown

Project No.: SP-04-06582 **Client:** CNA Consulting Engineers

Project: MN Roads Test Compactor, Albertville, MN

● **Source:** **Sample No.:** P-1

Moisture-Density Relationship Test

BRAUN INTERTEC

Remarks:

Date 10/14/04

BRAUN
INTERTEC

Braun Intertec Corporation
1017 109th Avenue NE
Blaine, MN 55434

Phone: 651.487.7070
Fax: 763.754.2750
Web: braunintertec.com

Sieve Analysis of Fine and Coarse Aggregates

Date: October 14, 2004

Project: SP-04-06582

Client:
Lee Peterson
CAN Consulting Engineers
2800 University Avenue SE
Minneapolis, MN 55414

Project Description:
MN Roads Test Compactor
Albertville, MN

Field Data

Sample Number:	PG-1 (Compare to Proctor P-1)
Sampled By:	PLE/Braun
Date Sampled:	9/27/2004
Date Received:	10/1/2004
Date Tested:	10/4/2004
Classification:	SM, Silty Sand, mostly fine grained, brown
Sample Location:	MN Road Research

Laboratory Results

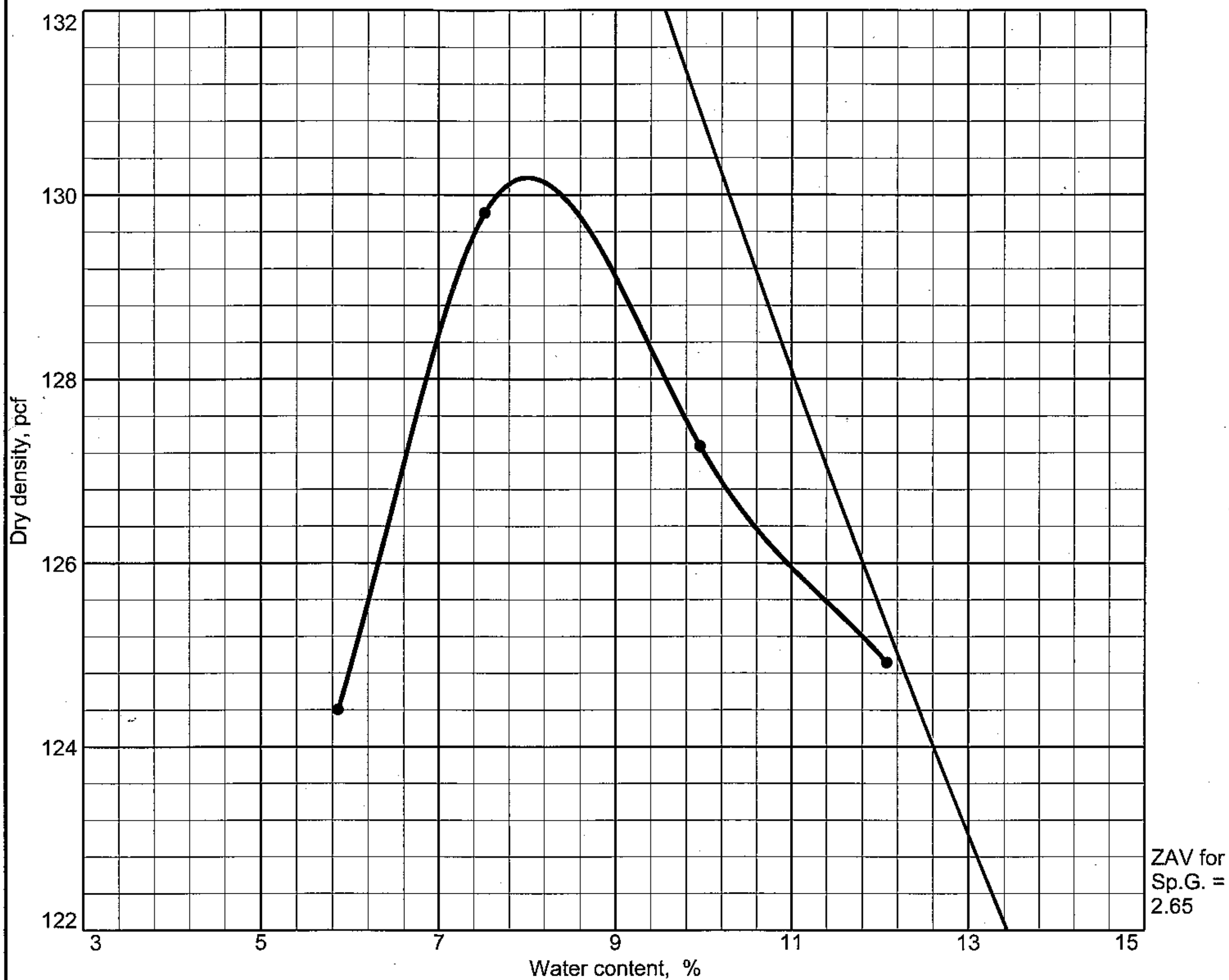
Sieve Size	% Passing	Specifications
1"	100	---
3/4"	99	---
1/2"	98	---
3/8"	97	---
#4	95	---
#10	89	---
#20	81	---
#40	72	---
#80	59	---
#100	45	---
#200	32.7	---

Remarks: The above results are for informational purposes only.

c:

Perry Elstrom
Project Manager

Moisture-Density Relationship Test



Test specification: ASTM D 698-91 Procedure A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > No.4	% < No.200
	USCS	AASHTO						
				2.65				

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 130.2 pcf Optimum moisture = 8.0 %	SP, Poorly Graded Sand, with gravel, fine to medium grained, brown

Project No.: SP-04-06582 **Client:** CNA Consulting Engineers

Project: MN Roads Test Compactor, Albertville, MN

● **Source:** **Sample No.:** P-2

Remarks:

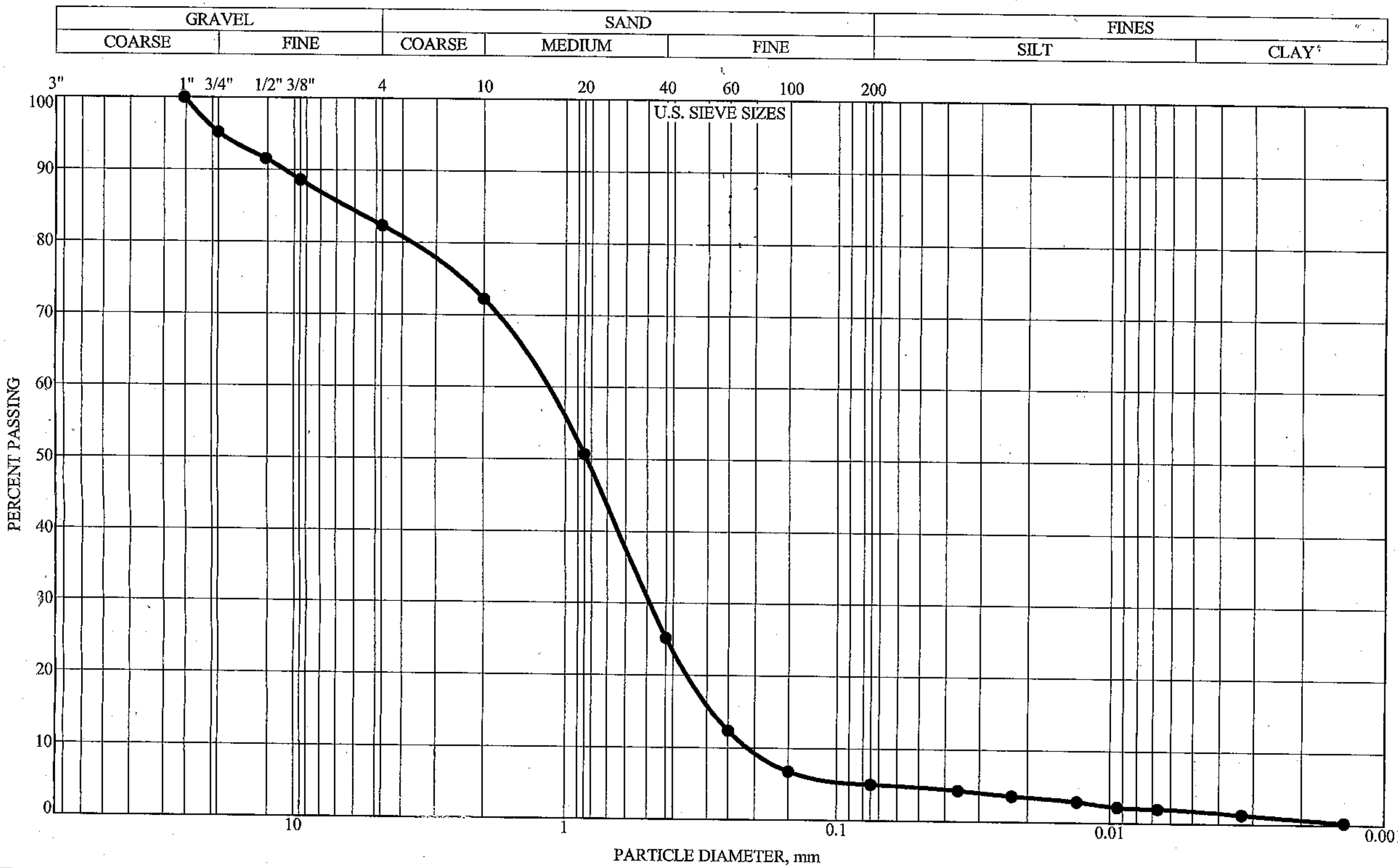
**Mannual Rammer

Moisture-Density Relationship Test

BRAUN INTERTEC

Date 10/14/04

GRAIN SIZE ACCUMULATION CURVE (ASTM)



BRAUN℠ INTERTEC

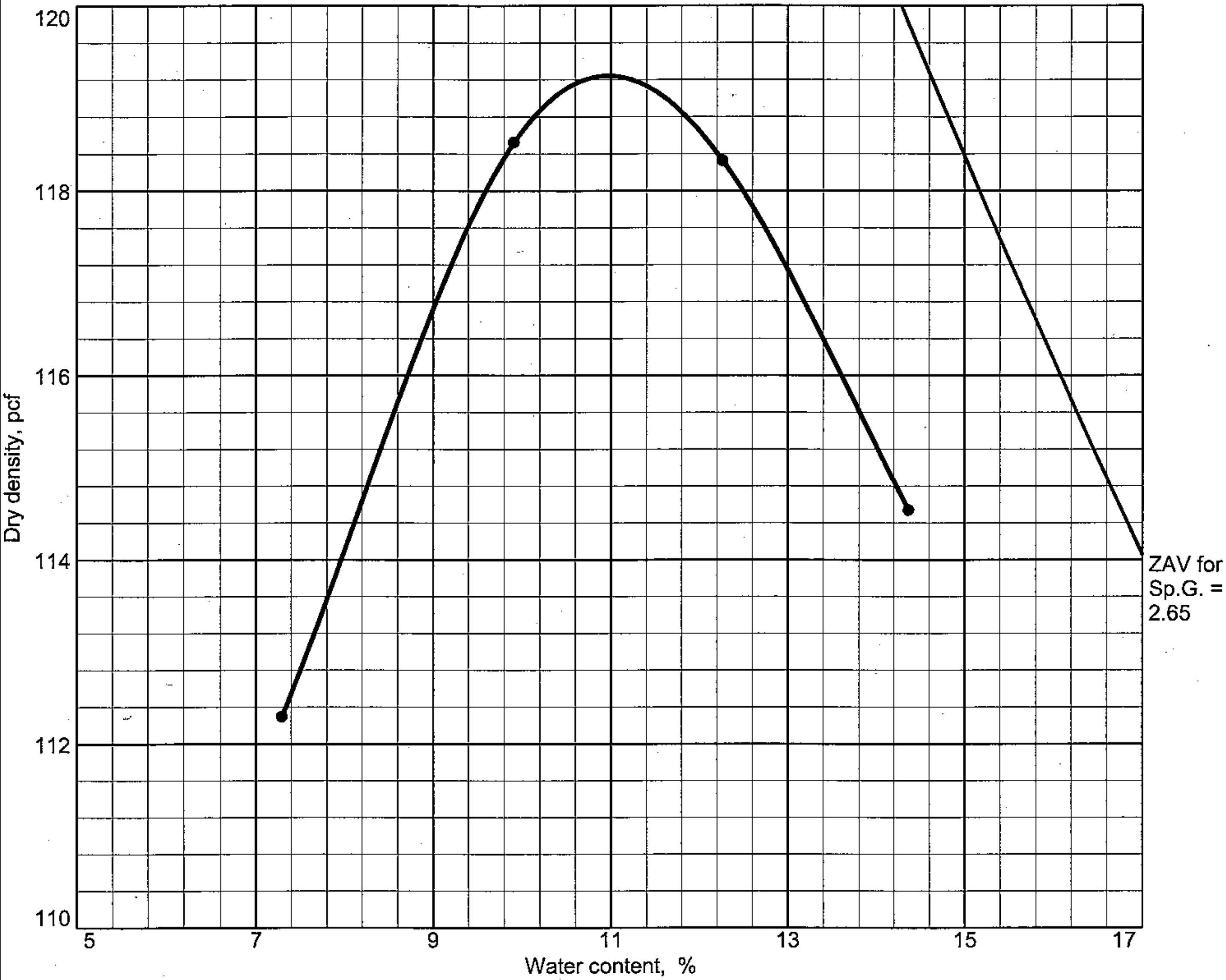
Braun Project SP-04-06582
Mn Road Research

PG-2 (Compare to Proctor Sample P-2)

GRAVEL	17.7%
SAND	77.3%
SILT	3.3%
CLAY	1.7%
D60=1.231	
D30=0.484	Cu=6.1
D10=0.201	Cc=0.9

CLASSIFICATION:
SP - Poorly Graded Sand, with gravel, fine to medium grained, brown

Moisture-Density Relationship Test



Test specification: ASTM D 698-91 Procedure A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > No.4	% < No.200
	USCS	AASHTO						

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 119.2 pcf Optimum moisture = 11.0 %	SM, Silty Sand, mostly fine grained, brown

Project No.: SP-04-06582 **Client:** CNA Consulting Engineers

Project: MN Roads Test Compactor, Albertville, MN

● **Source:** **Sample No.:** P-3

Remarks:

**Mannual Rammer

Moisture-Density Relationship Test

BRAUN INTERTEC

Date 10/14/04

BRAUN
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Braun Intertec Corporation
1017 109th Avenue NE
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Sieve Analysis of Fine and Coarse Aggregates

Date: October 14, 2004

Client:
Lee Peterson
CAN Consulting Engineers
2800 University Avenue SE
Minneapolis, MN 55414

Project: SP-04-06582

Project Description:
MN Roads Test Compactor
Albertville, MN

Field Data

Sample Number:	PG-3 (Compare to Proctor P-3)
Sampled By:	PLE/Braun
Date Sampled:	9/27/2004
Date Received:	10/1/2004
Date Tested:	10/4/2004
Classification:	SM, Silty Sand, mostly fine grained, brown
Sample Location:	MN Road Research

Laboratory Results

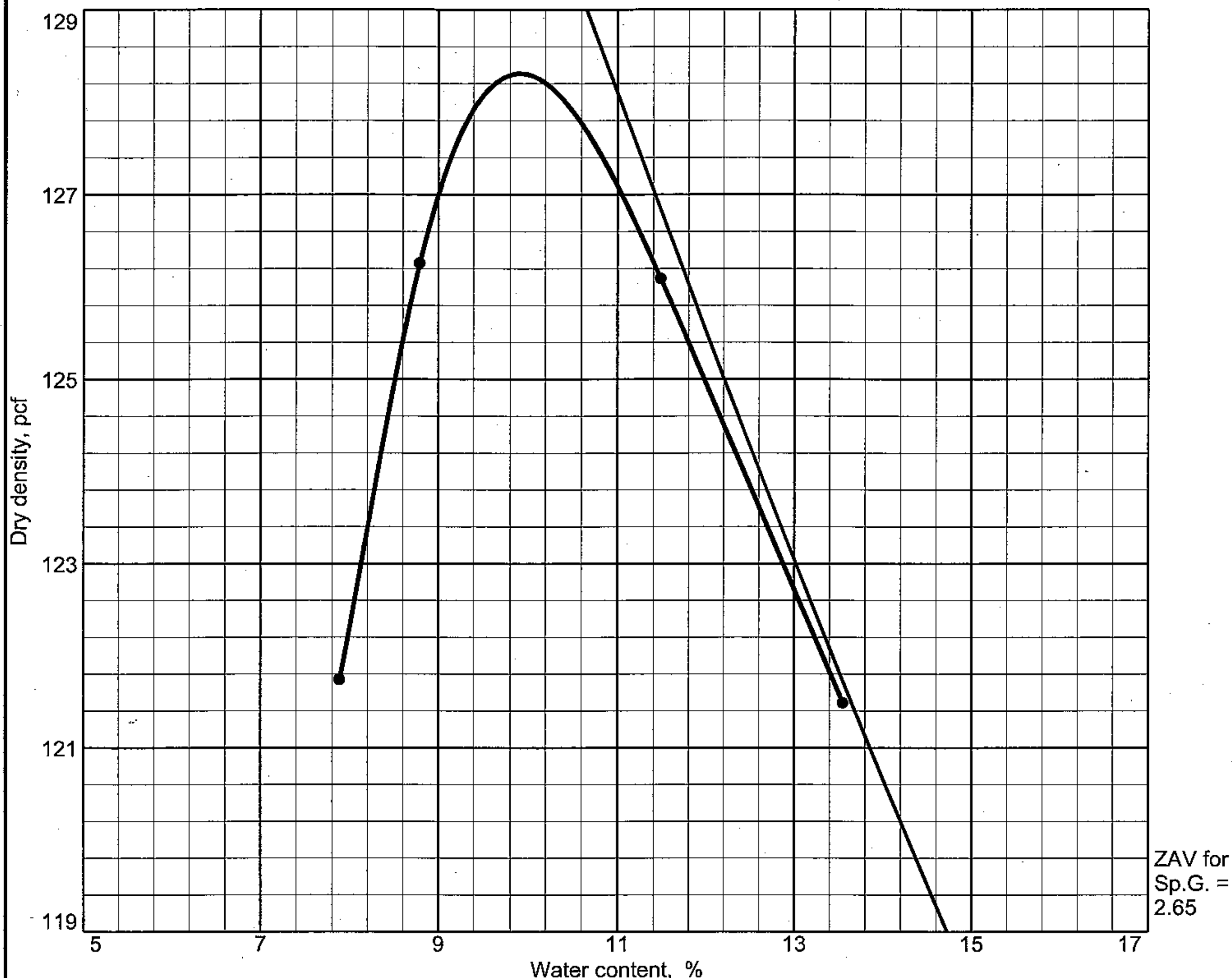
Sieve Size	% Passing	Specifications
1"	100	---
3/4"	99	---
1/2"	98	---
3/8"	98	---
#4	96	---
#10	91	---
#20	80	---
#40	68	---
#80	56	---
#100	45	---
#200	34.4	---

Remarks: The above results are for informational purposes only.

c:

Perry Elstrom
Project Manager

Moisture-Density Relationship Test



Test specification: ASTM D 698-91 Procedure A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > No.4	% < No.200
	USCS	AASHTO						
				2.65				

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 128.3 pcf Optimum moisture = 9.9 %	SM, Silty Sand with some gravel, mostly fine grained, brown

Project No.: SP-04-06582 **Client:** CNA Consulting Engineers

Project: MN Roads Test Compactor, Albertville, MN

● **Source:** **Sample No.:** P-4

Remarks:

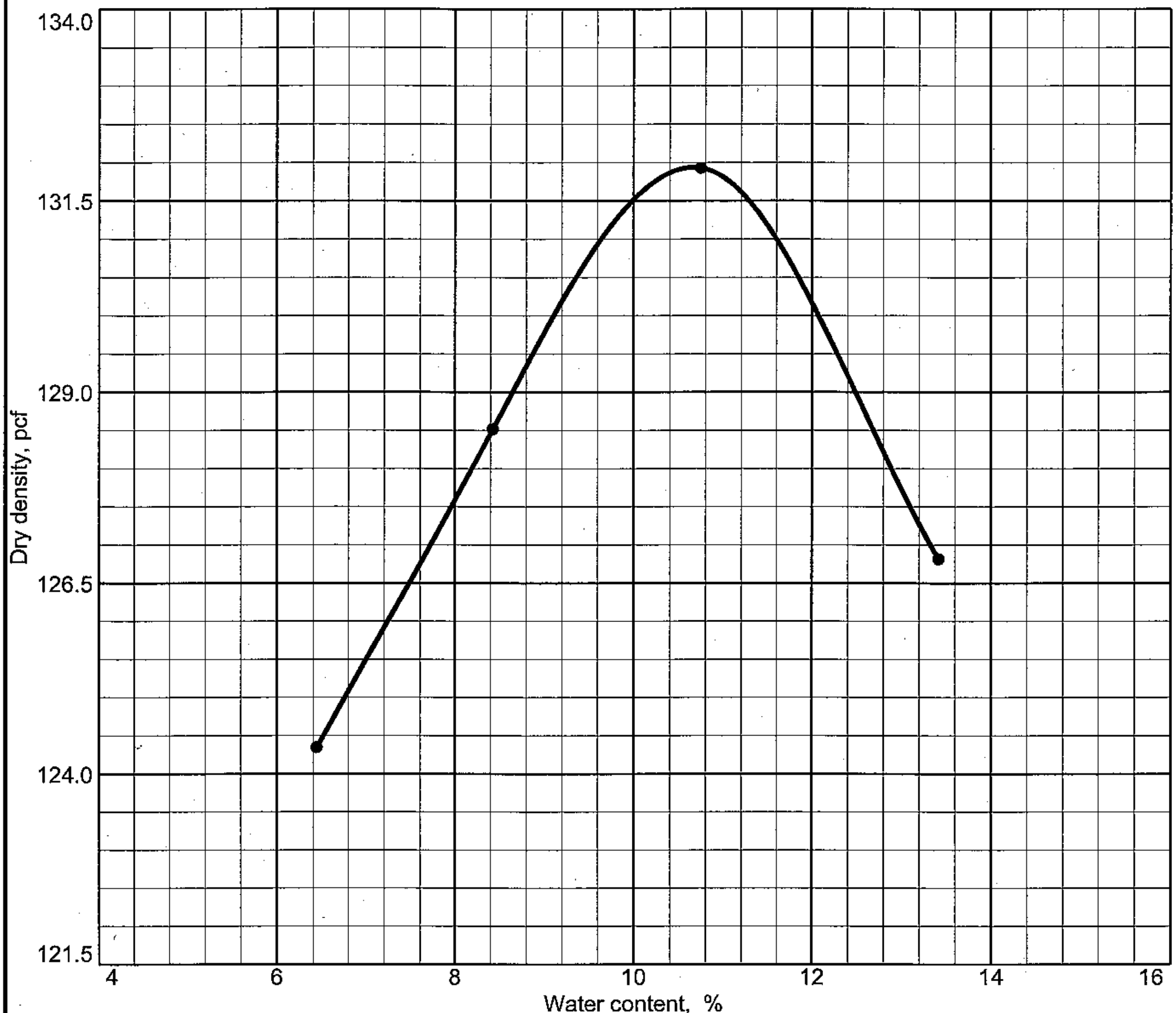
**Mannual Rammer

Moisture-Density Relationship Test

BRAUN INTERTEC

Date 10/14/04

Moisture-Density Relationship Test



Test specification: ASTM D 698-91 Procedure A Standard

Elev/ Depth	Classification		Nat. Moist.	Sp.G.	LL	PI	% > No.4	% < No.200
	USCS	AASHTO						

TEST RESULTS	MATERIAL DESCRIPTION
Maximum dry density = 131.9 pcf Optimum moisture = 10.7 %	Commercially Produced Aggregate (Class 6)

Project No.: SP-04-06582 **Client:** CNA Consulting Engineers

Project: MN Roads Test Compactor, Albertville, MN

● **Source:** **Sample No.:** P-5

Remarks:

**Mannual Rammer

Moisture-Density Relationship Test

BRAUN INTERTEC

Date 10/14/04

BRAUN
INTERTEC

Braun Intertec Corporation
1017 109th Avenue NE
Blaine, MN 55434

Phone: 651.487.7070
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Web: braunintertec.com

Sieve Analysis of Fine and Coarse Aggregates

Date: October 14, 2004

Client:
Lee Peterson
CAN Consulting Engineers
2800 University Avenue SE
Minneapolis, MN 55414

Project: SP-04-06582

Project Description:
MN Roads Test Compactor
Albertville, MN

Field Data

Sample Number:	PG-5 (Compare to Proctor P-5)
Sampled By:	PLE/Braun
Date Sampled:	9/29/2004
Date Received:	9/29/2004
Date Tested:	10/4/2004
Classification:	Commercially Produced Aggregate (Class 6)
Sample Location:	MN Road Research

Laboratory Results

Sieve Size	% Passing	Specifications
1"	100	100
3/4"	98	90-100
3/8"	72	50-85
#4	49	35-70
#10	33	20-55
#20	21	---
#40	15	10-30
#80	9	---
#100	9	---
#200	6.0	3-7

Remarks: The above results are for informational purposes only.

c:

Perry Elstrom
Project Manager