LTPP Materials Characterization Program: Resilient Modulus of Unbound Materials (LTPP Protocol P46) Laboratory Startup and Quality Control Procedure

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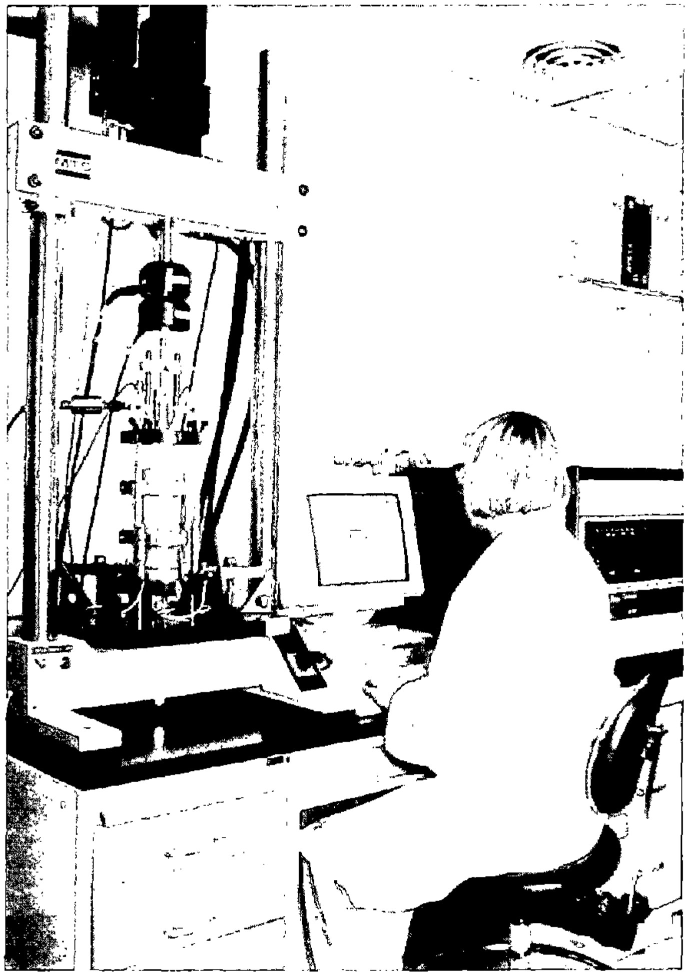

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

As part of the Federal Highway Administration's (FHWA) Long-Term Pavement Performance Program (LTPP) Materials Characterization effort, a quality control/quality assurance (QC/QA) program for the resilient modulus testing of unbound granular materials (LTPP Protocol P46) has been developed. The P46 resilient modulus test protocol was developed to ascertain the strength of pavement base, subbase, and subgrade materials. This test is performed at stress states that are comparable to in-situ pavement conditions. The resilient modulus testing process, generally regarded as a research-type procedure, has historically been performed in a university setting and on a relatively small number of samples. Because the modulus value derived from this testing process is a key parameter for pavement design, the test is being performed for the LTPP program in a production testing environment in what may be the largest single resilient modulus testing program ever undertaken. It is of paramount importance to provide the LTPP researchers with the highest quality data possible. As such, a quality control/quality assurance (QC/QA) procedure was developed to verify the ability of the laboratory equipment and personnel to perform P46 resilient modulus testing for the LTPP program. This report describes the procedure used by the FHWA to perform this verification process. The concepts and testing processes outlined in this report can be applied to many test procedures and a variety of test equipment. The implementation of this procedure in the FHWA LTPP contractor laboratories has had a great impact on achieving repeatable, reliable, high quality resilient modulus data for the LTPP program.

Charles Nemmers, Director
Office of Engineering,
Research and Development

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7. Author(s)
S. Alavi, T. Merport, T. Wilson, J. Groeger, A. López

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PCS/Law Engineering
A Division of Law Engineering and Environmental Services, Inc.
12104 Indian Creek Court, Suite A
Beltsville, Maryland 20705-1242

ERES Consultants, Inc.
505 West University Avenue
Champaign, Illinois, 61820-3915

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16. Abstract

This document describes a procedure for resilient modulus quality control checks. The procedure evaluates the ability of laboratory personnel and the test system to complete LTPP P46 protocol for resilient modulus testing. The procedure is divided into three general phases: (1) Electronic System Performance Verification, (2) Calibration Check and Overall System Performance Verification, and (3) Proficiency Testing. The implementation of this procedure in the FHWA Contractor Laboratories has greatly reduced the within and between-lab variability associated with the LTPP P46 test procedure.

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Resilient Modulus; Quality Control; Laboratory Testing; Base; Subbase; Subgrade; Servo-hydraulic; LTPP

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**	**Symbol**	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH					**LENGTH**		
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	square meters	1.195	square yards	yd^2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	cubic meters	35.71	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.									
		MASS					**MASS**		
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.202	pounds	lb
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
fc	foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS					**FORCE and PRESSURE or STRESS**		
lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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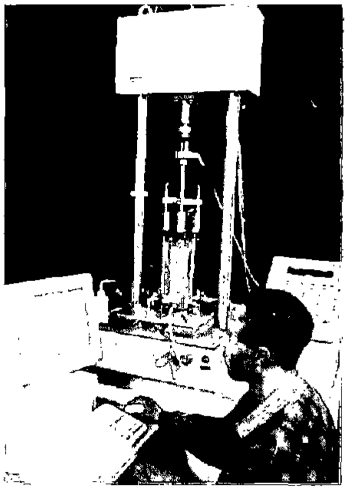
I. INTRODUCTION

General



The Long-Term Pavement Performance (LTPP) P46 resilient modulus test protocol (Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soils) was developed to ascertain the strength of pavement base, subbase, and subgrade materials. This test is performed at stress states that are comparable to in-situ pavement conditions. The resilient modulus testing process, generally regarded as a research-type procedure, has historically been performed in a university setting and on a relatively small number of samples. Because the modulus value derived from this testing process is a key parameter for pavement design, the test is being performed for the LTPP program in a production testing environment in what may be the largest single resilient modulus testing program ever undertaken. It is of paramount importance to provide the LTPP researchers with the highest quality data possible. As such, a quality control/quality assurance (QC/QA) procedure was developed to verify the ability of the laboratory equipment and personnel to perform P46 resilient modulus testing for the LTPP program. This report describes the procedure used by the FHWA to perform this verification process.

The Laboratory Startup and Quality Control Procedure was developed to ensure the accuracy and reliability of the raw data produced while testing materials using closed-loop servo-hydraulic systems. It is based on the premise that any engineering analysis requires reliable raw data, and the prerequisite for reliable raw data is properly operating equipment. The Laboratory Startup and Quality Control Procedure is designed to verify the operating accuracy of all the essential system components in a logical manner. Each part of the system is verified individually and then the entire system is checked to make sure all of the parts work together. As part of the Electronics System Verification Procedure, the signal conditioning channels, data acquisition processes, and transducers are checked for proper operation. Following the Electronics System Verification Procedure, the Calibration Check and Overall System Performance Verification Procedure is performed. Load and displacement measuring devices; (i.e., load cells, linear variable deformation transducers-LVDT's) are checked for linearity and proper calibration. The ability of the software to control and acquire data is also assessed. When the process of verifying the individual system components is complete, the overall capability of the machine to conduct a specific experiment is assessed through specially designed static and dynamic experiments on materials with known properties. Once the system has been evaluated, the Proficiency phase of the procedure will address the competence of the laboratory personnel to prepare samples and test both Type 1 (coarse-grained) and Type 2 (fine-grained) samples. For both sample types, the entire test procedure is observed, beginning with breaking down the bulk material samples all the way through the actual testing and recording of load and deformation data. Through the use of this procedure, all of the components necessary to obtain repeatable, accurate resilient modulus test results are verified.

The procedure enables laboratories to verify their testing systems and procedures prior to the start of production testing by using a simple and inexpensive process. It can also be used to perform ongoing quality control checks of the equipment and testing processes being used by the laboratory during the production testing process.

The equipment required to conduct the procedure was specifically chosen to be readily available in the market at very reasonable costs. This equipment includes instruments such as an oscilloscope, function generator and a computer which are available in most testing laboratories. The P46 procedure has been successfully implemented at FHWA facilities in McLean, VA and in two commercial laboratories under contract to FHWA. Although the original intention for developing the procedure was for the resilient modulus program, this efficient and inexpensive procedure can be implemented to verify most closed-loop servo-hydraulic testing systems.

Structure and Use

The procedure is divided into three distinct components:

1. Electronics System Performance Verification Procedure.
2. Calibration Check and Overall System Performance Verification Procedure.
3. Proficiency Procedure.

The *Electronics System Performance Verification Procedure* will characterize the frequency response of the signal conditioners and data acquisition system of the test system. This procedure is generally used prior to the initiation of a resilient modulus testing program. As long as all of the electronic parts of the test system remain the same, this procedure does not necessarily need to be repeated on a continuing basis (i.e. monthly). However, the procedure should be conducted at least every year to verify the equipment meets the acceptance criteria indicated in this document or when any part of the electronics is replaced or modified. Also, this procedure should be performed when other circumstances suggest that the electronics may be suspect. Generally, an electronics technician well-versed in data acquisition systems is needed to perform these experiments. The amount of time required to perform this procedure depends on the complexity of the test system and the experience of the electronics technician. On average, this procedure should take approximately 8 to 10 h to complete (including data analysis).

The P46 resilient modulus testing procedure requires a system made up of many different pieces of equipment: load frame, load cells, hydraulic system, LVDT's, triaxial pressure chamber, computer, signal processor, etc. For the *Calibration Check and Overall System Performance Verification Procedure*, individual elements of the test equipment will be checked first followed by the overall test setup. This will verify that the test system is producing the expected responses. By first checking the individual components of the test system, it is expected that many problems that would be encountered during actual P46 testing can be identified and eliminated prior to checking the overall system. This procedure is generally used prior to initiation of a resilient modulus testing program and subsequently on a continuing basis (i.e.

monthly) to verify the system response. On average, the procedure requires approximately 8 h to complete.

The ability of the laboratory personnel to conduct P46 testing is evaluated in the *Proficiency Procedure*. For both Type 1 and Type 2 samples, the entire test procedure should be observed by personnel who are very familiar with P46 procedures, beginning with breaking down the bulk material samples through the actual testing and recording of load and deformation data. This procedure is generally used prior to initiation of a resilient modulus testing program and subsequently on a continuing basis (i.e. quarterly) to verify the operators ability to conduct resilient modulus testing. The procedure requires approximately 2 days to complete (including preparation, compaction, etc.).

Disclaimer

This procedure was designed based on three criteria; effectiveness, simplicity, and low cost. It was formulated to be as general as possible so that it could be implemented by a wide variety of testing laboratories. Its growing implementation by laboratories nationwide is an indication of the procedure reaching its main objective which is to reduce test variability as much as possible. Nonetheless, with the wide range of technology used in testing laboratories, each laboratory may have to adapt slightly different methods to perform this procedure, especially the electronics verification procedure. **The purpose of this procedure is not to verify the manufacturer's specifications nor to set new specifications for manufacturing equipment**. This procedure is merely a powerful and inexpensive tool for the equipment operator to verify equipment accuracy before and regularly during production testing. A certain level of expertise is required at each laboratory to ensure proper wiring for the Electronics System Performance Verification Procedure. This procedure should be implemented with caution and by expert technicians or engineers. Laboratories should use this procedure at their own discretion and neither the FHWA nor the LTPP Pavement Engineering Technical Assistance Contractor Team is responsible for any personal injury or property damage due to the use of this procedure.

II. EQUIPMENT REQUIREMENTS

In order to perform the Resilient Modulus of Unbound Materials (LTPP Protocol P46) Laboratory Startup and Quality Control Procedure, in addition to the resilient modulus test system and the latest version of LTPP Protocol P46, it is necessary to have available certain pieces of equipment. This equipment includes:

- Computer with sufficient hardware/software for data analysis.
- Analog Oscilloscope:
  Tektronix 2465B (or similar)
  - 4 channels
  - cursor measurements
  - auto and normal sweep modes
- Function Generator/Balanced Modulator
  Leader LFG-1300S (or similar)
  - sinusoidal output signal
  - output amplitude: 20 volts peak-to-peak open circuit
  - output attenuation control to 0.01 volts peak-to-peak open circuit
  - balanced modulation with external input (for carrier signal)
  - modulation signal generation with external output of modulation signal (reference signal)
  - modulation frequency from 2Hz to 1,000Hz
  - carrier and modulation level controls
- Strain Indicator
  Measurements Group P-3500 (or similar)
  - 1 microstrain resolution
  - balanced signal disable capability
  - digital readout
- Cables for connecting signal conditioner/data acquisition inputs and outputs to test instruments. These cables may incorporate attenuation, termination, or identification resistors.
- Cables for connecting the load cell(s) to the strain indicator.
- NIST-traceable proving ring with 2.22 kN capacity.
- NIST-traceable proving ring with 26.7 kN capacity.
- A micrometer head based LVDT calibrator with .001 mm resolution (for ±2.5 mm LVDT calibration).

- Pressure gauge for an independent measurement (secondary pressure gauge) of the pressure inside the triaxial cell. The gauge should have a capacity of at least 170 kPa.
- All applicable equipment required by LTPP Protocol P46.

These pieces of equipment will be used to verify the operating accuracy of all the essential system components in a logical manner. The equipment referenced in LTPP Protocol P46 will be used to prepare and test the samples.

III. ELECTRONIC SYSTEMS PERFORMANCE VERIFICATION PROCEDURE

Background

The signal conditioning/data acquisition and control system frequency response tests utilize a known signal which simulates an LVDT or load cell's response to dynamic motion. A component of this known signal is compared to the output of the signal conditioner(s) and the recorded data. With DC-type signal conditioners this simulation requires a sine source (function generator) applied directly to the signal conditioner. The only consideration is that the amplitude level must be appropriate for the gains involved.

AC-type signal conditioners expect an input signal which is the same frequency (synchronized) as the transducer input voltage (carrier signal). AC-type signal conditioners typically excite the input of the transducers with a carrier signal in the frequency range of 2 kHz to 10 kHz. For example, if $A\sin\varpi t$ describes the carrier signal to the primary of an LVDT, the LVDT output will equal $(A\sin\varpi t)(x)$, where x is a variable dependent on the displacement of the LVDT core. For the frequency response tests, let $x = B\sin\omega t$, where ω is the low frequency modulation signal $((2\pi)\bullet 2\text{Hz}$ to $(2\pi)\bullet 50\text{Hz})$. To simulate the response of an LVDT to dynamic motion, a multiplication is required in the form of $(A\sin\varpi t)(B\sin\omega t)$. The technical term for this type of signal multiplication is "Double Sideband Suppressed Carrier Modulation" or "Balanced Modulation." This term is used because the Fourier Amplitude Spectrum of the resulting signal does not contain any carrier component ϖ, only components at the sidebands: $\varpi\pm\omega$. Therefore, to generate the simulation for the frequency response tests an analog multiplication of 2 sinusoids is required. Since most of the "off the shelf" function generators are designed to simulate communication signals which utilize the carrier component, a simple modification to the function generator is required which is described in the following paragraph.

Required Modification to the Function Generator

A Leader function generator (LFG-1300S) is a typical piece of equipment that can be utilized for performing this procedure. This type of function generator contains the appropriate source and multiplier to produce the necessary signals. The function generator requires a slight modification to access the modulation source so that it could be observed on the oscilloscope and digitized by the data acquisition system. The steps required to modify the Leader LFG-1300S are outlined below:

1. Remove the existing connection to the rear panel BNC connector labeled VCG IN.

2. Relabel BNC connector "INTERNAL MODULATION OUT."

3. Connect TP-7 on the main circuit board through a 1000 ohm resistor (1/4 watt) to the BNC connector now labeled "INTERNAL MODULATION OUT."

Figure 1 is a wiring diagram of the modification.

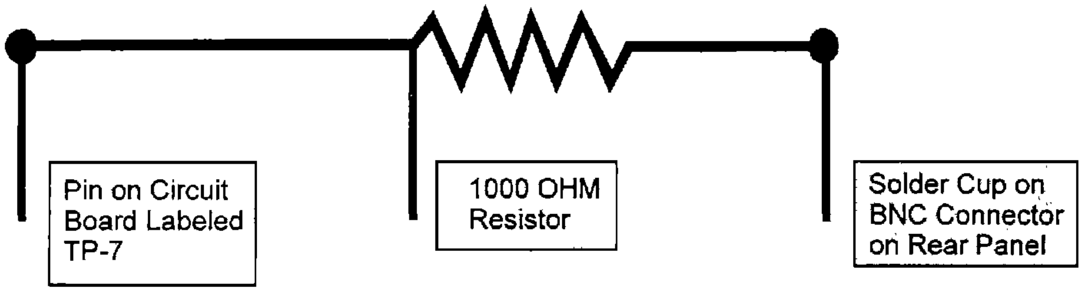


Figure 1. Leader LFG-1300S wiring modification.

Figure 2 shows a block diagram for the frequency response tests for both AC and DC type signal conditioners.

Procedure

The following experiment will characterize the frequency response of the signal conditioners and data acquisition system. A function generator/balanced modulator is used to simulate the response of the transducers to dynamic motion. The response of the system is determined through analysis of digitized data and through oscilloscope measurements. The results will verify channel-to-channel phase matching and flat amplitude response to 50Hz. Channels to be tested include the load cell and all deformation or strain recording channels.

Note that phase and amplitude errors can affect material property calculations. These errors can be caused by both mechanical and electronic means. The experiment will ensure that the electronic signal conditioning and data acquisition system do not contribute excessive errors to the measurement result. Phase and amplitude errors in signal conditioners are usually caused by low pass filters (utilized to reduce noise and sampling related errors). These filters are an integral part of any signal conditioner. Figure 3 can be used as a wiring guide for DC and AC-type signal conditioners.

With the hydraulic power off, the following tests will be performed for each signal conditioning channel:

1. Connect the test equipment as shown on figure 3. Use configuration 1 for DC-type signal conditioners and configuration 2 for AC-type signal conditioners. For configuration 2, adjust the carrier and modulation levels to produce a double sideband suppressed carrier signal as shown in figure 4.

2. Set the frequency of the function generator to 2 Hz (sine function).

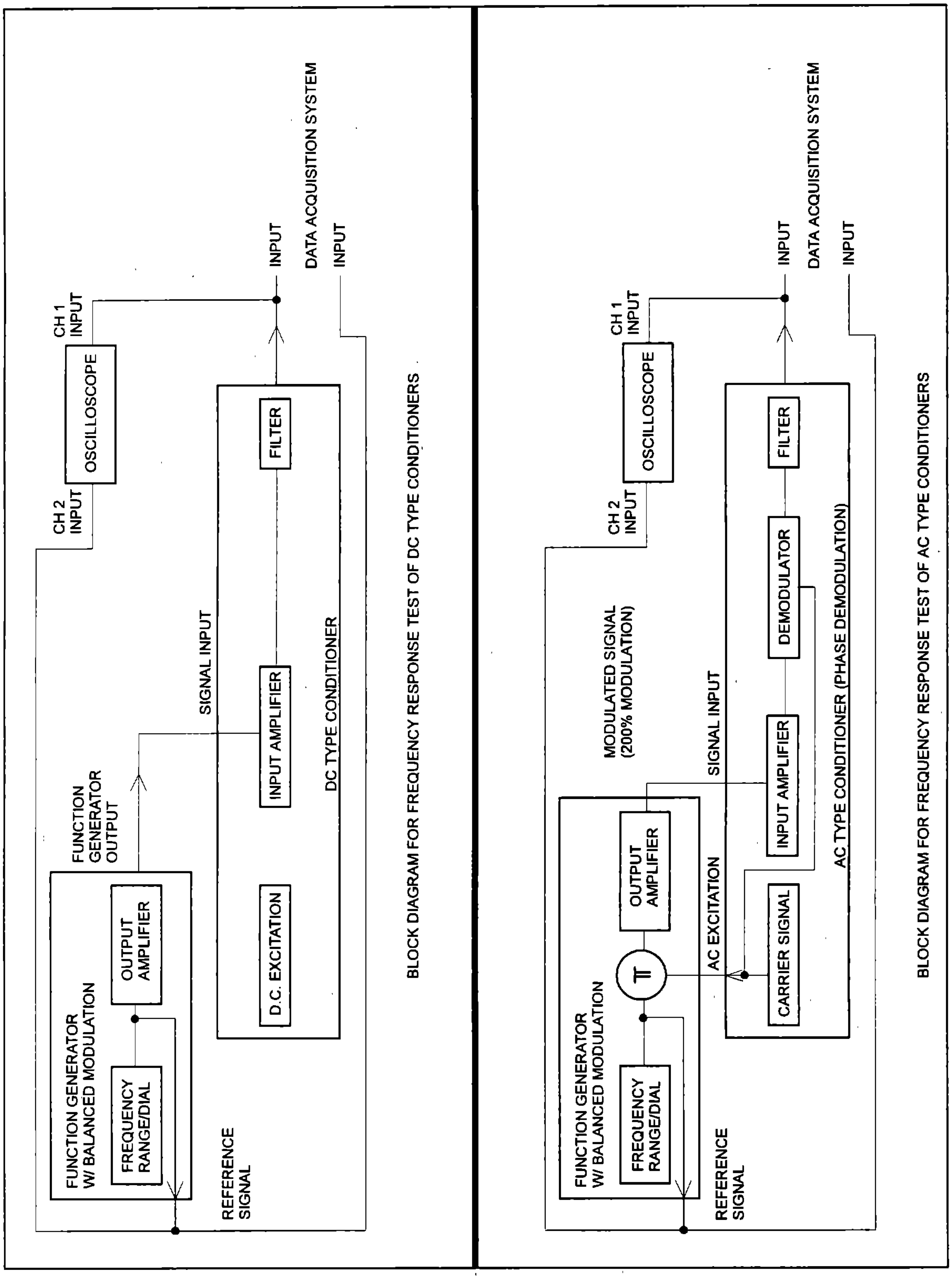


Figure 2. Frequency response test setup block diagram.

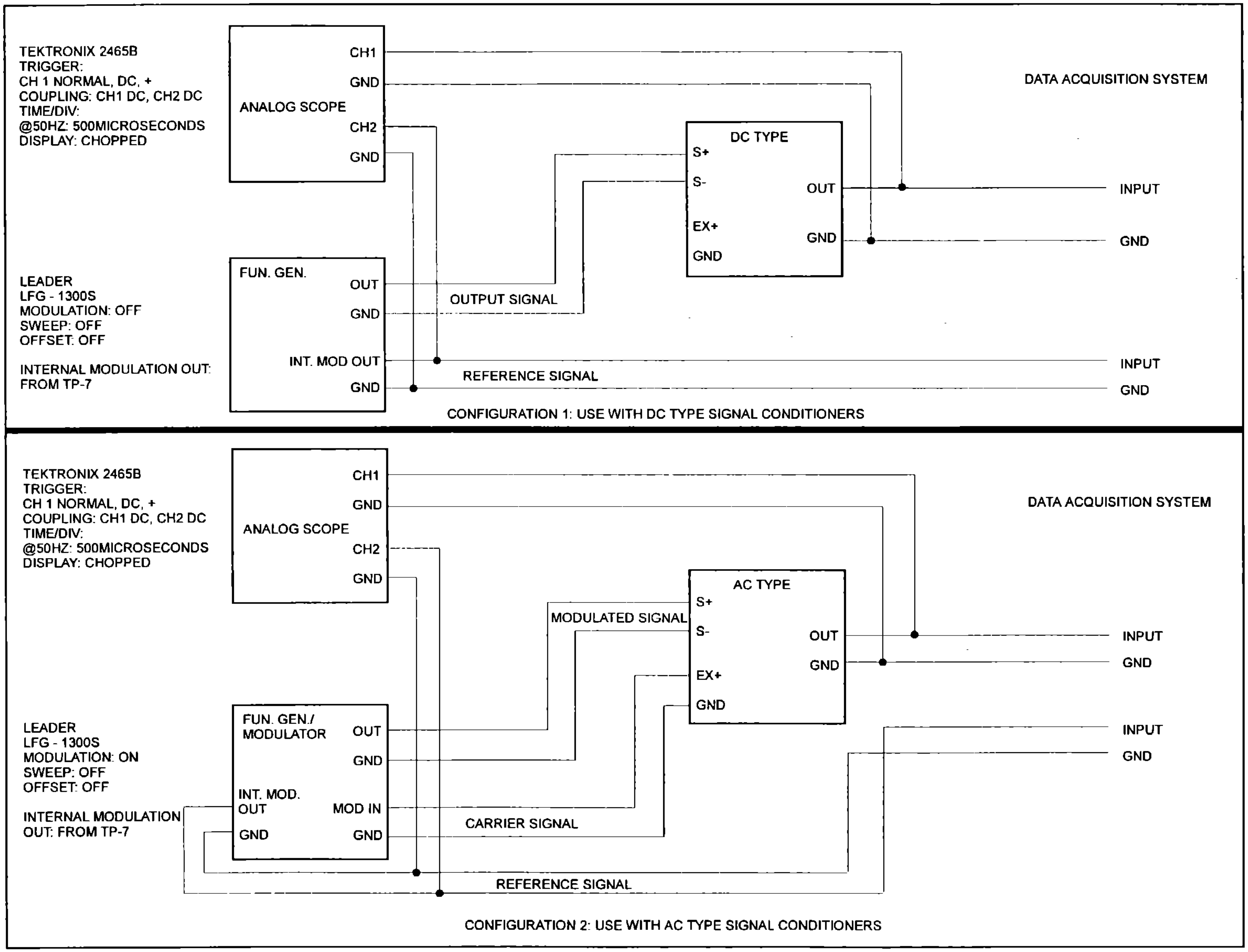


Figure 3. Frequency response test setup (simplified wiring).

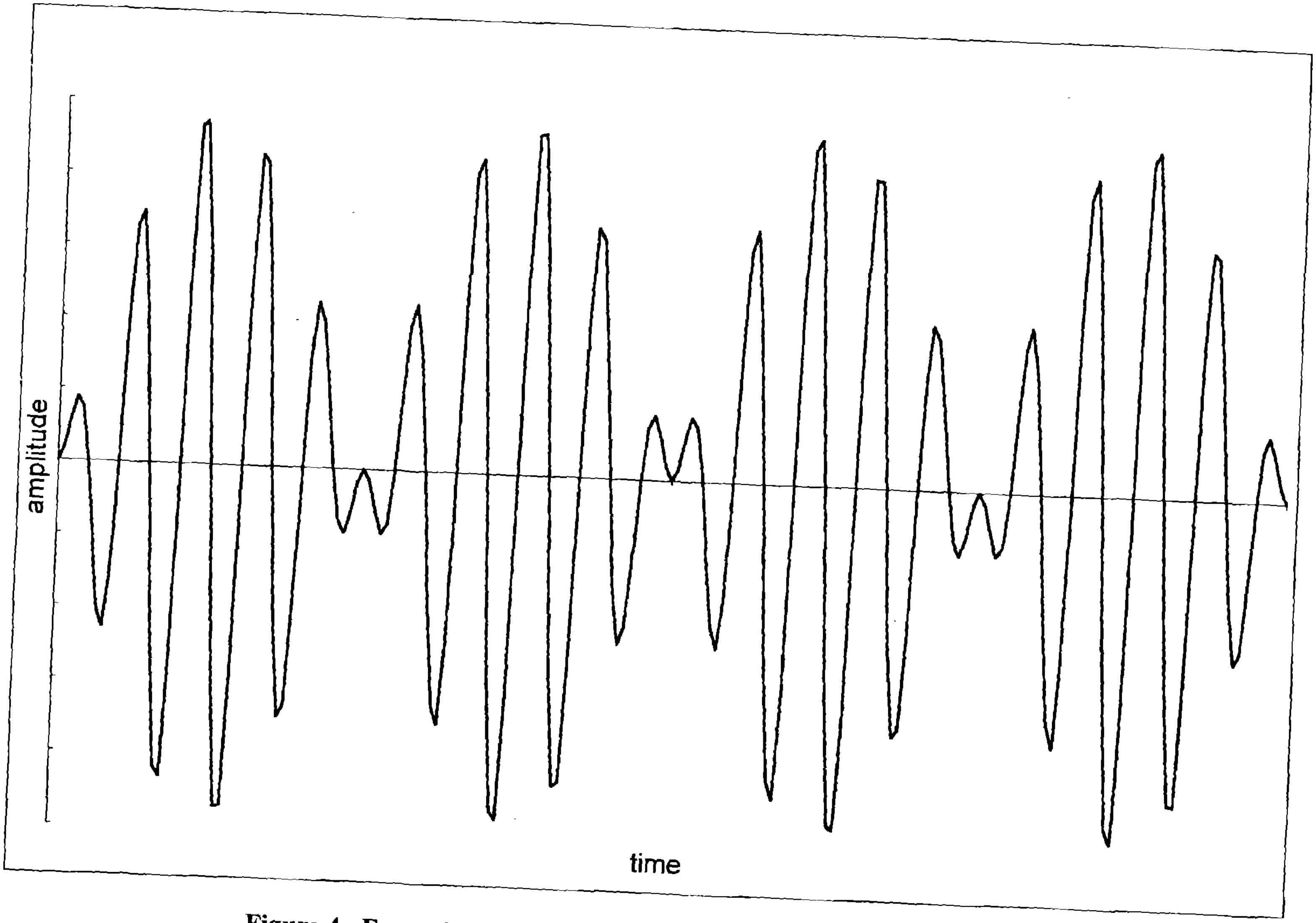


Figure 4. Example of double sideband suppressed carrier modulation.

3. Set the output voltage of the function generator to an appropriate level for the signal conditioner used (approximately 0.02 volts peak-to-peak for load cell conditioners and 0.2 volts peak-to-peak for LVDT signal conditioners). Note that the voltage amplitude must remain constant throughout this procedure.

4. If the conditioners have not been previously calibrated for a particular transducer, adjust the gain of the signal conditioners such that the output is set to 90 percent of the full-scale output level. Otherwise do not modify the setting of the signal conditioner.

5. Observe the output of the signal conditioner on the oscilloscope. Record the peak-to-peak amplitude of the signal conditioner as observed on the oscilloscope using form 1 provided in appendix A. In addition, record the output of the signal conditioner and reference signal using the data acquisition system.

6. Repeat step 5 at frequencies from 4 Hz to 20 Hz in 2-Hz intervals.

7. Repeat step 5 at 50 Hz. Record the time delay between the input and output of the signal conditioner observed on the oscilloscope on form 1 (the time delay derived from the digitized data will also be noted on form 1). Refer to figure 5 for guidance on making the delay measurements.

8. Repeat this procedure for each channel which will be used to collect data during actual testing.[1]

9. Record signal conditioner filter and gain settings on form 1.

10. Using the digitized data, calculate the signal frequency and amplitude and record on form 1.

Acceptance Criteria

- All channels should have matched input-to-output delays within ± 0.000500 s at 50 Hz as measured on the oscilloscope. Delays derived from digital data should indicate matched input-to-output delays within ± 0.000400 s at 50 Hz.

- The recorded data should indicate an amplitude within 3 percent of the oscilloscope measurement times a constant. The constant is determined from comparing the two measurements at 2 Hz.[2] If the signal conditioner output is passed directly to the analog-to-digital conversion system, this constant is equal to

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[1] In some cases multiple channels can be tested simultaneously.

[2] The oscilloscope observations can quickly determine if the filters are improperly set by observing the signal conditioner output amplitude characteristics from 2 Hz to 50 Hz.

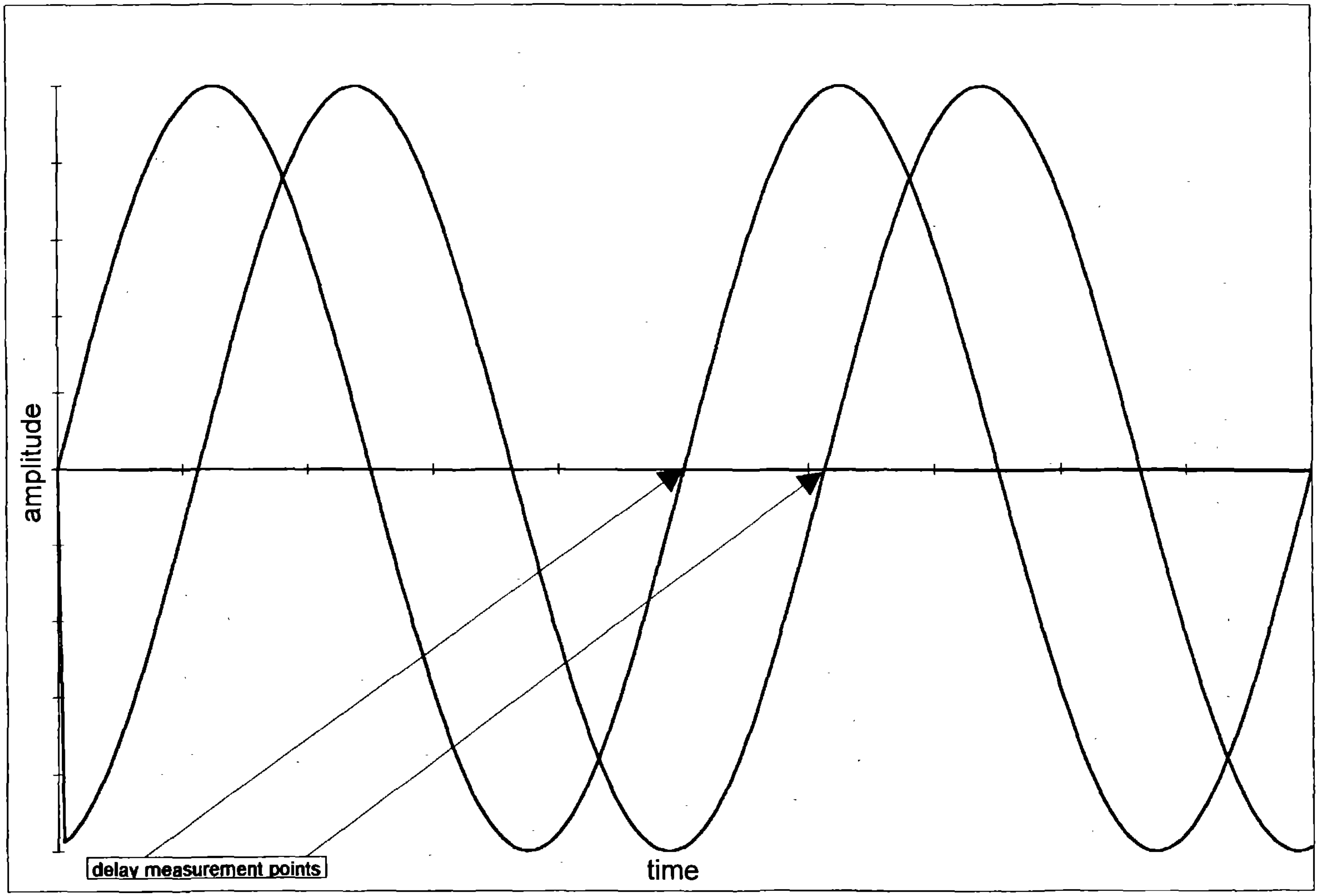

Figure 5. Example of reference signal/signal conditioner waveforms.

1.0. The frequency obtained from the recorded data should be within 3 percent of the function generator dial (previously calibrated with a precision counter).

- The maximum deviation in amplitude (signal attenuation) from 2 Hz to 10 Hz for a single channel should be less than 0.5 percent as determined from the digitized data.

If the above criteria are not met, problems such as inadequate filters (or unmatched filters) or inadequacies in data acquisition hardware/software should be investigated and the tests should be repeated.[3] Filter characteristics should not cause excessive amplitude or phase errors in the signals. Error tolerances are specified in the acceptance criteria. Note that improper filter settings in a servo-hydraulic feedback channel can cause violent oscillations to occur in the hydraulic actuator. Filter settings should remain unchanged after the electronics system has passed the acceptance criteria.

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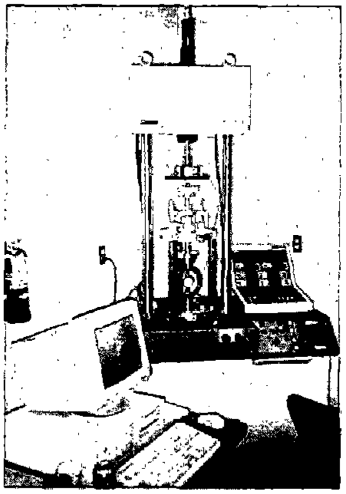
[3] It should be noted that the above requirements were developed for detection of gross errors in the system and are based on the performance of specific equipment used in LTPP P46 Startup and Quality Control Procedure. For example, if an oscilloscope is used without cursor measurements, the amplitude and phase measurements will have more uncertainty.

IV. CALIBRATION CHECK AND OVERALL SYSTEM PERFORMANCE VERIFICATION PROCEDURE



The P46 resilient modulus testing procedure requires a device made up of many different pieces of equipment: load frame, load cells, hydraulic system, LVDT's, triaxial pressure chamber, computer, signal processor, etc. For this procedure, elements of the overall test setup will be checked to verify that their operation is producing the expected responses. By first checking the individual components of the test system, it is expected that many problems that would be encountered during actual P46 testing can be identified and eliminated prior to checking the overall system.

The following sections detail the procedures to be used for checking each of the individual test system components.

LVDT's

Checking of the LVDT's will be done using a micrometer head based LVDT calibrator capable of accurate calibration of ± 2.5 mm LVDT movement. The calibration should be performed for all ranges required for the P46 tests. A minimum of an eight-point calibration should be conducted starting with the zero offset (0 volt = 0 mm). For each increment, register the values of the micrometer reading and the voltage reading. Repeat this procedure by moving the calibrator knob back and forth four times between 0 mm and the maximum calibration value. Plot the voltage readings versus displacement readings.

Acceptance Criteria

- The best fit curve should have a zero intercept, a R^2 value of at least 0.99, and a coefficient of variation of less than 2 percent.[4]

Load Cell

The following test will determine the load cell zero reading. An excessive zero reading indicates a damaged load cell due to over ranging or fatigue.

1. Connect the 2.22 kN load cell to the strain indicator.

2. Set the gauge factor to 2.00 on the strain indicator.

3. Disable or zero any balance signal on the strain indicator to ensure that no balance signal is injected into the load cell signal.

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[4] In a production testing environment, it is recommended that recalibration of the LVDT's occur on a weekly basis.

4. Set the strain indicator to full bridge mode.

5. Convert the initial strain to units of mv/v by dividing the indicated microstrain by 2000. Record the measured mv/v on the form provided in the column labeled "measured zero." (Note that the maximum zero value can be determined from the manufacturer's calibration certificate by multiplying the full-scale output in mv/v by 0.015).

6. Repeat steps 1 to 5 for the 22.2 kN load cell.

Record the results of the load cell zero reading check on form 2 (appendix A).

Acceptance Criteria

- If the load cell zero reading exceeds 1.5 percent of its full-scale factory indicated sensitivity, then it should be returned to the manufacturer for evaluation. If the load cell meets the specifications using the manufacturer's test equipment then the load cell is considered suitable for use. If it does not meet the manufacturer's specifications, then it should be repaired or replaced.

Load Cell Calibration

The load cell verification (calibration) should be performed using a calibration service with a National Institute of Standards and Technology (NIST) traceable cell using the latest version of the American Society for Testing and Materials (ASTM) E4 standard. The calibration should be performed for all load ranges required for P46 resilient modulus testing. The loading device should be verified annually and/or immediately after any repair or any relocation of the testing machine regardless of the time interval since the last verification.

Acceptance Criteria

- The laboratory must keep a current load cell calibration certificate on hand for each load cell used for P46 testing.

Verification of Load Cell Calibration (Static)

A NIST-traceable proving ring will be used to allow the laboratories to verify the load cell calibration on a periodic basis. For a 2.22 kN load cell use a 2.22 kN proving ring, and for a 22.2 kN load cell use a 26.7 kN proving ring.[5]

The steps for checking the load cell once it is calibrated are described below:

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[5] Note that a 26.7 kN proving ring was used for these experiments based on availability, a 22.2 kN proving ring will perform equally as well for these experiments.

1. Position the proving ring in the triaxial chamber so that the chamber piston rod is in contact with the proving ring mounting block. If the proving ring is too big to fit inside the chamber, remove the chamber (perform the steps without the chamber) and fabricate special rods to hold the top plate of the chamber in place. **Note that the proving ring must be bolted down to the bottom plate of the triaxial cell. Furthermore, the bottom plate of the triaxial cell must be bolted down (or tightly fastened) to the bottom loading platen of the load frame.**[6,7]

2. Place the two LVDT's in the LVDT holders (mounted on the top plate of the triaxial chamber) and position the LVDT's at their mid-range.

3. Using the system controls, apply a static load equal to 10 percent of proving ring capacity. Record the proving ring dial indicator value (using form 3 or 4, as appropriate, in appendix A) and register the load cell and LVDT readings using the data acquisition system.

4. Repeat step 3 at 10 percent loading increments up to 90 percent of proving ring loading capacity (but do not exceed the load cell capacity).[8]

5. Convert proving ring dial gauge values into load values using the proving ring load-dial gauge equation (accompanied with each proving ring) and record them on form 3 or form 4 (as appropriate) provided in appendix A.

6. Using the chart provided (i.e. in figures 6, 7) determine whether there is a significant difference (beyond the ±5 percent limit boundaries shown on the graphs) between the load values registered by the load cell and those measured by the proving ring. If a significant difference is identified between the measured loads, the load cell should be recalibrated, or a new load cell should be installed on the test system and the process repeated.

7. Convert the proving ring dial indicator value to displacement measurement at a given load (by using the dial gauge displacement conversion factor). Compare the proving ring displacement measurement with the average LVDT measurement. If the difference is beyond 5 percent, check the system for friction in the triaxial

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[6] Prior to performing the proving ring tests, it is recommended that a slow ramp load from 10 percent to 90 percent of proving ring capacity (do not exceed load cell capacity) be applied a minimum of five times to minimize the hysteresis of the proving ring.

[7] Prior to performing these experiments, be sure all appropriate stroke and load safeguards are in-place so as to protect the test machine and proving ring from damage.

[8] The proving rings used in this research were guaranteed to be linear in the range of 10 percent to 100 percent of their rated load capacity. Testing the proving rings outside of this range is not recommended.

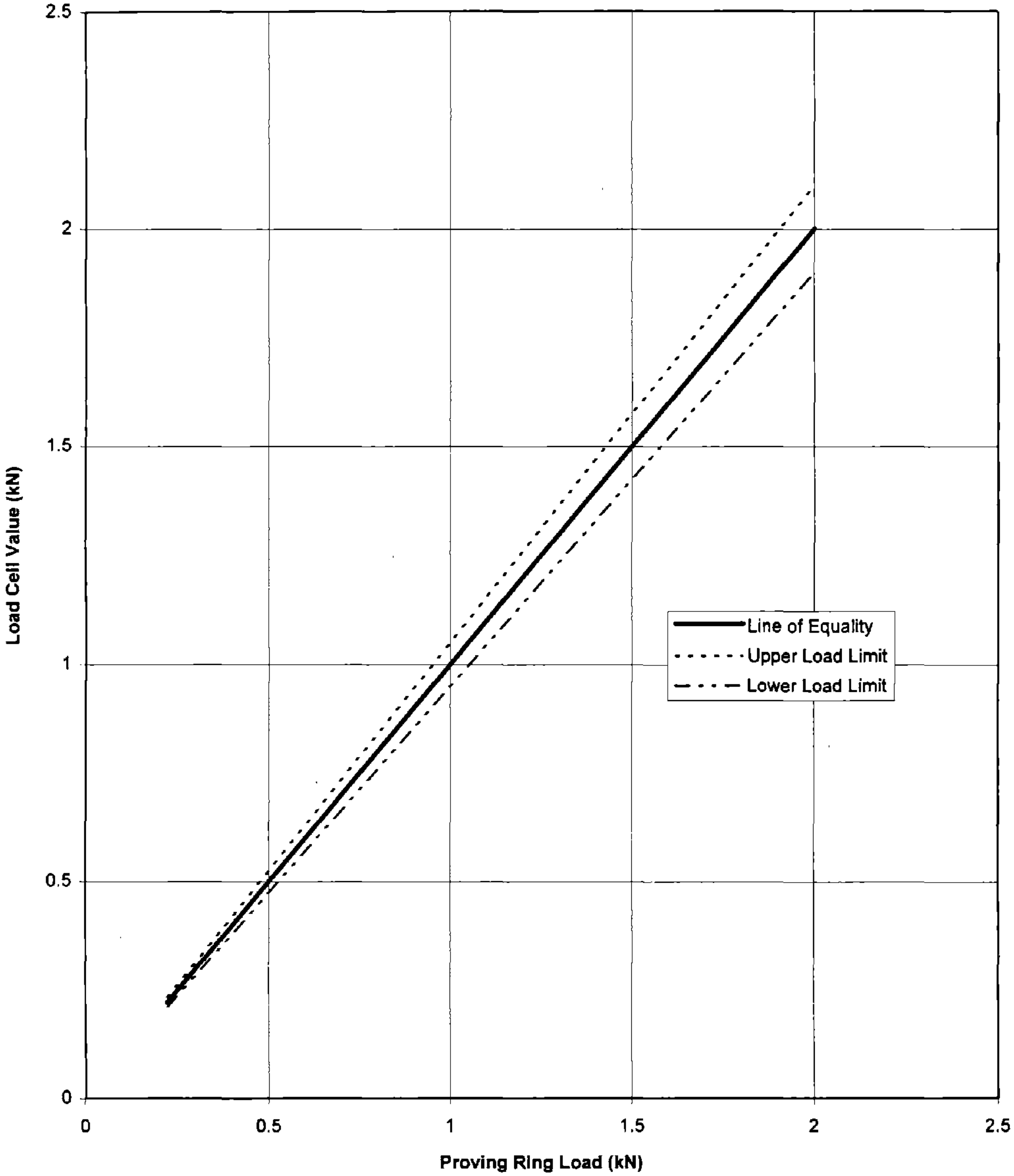

Figure 6. Load cell reading vs. 2.22-kN proving ring load values - static test.

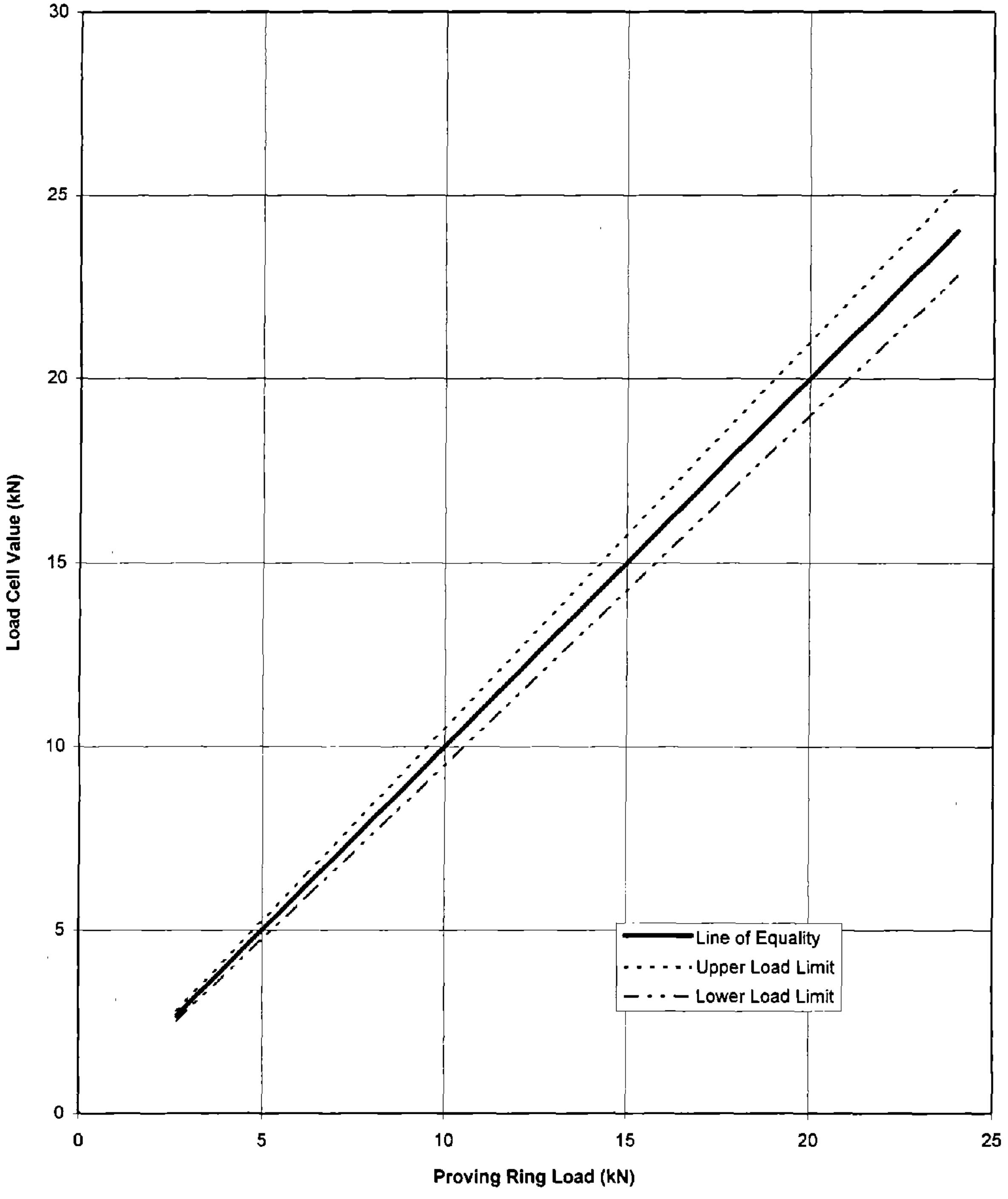

Figure 7. Load cell reading vs. 26.7-kN proving ring load values - static test.

piston, misalignment, loose triaxial cell, loose LVDT's, etc., and repeat the process.[9]

8. It is recommended that the process be repeated three times for each load cell and triaxial chamber. The entire assembly should be taken apart and reassembled in between each replicate test.

Acceptance Criteria

- Proving ring load value and the load cell value should be within ±5 percent of each other.
- Proving ring displacement measurement and the average LVDT measurement should be within ±5 percent of each other.

Load versus Deformation Response Check (Dynamic)

The steps described herein are general in nature and can be performed at any laboratory using different types (brands) of proving rings. However, the relationships shown on figure 8 and figure 9 are case specific to the proving rings used for the FHWA LTPP P46 Startup experiments. Since different proving rings may have different stiffness characteristics, the load versus deformation relationships developed at different laboratories using different proving rings may not be the same as that presented in figures 8 and 9. For the LTPP P46 verification procedure, FHWA's Turner-Fairbank laboratory was used as the reference laboratory where the procedure was first implemented. Figures 8 and 9 were developed at the Turner-Fairbank laboratory, and the experiments were carried out at the other laboratories under FHWA LTPP contract to conduct P46 resilient modulus testing. A laboratory using this verification procedure for the first time with its own proving rings will have to develop new regression lines for figures 8 and 9. The ±5 percent lines, as described below, can only be used for later periodic verification of the load-deformation response.

In order to check the system controls for load and deformation simultaneously, the following steps must be followed:

1. Position the 2.22 kN proving ring (without the dial indicator) in the triaxial chamber so that the chamber rod is in full contact with the top mounting block of the proving ring. If the proving ring is too big to fit inside the chamber, remove the chamber (perform the steps without the chamber) and fabricate special rods to hold the top plate of the chamber in place. **Note that the proving ring must be bolted down to the bottom plate of the triaxial cell. Furthermore, the bottom plate of the triaxial cell must be bolted down (or tightly fastened) to the bottom loading platen of the load frame.** With the 2.22 kN proving ring, use

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[9] The dial gauge readings can also be used to perform a very general verification of the stroke measurement (Ram LVDT). This would only detect gross errors in the Ram LVDT calibration.

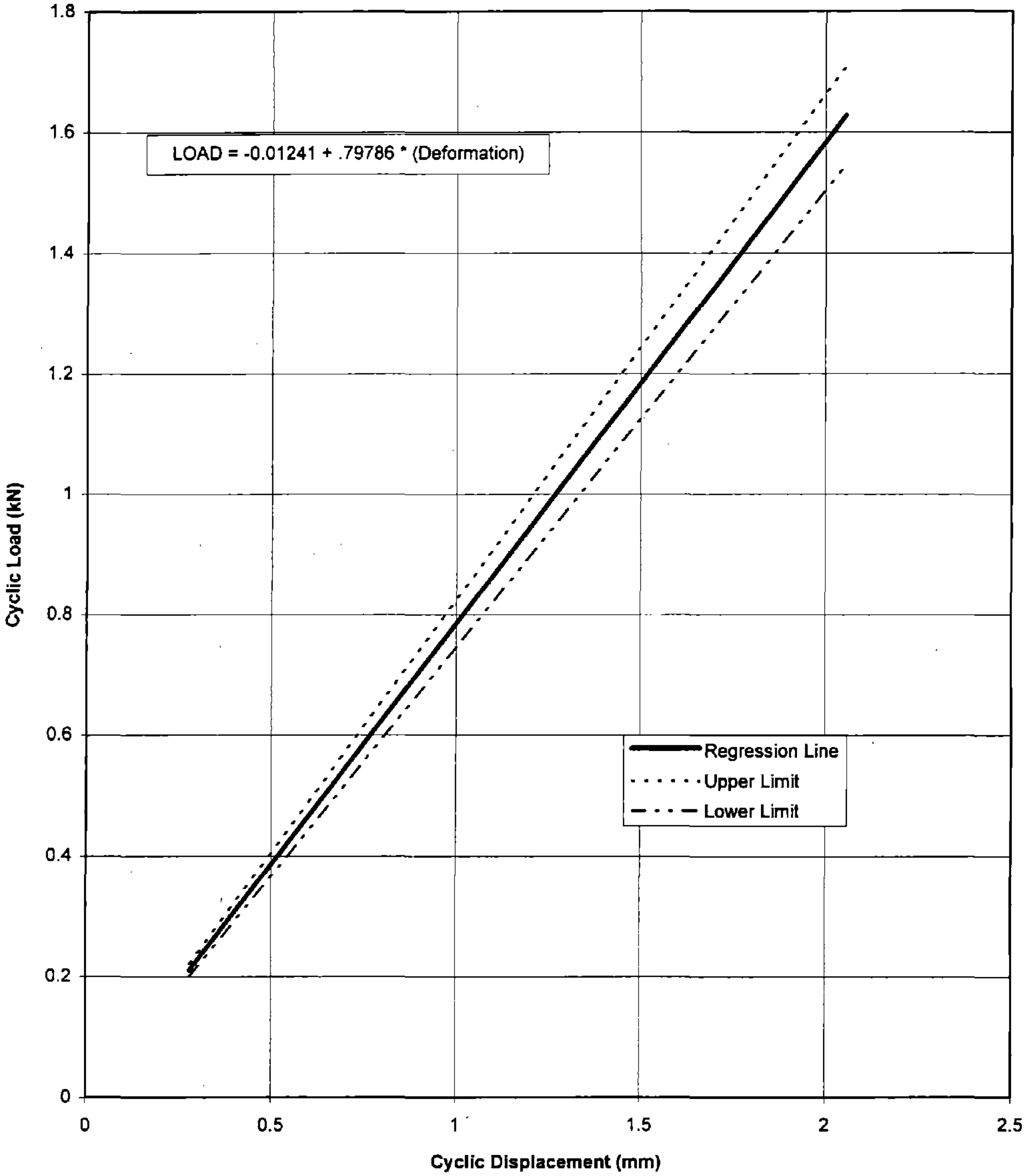

Figure 8. Load-deformation characteristics of 2.22-kN proving ring - dynamic tests.

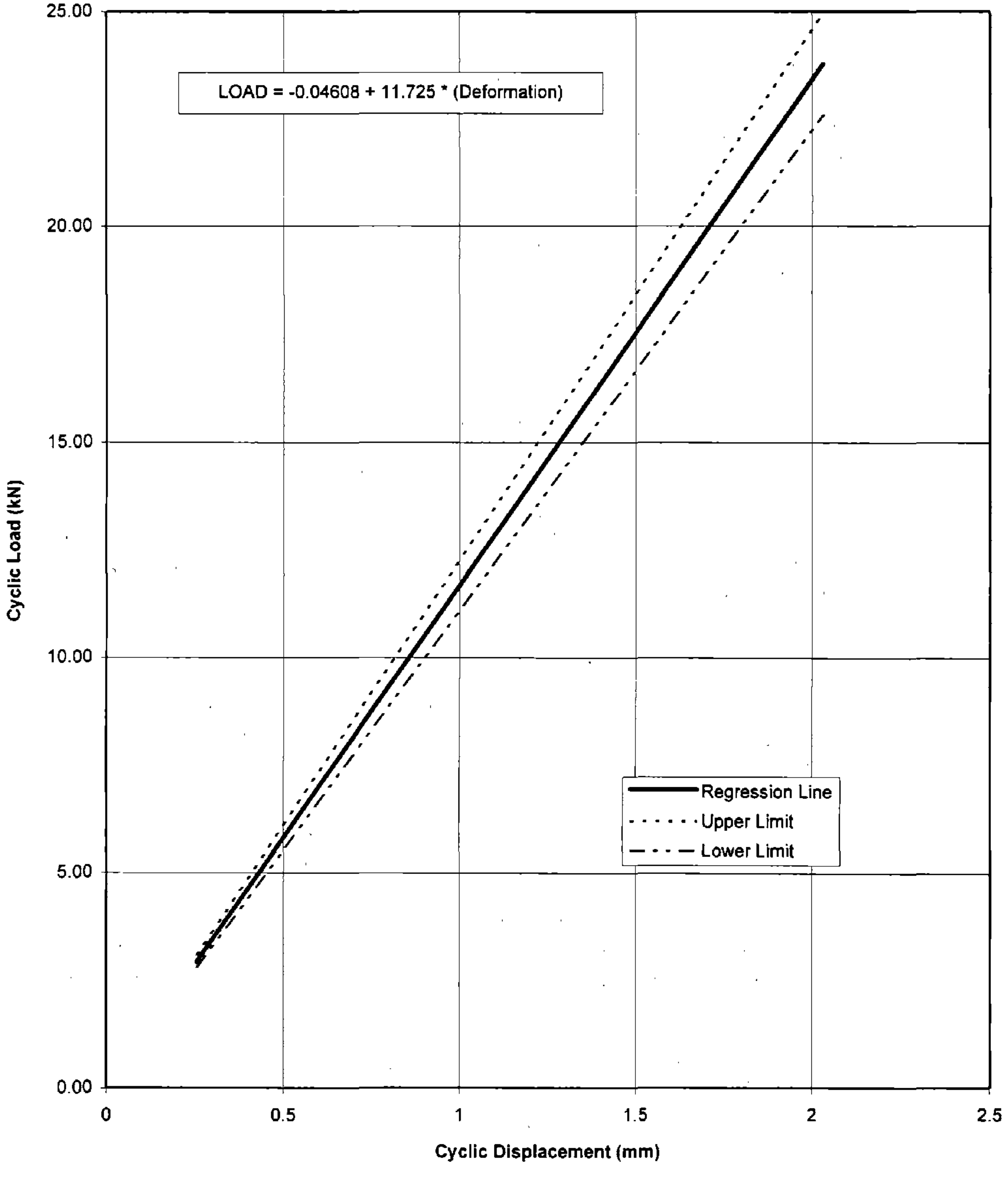

Figure 9. Load-deformation characteristics of 26.7-kN proving ring - dynamic tests.

the 2.22-kN load cell for load measurements.[10,11] The steps for checking the load and deformation measurements simultaneously are:

2. Place the two LVDT's in the LVDT holders (mounted on the top plate of the triaxial chamber) and position the LVDT's at their mid-range.

3. Using the system controls, apply 30 cycles of a haversine-shaped load pulse of 0.1-s duration and 0.9-s rest period with a seating load of .267 kN for all the tests and a final load of .467 kN, .667 kN, .867 kN, 1.07 kN, 1.27 kN, 1.47 kN, 1.67 kN, 1.87 kN, and 2.07 kN, respectively. Use a scan rate of at least 500 scans per second (500 data points per second per channel) and record time, load, and deformations for the last 10 load cycles using the data acquisition system. Use the two external LVDT's mounted on the triaxial chamber top plate for displacement measurements and the load cell for the load measurements.

4. Plot the load values (readings from the load cell) versus time for a representative cycle at each load. Superimpose an ideal (theoretical) haversine over this typical load pulse with the two peaks occurring at the same time. Compare the actual load pulse with the ideal load pulse for symmetry and loading-unloading durations (0.05 s each). If the typical load pulse is not reasonably symmetrical and cycle time differs from 0.1 s of loading-unloading (1.0 s total including rest period) consult the system documentation to determine adjustments necessary to generate a reasonable load pulse.

   If pulse duration and shape are not improved within a reasonable number of iterations, problems such as friction in the servoram piston, inadequate servo-valve size, problems with software controlling the load, etc., should be investigated.

5. Plot load and deformation values (readings from the two external LVDT's connected to the top plate of the triaxial chamber) versus time for a typical cycle at each load level. Assess the reasonableness of the displacement patterns with the load pulse over time. If displacement patterns are not reasonable (similar pattern as load pulse with peaks occurring at the same time as the load peak) problems such as slippage of the LVDT holder should be investigated and the test repeated.

6. Plot the mean deformation values versus mean applied load for each load level using the chart provided in figure 8. The recorded values should be within the ± 5 percent lines shown for the 2.22 kN proving ring at all load levels. The R^2 of the best fit line connecting the data points should be greater than 0.99.

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[10] Prior to performing the proving ring tests, it is recommended that a slow ramp load from 10 percent to 90 percent of proving ring capacity (do not exceed the capacity of the load cell) be applied a minimum of five times to minimize the hysteresis of the proving ring.

[11] Prior to performing these experiments, be sure all appropriate stroke and load safeguards are in place so as to protect the test machine and proving ring from damage.

7. The collected deformation readings will be checked to ensure that acceptable vertical deformation ratios are being measured using form 5. Acceptable vertical deformation ratios (R_v) are defined as $R_v = Y_{max}/Y_{min} \leq 1.10$, where Y_{max} equals the larger of the two vertical deformations and Y_{min} equals the smaller of the two vertical deformations. If unacceptable vertical deformations are obtained (i.e., $R_v > 1.10$), then the test should be discontinued and proving ring placement, alignment difficulties and slippage of the LVDT holders should be investigated and alleviated.

8. Repeat steps 1 through 7 for the 26.7-kN proving ring and the 22.2-kN load cell using the chart provided in figure 9. Set the seating load at 2.67 kN for all the tests and the final load at 5.07 kN, 7.47 kN, 9.88 kN, 12.3 kN, 14.7 kN, 17.1 kN, and 19.5 kN, respectively.

9. It is recommended that the process be repeated three times for each load cell and triaxial chamber. The entire assembly should be taken apart and reassembled in between each replicate test.

Acceptance Criteria

- Generated haversine waveform is close to ideal haversine waveform.
- Generated deformation output is reasonable (similar pattern as load pulse with peaks occurring at the same time as the load peak).
- Mean deformation values versus mean applied load within the ±5 percent lines.
- The R^2 of the best fit line should be greater than .99.

System Dynamic Response Check

To further investigate the system dynamic response and investigate the possibility of excessive frictional forces, triaxial fixture misalignment, and machine induced time lag between load and displacement (phase angle) conduct a series of frequency sweep sinusoidal dynamic loading experiments as shown in figures 10 and 11 using the 2.22-kN and the 26.7-kN proving rings without the dial gauge indicators. Use the two external LVDT's mounted on the triaxial chamber top plate for displacement measurements. With the 2.22-kN proving ring, use the 2.22-kN load cell for load measurements. The steps for checking the system dynamic response are:

1. Using the system controls, apply 100 cycles of a sinusoidal dynamic load with a peak-to-peak amplitude of 1.33 kN and a mean compression load of 1.11 kN at 1 Hz, 5 Hz, and 10 Hz frequencies. Record load and deformation measurements for the last 5 cycles at: 200 data points per period at 1 Hz (200 points/s), 200 data points per period at 5 Hz (1000 points/s). At 10 Hz collect 200 data points per period (2000 points/s) if possible, otherwise collect 100 data points per period (1000 points/s).

2. Calculate the phase angle between load and displacement using the digitized data (an example method to calculate the phase angle is contained in appendix D of this document). The phase angle measurement should remain consistent for all five periods at a given frequency (within ±0.5 degree). The maximum average

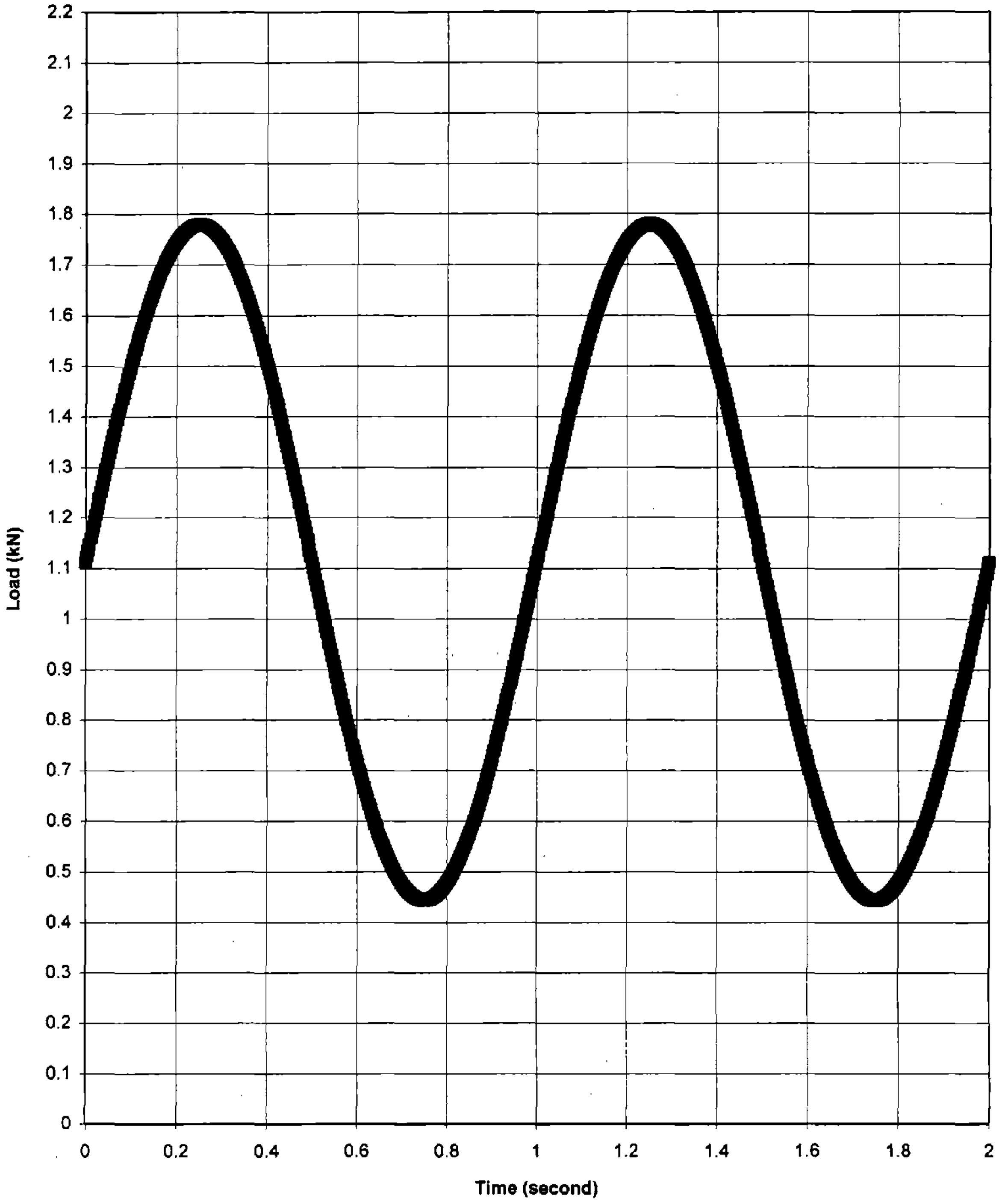

Figure 10. Sinusoidal loading pulse at 1 Hz, 2.22-kN proving ring.

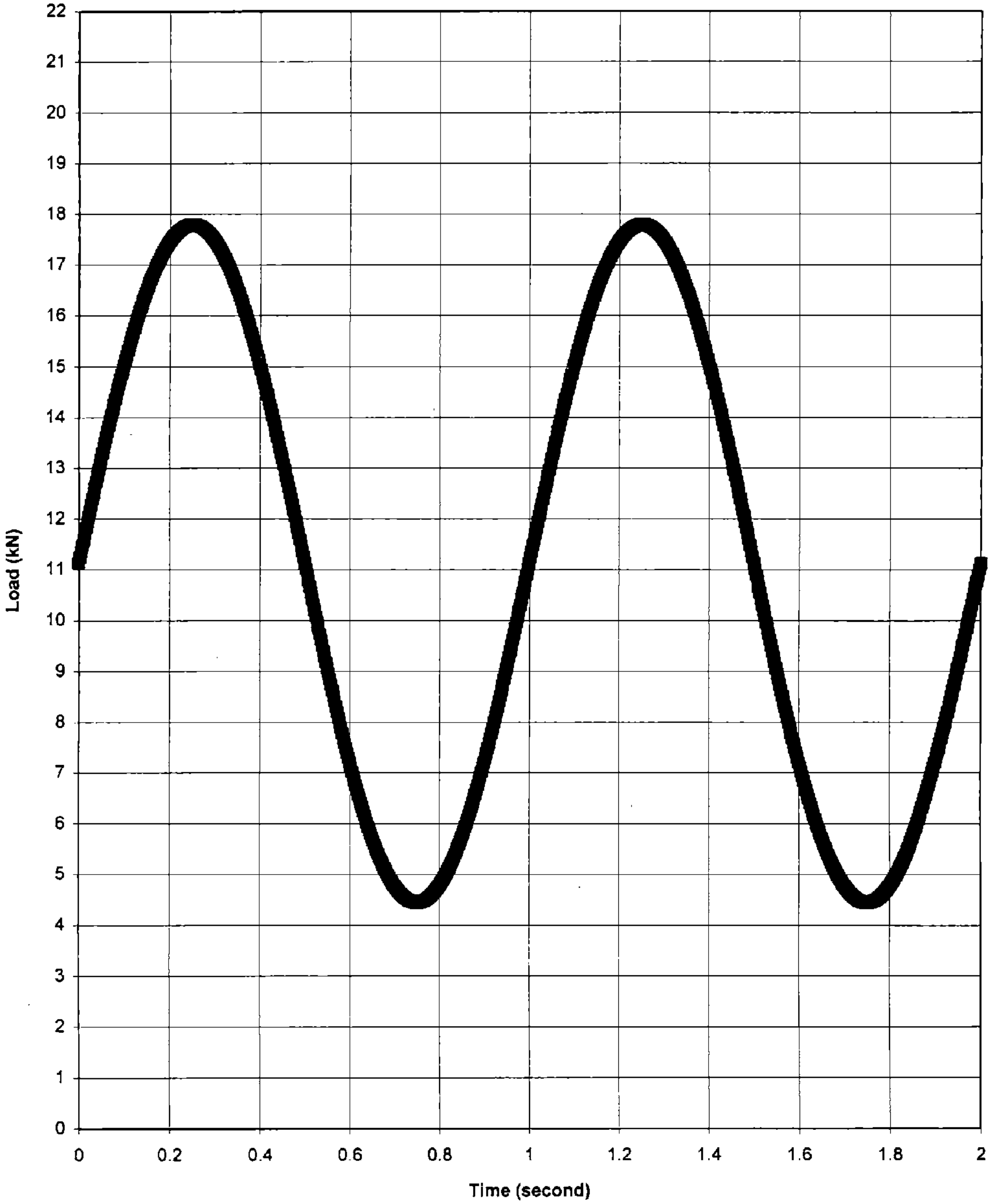

Figure 11. Sinusoidal loading pulse at 1 Hz, 26.7-kN proving ring.

phase angle (average of the 5 periods) observed should be less than 2.8 degrees at each of the three frequencies. If the phase angle value is greater than 2.8 degrees, the system should be checked for discrepancies such as mechanical misalignment (of triaxial cell, triaxial piston, specimen), frictional forces, and machine induced phase angle (due to factors such as an accidental change in filter setting), etc. Then the dynamic experiments should be repeated. The 2.8-degrees criterion was chosen based on a desired phase angle of less than 1 degree in addition to the electronics tolerance phase shift of 1.8 degrees. Note that using different equipment than stated in this procedure may result in more (or less) measurement uncertainties.

3. Repeat steps 1 and 2 for the 26.7-kN proving ring using the 22.2-kN load cell. Use a peak-to-peak amplitude of 13.3 kN and a mean compression load of 11.1 kN.

4. It is recommended that the process be repeated three times for each load cell and triaxial chamber. The entire assembly should be taken apart and reassembled in between each replicate test.

Acceptance Criteria

- Phase angle measurement less than 2.8 degrees.

Triaxial Pressure Chamber

Each triaxial pressure chamber to be used for P46 testing should be able to maintain pressure in accordance with Type 1 and Type 2 testing parameters. The pressure should remain constant for a period of 10 min for each pressure level. Checking of the triaxial chamber should follow the steps listed below:

1. Mount the pressure gauge onto the triaxial chamber secondary pressure outlet.[12] Seal the triaxial chamber so that pressure may be applied.

2. Using the test system controls, bring the triaxial pressure up to the prescribed pressure (as shown on form 6, appendix A) and hold for 10 min. For a Type 1 triaxial cell, pressures should be maintained at five levels (21, 34, 69, 103 and 138 kPa). For a Type 2 triaxial cell, pressures shall be maintained at three levels (14, 28 and 41 kPa).

3. Check the pressure readings for both the system controls and the pressure gauge every minute for the 10-min observation period.

Data should be recorded on form 6 provided in appendix A.

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[12] The pressure must be checked using an autonomous calibrated pressure gauge attached to a secondary outlet, if available. However, if a secondary pressure outlet is not available, then it will be sufficient to monitor the pressure on the primary pressure outlet using a second (non-system) calibrated pressure gauge. Repeat the experiment using the system pressure gauge and compare the results with the results from the second (non-system) calibrated pressure gauge (refer to the acceptance criteria above).

Acceptance Criteria

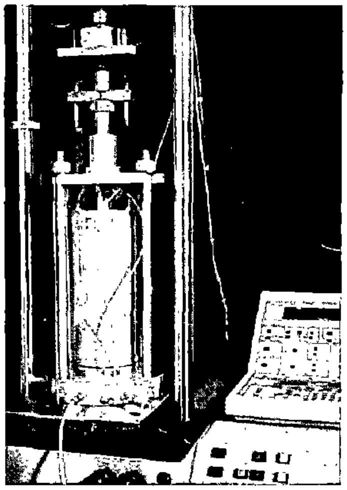
- All system and gauge pressure readings should be within ±2.5 percent of the target values for the duration of the test procedure.

V. PROFICIENCY PROCEDURE

The following procedure is primarily based upon Protocol P46. Those sections that are included herein that are similar to P46 (primarily sample preparation, compaction and resilient modulus testing) have been incorporated in this document for completeness. If the procedures referenced herein are not similar or are in conflict with the latest version of P46, the procedures in the latest version of P46 govern.[13]

Once the system has been evaluated, the proficiency of the laboratory personnel will be evaluated for both Type 1 and Type 2 samples. For both sample types, the entire test procedure should be observed by personnel that are very familiar with P46 procedures, beginning with breaking down the bulk material samples through the actual testing and recording of load and deformation data.

Type 1 Proficiency



The Type 1 proficiency check requires acceptable performance of the following major activities: (1) material preparation, (2) sample compaction, (3) resilient modulus testing, and (4) completing the appropriate data forms for a Type 1 bulk sample. It is assumed throughout this testing process that the Type 1 material (as defined by the latest version of LTPP Protocol P46) is from a base/subbase pavement layer.

Reconstituted test specimens of the Type 1 soils shall be prepared to approximate the dry density (γ_d) and moisture content (w) provided with the sample. For each bulk sample, target values of dry density and moisture content should be given.

Sample Preparation

The following steps should be taken for Type 1 sample preparation:

1. If the sample is damp, completely dry it. Drying may be in air or by use of a drying apparatus such that the temperature does not exceed 60 °C. Then thoroughly break up the aggregations in such a manner as to avoid reducing the natural size of individual particles.

2. Determine the moisture content (w_i) of the air-dried sample per LTPP Protocol P49 (Determination of Moisture Content). The sample for moisture content shall weigh not less than 200 g for samples with a maximum particle size smaller than the 4.75 mm sieve and not less than 500 g for samples with a maximum particle size greater than the 4.75 mm sieve.

3. Determine the appropriate total volume (V) of the compacted specimen to be prepared. The total volume must be based on a height of the compacted specimen slightly greater than that required for resilient testing to allow for trimming of the

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[13] It should be noted that many portions of the following section are not necessarily the original work of the authors. Protocol P46 has evolved over many years and has had many contributors, some of whom are authors of this report. However, the efforts of others in the development of the P46 protocol incorporated herein would like to be recognized by the authors of this report.

specimen ends if necessary. Compacting to a height/diameter ratio of 2.1 to 2.2 will provide adequate material for this purpose.

4. Determine the weight of oven-dry soil solids (W_s) and water (W_w) required to obtain the desired dry density (γ_d) and moisture content (w) as follows:

   W_s (pounds) = γ_d (pounds per cubic foot) x V (cubic feet)
   W_s (grams) = W_s (pounds) x 454
   W_w (pounds) = W_s (pounds) x w (%/100)
   W_w (grams) = W_w (pounds) x 454

5. Determine the total weight of the prepared material sample (W_t) required to obtain W_s to produce the desired specimen of volume V at dry density γ_d and moisture content, w.

   W_t (grams) = W_s x (1 + w/100)

6. Determine the weight of the dried sample (W_{ad}), with the moisture content (w_1), required to obtain W_s, including an additional amount W_{as} of at least 500 g to provide material for the determination of moisture content at the time of compaction.

   W_{ad} (grams) = (W_s + W_{as}) x (1 + w_1/100)

7. Determine the weight of water (W_{aw}) required to increase the weight from the existing dried weight of water (W_1) to the weight of water (W_w) corresponding to the desired compaction moisture content (w).

   W_1 (grams) = (W_s + W_{as}) x (w_1/100)
   W_2 (grams) = (W_s + W_{as}) x (w/100)
   W_{aw} (grams) = W_2 - W_1

8. Place the sample (W_{ad}) determined above into a mixing pan.

9. Add the water (W_{aw}) to the sample in small amounts and mix thoroughly after each addition.

10. After mixing, weigh the wet soil and container to the nearest gram and record this value on the appropriate form (see Worksheet T46 in appendix A).

Sample Compaction

Type 1 specimens should be compacted using the procedures described in appendix B of this document. Specimen length should not be less than two times the diameter. The minimum specimen diameter is 152 mm or five times the nominal particle size (nominal particle size is the sieve opening for which 95 percent of the material passes during the sieve analysis). Use 152-mm inside diameter split molds to prepare 305-mm high test specimens for all Type 1 materials with nominal particle sizes less than or equal to 31.8 mm, without removing any coarse aggregate.[14] The moisture content of the laboratory compacted specimen should not vary more than ± 1 percentage point from the moisture content required for the sample. The dry density of the laboratory compacted specimens should not vary by more than ± 3 percent of the dry density required for the sample.[15] If the remolded sample does not meet this criterion, it should be broken up and reconditioned to the proper moisture and density.

The specimen should be protected from moisture change by applying the triaxial membrane and testing as soon as possible.

Resilient Modulus Procedure

The following steps should be taken to conduct Type 1 resilient modulus testing.

When compaction is completed, place the dry porous stone and top sample cap on the surface of the specimen. Roll the rubber membrane off the rim of the mold and over the sample cap. If the sample cap projects above the rim of the mold, the membrane should be sealed tightly against the cap with the O-ring seal. If it does not, the seal can be applied later. Install the sample in the triaxial chamber according to the following steps:

1. Place a dry porous stone or porous bronze plate on the top of the pedestal or bottom end plate of the triaxial chamber. A paper filter should be placed between the porous stone and the sample.

2. Carefully place the specimen on the porous stone. Place the membrane on a membrane expander, apply vacuum to the membrane expander, then carefully place the membrane on the sample and remove the vacuum and the membrane expander. Seal the membrane to the pedestal (or bottom plate) with an O-ring or other pressure seals.

3. Place the dry porous stone and the top platen on the specimen, fold up the membrane, and seal it to the top platen with an O-ring or some other pressure seal. A paper filter should be placed between the porous stone and the sample. After the "specimen assembly" is in place, check the top platen to ensure that it is level. A "cross-check" level, or similar, may be used for this determination.

4. If the specimen has been compacted or stored inside a rubber membrane and the porous stones and sample are already attached to the rubber membrane in place, the previous three steps are omitted. Instead, the "specimen assembly" is placed on the top of the pedestal or bottom end plate of the triaxial chamber.

5. Connect the specimen's bottom drainage line to the vacuum source through the medium of a bubble chamber. Apply a vacuum of 7 kPa. If bubbles are present,

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[14] If 10 percent or less of a Type 1 sample is retained on the 31.8 mm sieve, the material greater than this sieve shall be scalped off prior to testing. If <u>more</u> than 10 percent of the sample is retained on the 31.8 mm sieve, the material shall not be tested.

[15] For example: if the desired dry density is 1922 kg/m^3 and desired moisture content is 8.0 percent for a Type 1 soil, a dry density between 1864 and 1980 kg/m^3 and a moisture content between 7.0 and 9.0 percent would be acceptable.

check for leakage caused by poor connections, holes in the membrane, or imperfect seals at the cap and base. The existence of an airtight seal ensures that the membrane will remain firmly in contact with the specimen. Leakage through holes in the membrane can frequently be eliminated by coating the surface of the membrane with liquid rubber latex or by using a second membrane.

6. When leakage has been eliminated, disconnect the vacuum supply and place the chamber on the base plate, and the cover plate on the chamber. Insert the loading piston and obtain a firm connection with the load cell. Tighten the chamber tie rods firmly. The cover plate of the triaxial chamber shall be checked to ensure that it is level after tightening the tie rods. A "cross-check" level, or similar, may be used for this determination.

7. Slide the assembly apparatus into position under the axial loading device. Positioning of the chamber is extremely critical in eliminating all possible side forces on the piston rod. The bottom plate of the triaxial cell must be bolted down (or tightly fastened) to the bottom loading platen of the load frame. Couple the loading device to the triaxial chamber piston rod and apply a seating pressure to the sample of 14 kPa in order to obtain full contact of the piston with the top platen. Bolt or firmly fasten the triaxial chamber to the bottom loading platen of the test system. For Type 1 samples, a minimum of four bolts or fasteners should be used. After fastening the triaxial chamber to the bottom loading platen, the chamber shall be checked to ensure that it is level.[16]

8. Connect the chamber pressure supply line and apply a confining pressure of 103 kPa.

9. Remove the vacuum supply from the vacuum saturation inlet and open the top and bottom head drainage ports to atmospheric pressure.

After the test specimen has been prepared and placed in the loading device as described above, the following steps are necessary to conduct the resilient modulus testing:

1. If not already done, adjust the position of the axial loading device or triaxial chamber base support as necessary to couple the load-generation device piston and the triaxial chamber piston. The triaxial chamber piston should bear firmly on the load cell. This can be done by applying a seating pressure of 14 kPa. A contact load of 10 percent ($.1S_{max}$) of the maximum applied load during each sequence number shall be maintained during all repeated load determinations.

2. Adjust the recording devices for the LVDT's and load cell as needed.

3. Set the confining pressure to 103 kPa and apply a minimum of 500 repetitions of a maximum axial load equivalent to a peak stress of 103 kPa using a haversine shaped load pulse consisting of a 0.1 s load followed by a 0.9 s rest period. If the sample is still decreasing in height at the end of the conditioning period, stress cycling shall be continued up to 1000 repetitions prior to testing. The foregoing

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[16] Care should be taken when preparing the sample and aligning the specimen in the triaxial chamber to produce no unnecessary damage to the specimen that may effect the test results.

stress sequence constitutes sample conditioning, that is, the elimination of the effects of the interval between compaction and loading and the elimination of initial loading versus reloading. This conditioning also aids in minimizing the effects of initially imperfect contact between the end platens and the test specimen. The drainage valves should be open to atmospheric pressure throughout the resilient modulus testing.

The operator/technician shall conduct appropriate QC/QA comparative checks of the individual deformation output from the two vertical transducers during the conditioning phase of each M_r test in order to recognize specimen misplacement and misalignment. During the preconditioning phase, the two vertical deformation curves should be viewed to ensure that acceptable vertical deformation ratios are being measured. Desired vertical deformation ratios (R_v) are defined as $R_v = Y_{max}/Y_{min} \leq 1.10$, where Y_{max} equals the larger of the two vertical deformations and Y_{min} equals the smaller of the two vertical deformations. Unacceptable vertical deformations are obtained when $R_v > 1.30$. In this case, the test should be discontinued and specimen placement/alignment difficulties alleviated. Once acceptable vertical deformation values are obtained, ($R_v < 1.30$) then the test should be continued to completion. It is emphasized that specimen alignment is critical for proper M_r results.

4. The testing is performed following the loading sequences in table 1 using a haversine shaped load pulse as described in Protocol P46. Decrease the maximum axial stress to 21 kPa and set the confining pressure to 21 kPa (Sequence No. 1, table 1). Apply 100 repetitions of the maximum axial stress and record the average of the deformations of the last five load cycles on the appropriate testing form as shown on Worksheet T46 in appendix A.

   The contact stresses should be adjusted to compensate for the resultant force created by the chamber pressure (upward force) and the weight of the chamber piston rod, including the LVDT holder, (downward force). Instructions for adjusting the contact load are given in Attachment D of Protocol P46.

5. Continue with Sequence No. 2 increasing the maximum axial stress to 41 kPa and repeat step 4 at this new stress level.

6. Continue the test for the remaining load sequences in table 1 (3 to 15) recording the vertical recovered deformation. If, at any time the total vertical permanent strain deformation exceeds 5 percent, stop the test and report the results on Worksheet T46 in appendix A.

7. After completion of the resilient modulus test procedure, check the total vertical permanent strain that the specimen was subjected to during the resilient modulus (after preconditioning) portion of the test procedure. If the total vertical permanent strain exceeds 5 percent, the test is completed. No additional testing is to be conducted on the specimen. If the total vertical permanent strain did not exceed 5 percent, proceed with the quick shear test procedure (steps 8 and 9).

8. After removal or repositioning of the paired LVDT's used for cycle strain measurements apply load as necessary to produce an axial strain rate of 1 percent

per minute under a strain controlled loading procedure. Continue loading until (1) the load values decrease with increasing strain, (2) 5 percent strain is reached (from the initiation of the quick shear test) or (3) the capacity of the load cell is reached.[17] Data from the internally mounted deformation transducer in the actuator shaft and from the load cell shall be used to record specimen deformation and load at a maximum of 1-s intervals.

It has been noted that even though some samples visually bulge and appear to have failed, they do not achieve the above definition of failure at the maximum strain value (5 percent). In some cases, the stress-strain curve "levels out" and the load values remain at, or near, constant and do not decrease with increasing strain. If a sample appears to fail without achieving the aforementioned criteria, a comment note should be added to the test data reporting sheet to document this occurrence.

Table 1. Testing sequence for Type 1 (base/subbase) soils.

Sequence No.	Confining kPa	Max. Axial kPa	Cyclic Stress kPa	Contact Stress kPa	No. of Load Applications
0	103.4	103.4	93.1	10.3	500-1000
1	20.7	20.7	18.6	2.1	100
2	20.7	41.4	37.3	4.1	100
3	20.7	62.1	55.9	6.2	100
4	34.5	34.5	31.0	3.5	100
5	34.5	68.9	62.0	6.9	100
6	34.5	103.4	93.1	10.3	100
7	68.9	68.9	62.0	6.9	100
8	68.9	137.9	124.1	13.8	100
9	68.9	206.8	186.1	20.7	100
10	103.4	68.9	62.0	6.9	100
11	103.4	103.4	93.1	10.3	100
12	103.4	206.8	186.1	20.7	100
13	137.9	103.4	93.1	10.3	100
14	137.9	137.9	124.1	13.8	100
15	137.9	275.8	248.2	27.6	100

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[17] The laboratory must set limits so that the loading capacity of the load cell is not exceeded.

9. Plot the stress-strain curve for the specimen for the triaxial shear test procedure.

10. At the completion of the triaxial shear test, reduce the confining pressure to zero and remove the sample from the triaxial cell.

11. Remove the membrane from the specimen and use the entire sample to determine the moisture content in accordance with LTPP Protocol P49 (Determination of Moisture Content). Record this value on the appropriate form (see Worksheet T46 in appendix A).

Acceptance Criteria

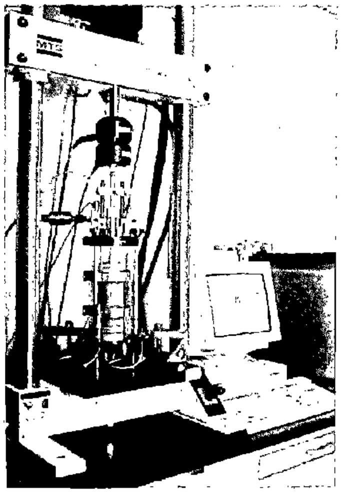
- The pressure inside the triaxial cell should be maintained within ±2.5 percent of the target pressure for the duration of the test.

- Vertical deformation readings from each of the sequences shall be checked to ensure that the LVDT's are recording values with averages that (for the collected cycles) have a coefficient of variation less than 2.5 percent for at least 14 of the 15 testing sequences (see Worksheet T46 in appendix A).

- Vertical deformation ratios of less than 1.30 should be observed for all the test sequences.

Type 2 Proficiency

The Type 2 proficiency check requires acceptable performance of the following major activities: (1) material preparation, (2) sample compaction, (3) resilient modulus testing, and (4) completing the appropriate data forms for a Type 2 bulk sample. It is assumed throughout this testing process that the Type 2 material (as defined by the latest version of LTPP Protocol P46) is from the subgrade of the pavement structure.



Reconstituted test specimens of the Type 2 soils shall be prepared to approximate the dry density (γ_d) and moisture content (w) provided with the sample. For each bulk sample, target values of dry density and moisture content should be given.

Sample Preparation

The following steps should be taken for Type 2 sample preparation:

1. If the sample is damp, completely dry it. Drying may be in air or by use of a drying apparatus such that the temperature does not exceed 60°C. Then thoroughly break up the aggregations in such a manner as to avoid reducing the natural size of individual particles.

2. Determine the moisture content (w_1) of the air-dried sample per LTPP Protocol P49 (Determination of Moisture Content). The sample for moisture content shall weigh not less than 200 g for samples with a maximum particle size smaller than the 4.75-mm sieve and not less than 500 g for samples with a maximum particle size greater than the 4.75-mm sieve.

3. Determine the appropriate total volume (V) of the compacted specimen to be prepared. The total volume must be based on a height of the compacted specimen slightly greater than that required for resilient testing to allow for trimming of the specimen ends if necessary. Compacting to a height/diameter ratio of 2.1 to 2.2 will provide adequate material for this purpose.

4. Determine the weight of oven-dry soil solids (W_s) and water (W_w) required to obtain the desired dry density (γ_d) and moisture content (w) as follows:

$$W_s \text{ (pounds)} = \gamma_d \text{ (pounds per cubic foot) x V (cubic feet)}$$
$$W_s \text{ (grams)} = W_s \text{ (pounds) x 454}$$
$$W_w \text{ (pounds)} = W_s \text{ (pounds) x w (\%/100)}$$
$$W_w \text{ (grams)} = W_w \text{ (pounds) x 454}$$

5. Determine the total weight of the prepared material sample (W_t) required to obtain W_s to produce the desired specimen of volume V at dry density γ_d and moisture content, w.

$$W_t \text{ (grams)} = W_s \text{ x } (1 + w/100)$$

6. Determine the weight of the dried sample (W_{ad}), with the moisture content (w_1), required to obtain W_s, including an additional amount W_{as} of at least 500 g to provide material for the determination of moisture content at the time of compaction.

$$W_{ad} \text{ (grams)} = (W_s + W_{as}) \text{ x } (1 + w_1/100)$$

7. Determine the weight of water (W_{aw}) required to increase the weight from the existing dried weight of water (W_1) to the weight of water (W_w) corresponding to the desired compaction moisture content (w).

$$W_1 \text{ (grams)} = (W_s + W_{as}) \text{ x } (w_1/100)$$
$$W_2 \text{ (grams)} = (W_s + W_{as}) \text{ x } (w/100)$$
$$W_{aw} \text{ (grams)} = W_2 - W_1$$

8. Place the sample (W_{ad}) determined above into a mixing pan.

9. Add the water (W_{aw}) to the sample in small amounts and mix thoroughly after each addition.

10. Place the mixture in a plastic bag. Seal the bag and place it in a second bag (to protect the sample if the first bag breaks) and seal it.

11. After mixing and storage at a minimum of overnight and a maximum of 2 days, weigh the wet soil and container to the nearest gram and record this value on the appropriate form (see Worksheet T46 in appendix A).

Sample Compaction

Type 2 specimens should be compacted using the procedures described in appendix C of this document. Specimen length should not be less than two times the diameter. The minimum specimen diameter is 71 mm or five times the nominal particle size (nominal particle size is the sieve opening for which 95 percent of the material passes during the sieve analysis). Use 71-mm inside diameter molds to prepare 142-mm high test specimens for all Type 2 material with nominal particle sizes less than or equal to 12.5 mm without removing any material.[18] The moisture content of the laboratory compacted specimen should not vary more than ± 0.5 percentage point from the moisture content required by the sample. The dry density of the laboratory compacted specimens should not vary by more than ± 3 percent of the dry density required by the sample.[19] If the remolded sample does not meet the criteria, it should be broken up and reconditioned to the proper moisture and density.

The specimen should be protected from moisture change by applying the triaxial membrane and test as soon as possible.

Resilient Modulus Procedure

The following steps should be taken to conduct Type 2 resilient modulus testing:

1. Place a dry porous stone or porous bronze plate on the top of the pedestal or bottom end plate of the triaxial chamber. A paper filter should be placed between the porous stone and the sample.

2. Carefully place the specimen on the porous stone. Place the membrane on a membrane expander, apply vacuum to the membrane expander, then carefully place the membrane on the sample and remove the vacuum and the membrane expander. Seal the membrane to the pedestal (or bottom plate) with an O-ring or other pressure seals.

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[18] If 10 percent or less of a Type 2 sample is retained on the 12.5-mm sieve, the material greater than the 12.5-mm sieve shall be scalped off prior to testing. If more than 10 percent of the sample is retained on the 12.5-mm sieve, the material shall not be tested.

[19] For example: if the desired dry density is 1442 kg/m^3 and desired moisture content is 20.0 percent for a Type 2 soil, a dry density between 1398 and 1485 kg/m^3 and a moisture content between 19.5 and 20.5 percent would be acceptable.

3. Place the dry porous stone and the top platen on the specimen, fold up the membrane, and seal it to the top platen with an O-ring or some other pressure seal. A paper filter should be placed between the porous stone and the sample. After the "specimen assembly" is in place, the top platen shall be checked to ensure that it is level. A "cross-check" level, or similar, may be used for this determination.

4. If the specimen has been compacted or stored inside a rubber membrane and the porous stones and sample are already attached to the rubber membrane in place, steps 1, 2, and 3 are omitted. Instead, the "specimen assembly" is placed on the top of the pedestal or bottom end plate of the triaxial chamber.

5. Connect the specimen's bottom drainage line to the vacuum source through the medium of a bubble chamber. Apply a vacuum of 7 kPa. If bubbles are present, check for leakage caused by poor connections, holes in the membrane, or imperfect seals at the cap and base. The existence of an airtight seal ensures that the membrane will remain firmly in contact with the specimen. Leakage through holes in the membrane can frequently be eliminated by coating the surface of the membrane with liquid rubber latex or by using a second membrane.

6. When leakage has been eliminated, disconnect the vacuum supply and place the chamber on the base plate, and the cover plate on the chamber. Insert the loading piston and obtain a firm connection with the load cell. Tighten the chamber tie rods firmly. The cover plate of the triaxial chamber shall be checked to ensure that it is level after tightening the tie rods. A "cross-check" level, or similar, may be used for this determination.

7. Slide the assembly apparatus into position under the axial loading device. Positioning of the chamber is extremely critical in eliminating all possible side forces on the piston rod. The bottom plate of the triaxial cell must be bolted down (or tightly fastened) to the bottom platen of the load frame. Couple the loading device to the triaxial chamber piston rod and apply a seating pressure to the sample of 14 kPa in order to obtain full contact of the piston with the top platen. Bolt or firmly fasten the triaxial chamber to the bottom loading platen of the test system. For Type 2 samples a minimum of 3 bolts should be used. After fastening the triaxial chamber to the bottom loading platen, the chamber shall be checked to ensure that it is level.[20]

The following steps are required to conduct the resilient modulus test on a specimen of Type 2 soil which has been installed in the triaxial chamber and placed under the loading frame:

1. Open all drainage valves leading into the specimen to atmospheric pressure.

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[20] Care should be taken when preparing the sample and aligning the specimen in the triaxial chamber to produce no unnecessary damage to the specimen that may effect the test results.

2. If it is not already connected, connect the air pressure supply line to the triaxial chamber and apply a confining pressure of 41 kPa to the test specimen. A contact stress of 10 percent ($.1S_{max}$) of the maximum applied load during each sequence number shall be maintained during all repeated load applications.

3. Begin the test by applying a minimum of 500 repetitions of a maximum axial load equivalent to a peak stress of 28 kPa using a haversine shaped load pulse consisting of a 0.1 s load followed by a 0.9 s rest period. If the sample is still decreasing in height at the end of the conditioning period, stress cycling shall be continued up to 1000 repetitions prior to testing. The foregoing stress sequence constitutes sample conditioning, that is, the elimination of the effects of the interval between compaction and loading and the elimination of initial loading versus reloading. This conditioning also aids in minimizing the effects of initially imperfect contact between the end platens and the test specimen.

   The operator/technician shall conduct appropriate QC/QA comparative checks of the individual deformation output from the two vertical transducers during the conditioning phase of each M_r test in order to recognize specimen misplacement and misalignment. During the preconditioning phase, the two vertical deformation curves should be viewed to ensure that acceptable vertical deformation ratios are being measured. Desired vertical deformation ratios (R_v) are defined as $R_v = Y_{max}/Y_{min} \leq 1.10$, where Y_{max} equals the larger of the two vertical deformations and Y_{min} equals the smaller of the two vertical deformations. Unacceptable vertical deformations are obtained when $R_v > 1.30$. In this case, the test should be discontinued and specimen placement/alignment difficulties alleviated. Once acceptable vertical deformation values are obtained, ($R_v < 1.30$) then the test should be continued to completion. It is emphasized that specimen alignment is critical for proper M_r results.

4. The testing is performed following the loading sequence shown in table 2. Begin by decreasing the maximum axial stress to 14 kPa (Sequence No. 1, table 2). Apply 100 repetitions of the maximum axial stress using a haversine shaped load pulse consisting of a 0.1-s load followed by a 0.9-s rest period and record the average of the recovered deformations of the last five cycles on Worksheet T46 in appendix A.

   The contact stresses should be adjusted to compensate for the resultant force created by the chamber pressure (upward force) and the weight of the chamber piston rod, including the LVDT holder, (downward force). Instructions for adjusting the contact load are given in attachment D of Protocol P46.

5. Increase the maximum axial stress to 28 kPa (Sequence No. 3) and repeat step 4 at this new stress level.

6. Increase the maximum axial stress to 41 kPa (Sequence No. 3) and repeat step 4 at this new stress level.

7. Continue the test for the remaining load sequences in table 2 (4 to 15) recording the vertical recovered deformation. If at any time the permanent strain of the sample exceeds 5 percent, stop the test and report the result on the appropriate worksheet (see Worksheet T46 in appendix A).

8. After completion of the resilient modulus test procedure, check the total vertical permanent strain that the specimen was subjected to during the resilient modulus (after preconditioning) portion of the test procedure. If the total vertical permanent strain did not exceed 5 percent, continue with the quick shear test procedure (steps 9 and 10). If the total vertical permanent strain exceeds 5 percent, the test is completed. No additional testing is to be conducted on the specimen.

9. Apply a confining pressure of 28 kPa to the specimen. Apply a load so as to produce an axial strain at a rate of 1 percent per minute. Continue loading until (1) the load values decrease with increasing strain, (2) 5 percent strain is reached (from the initiation of the quick shear test) or (3) the capacity of the load cell is reached.[21] Data from the internally mounted deformation transducer in the actuator shaft and from the load cell shall be used to record specimen deformation and loads at a maximum of 1-s intervals.

   It has been noted that even though some samples visually bulge and appear to have failed, they do not achieve the above definition of failure at the maximum strain value (5 percent). In some cases, the stress-strain curve "levels out" and the load values remain at, or near, constant and do not decrease with increasing strain. If a sample appears to fail without achieving the aforementioned criteria, a comment note should be added to the test data reporting sheet to document this occurrence.

10. Plot the stress-strain curve for the specimen for the triaxial shear test procedure.

11. At the completion of the triaxial shear test, remove the sample from the triaxial cell.

12. Remove the membrane from the specimen and use the entire specimen to determine moisture content in accordance with LTPP Protocol P49 (Determination of Moisture Content). Record this value on the appropriate form (see Worksheet T46 in appendix A).

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[21] The laboratory must set limits so that the loading capacity of the load cell is not exceeded.

Table 2. Testing sequence for Type 2 (subgrade) soils.

Sequence No.	**Confining Pressure, S_3**	**Max. Axial Stress S_{max}**	**Cyclic Stress S_{cyclic}**	**Contact Stress $0.1S_{max}$**	**No. of Load Applications**
	kPa	**kPa**	**kPa**	**kPa**	
0	41.4	27.6	24.8	2.8	500-1000
1	41.4	13.8	12.4	1.4	100
2	41.4	27.6	24.8	2.8	100
3	41.4	41.4	37.3	4.1	100
4	41.4	55.2	49.7	5.5	100
5	41.4	68.9	62.0	6.9	100
6	27.6	13.8	12.4	1.4	100
7	27.6	27.6	24.8	2.8	100
8	27.6	41.4	37.3	4.1	100
9	27.6	55.2	49.7	5.5	100
10	27.6	68.9	62.0	6.9	100
11	13.8	13.8	12.4	1.4	100
12	13.8	27.6	24.8	2.8	100
13	13.8	41.4	37.3	4.1	100
14	13.8	55.2	49.7	5.5	100
15	13.8	68.9	62.0	6.9	100

Acceptance Criteria

- The pressure inside the triaxial cell should be maintained within ±2.5 percent of the target pressure for the duration of the test.

- Vertical deformation readings from each of the sequences shall be checked to ensure that the LVDT's are recording values with averages that (for the collected cycles) have a coefficient of variation less than 2.5 percent for at least 14 of the 15 testing sequences (see Worksheet T46 in appendix A).

- Vertical deformation ratios of less than 1.30 should be observed for all the test sequences.

APPENDIX A
LABORATORY STARTUP AND QUALITY CONTROL PROCEDURE DATA COLLECTION FORMS

The forms needed for recording the appropriate data during the P46 verification testing are contained in this appendix. Forms T46A, T46B and the Worksheet T46 are taken from LTPP Protocol P46. A checklist of items to be completed, arranged in an order designed to follow the Proficiency Procedure from start to finish, has also been included.

Inspection Date: _____/______/_________

Laboratory Name: ______________________

Equipment Model: ______________________

Channel Designation: ______________________

Input Voltage Amplitude: (peak-to-peak) ________________

Data Collection Channels

Input Freq. (Hz)	Signal Conditioner Output Voltage (pp)[22]	Data Acquisition Recorded Voltage (pp)	Data Acquisition Recorded Freq. (Hz)	Oscilloscope Input-Output Delay (micro-sec)	Data Acquisition Derived Input-Output Delay (micro-sec)	Signal Conditioner Output Within ± 3% of Data Acquisition Voltage?[23]	Function Generator Dial Within ± 3% of Data Acquisition Freq.?
2	__.__	__.__	_.__	▨	▨	YES/NO	YES/NO
4	__.__	__.__	_.__	▨	▨	YES/NO	YES/NO
6	__.__	__.__	_.__	▨	▨	YES/NO	YES/NO
8	__.__	__.__	_.__	▨	▨	YES/NO	YES/NO
10	__.__	__.__	__.__	▨	▨	YES/NO	YES/NO
12	__.__	__.__	__.__	▨	▨	YES/NO	YES/NO
14	__.__	__.__	__.__	▨	▨	YES/NO	YES/NO
16	__.__	__.__	__.__	▨	▨	YES/NO	YES/NO
18	__.__	__.__	__.__	▨	▨	YES/NO	YES/NO
20	__.__	__.__	__.__	▨	▨	YES/NO	YES/NO
50	__.__	__.__	__.__	_____	_____	YES/NO	YES/NO

Gain Setting: ______________________

Filter Setting: ______________________

Figure 12. Form 1 - resilient modulus testing process data collection channel check.

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[22] As measured on the oscilloscope ("pp" means peak-to-peak).

[23] If the signal conditioner output is not passed directly to the analog-to-digital conversion system, the signal conditioner output times a constant should be within ± 3 % of the data acquisition voltage. Refer to the procedure for the electronic system performance verification.

Inspection Date: ______/______/________

Laboratory Name: ____________________________

Equipment Model: ____________________________

Range, kN	Load Cell Manufacturer	Model	Maximum Zero (mv/v)	Measured Zero (mv/v)
___ ___ ___ ___			___.___ ___ ___	___.___ ___ ___

Figure 13. Form 2 - resilient modulus testing process determination of load cell zero reading.

Inspection Date: ______/______/________

Laboratory Name: ____________________________

Equipment Model: ____________________________

Load Cell

Nominal Load Level (kN)	Dial Gauge Reading	Proving Ring Load Level, (kN)	Laboratory Load Cell, (kN)	Ratio of Proving Ring to Load Cell Readings
.222	_ _ _	_._ _ _	_._ _ _	_._ _ _
.445	_ _ _	_._ _ _	_._ _ _	_._ _ _
.667	_ _ _	_._ _ _	_._ _ _	_._ _ _
.890	_ _ _	_._ _ _	_._ _ _	_._ _ _
1.11	_ _ _	_._ _ _	_._ _ _	_._ _ _
1.33	_ _ _	_._ _ _	_._ _ _	_._ _ _
1.56	_ _ _	_._ _ _	_._ _ _	_._ _ _
1.78	_ _ _	_._ _ _	_._ _ _	_._ _ _
2.00	_ _ _	_._ _ _	_._ _ _	_._ _ _

Plot values for each nominal load. All points should fall within the ±5 percent lines shown in figure 6.

Figure 14. Form 3 - resilient modulus testing process load cell check.

Inspection Date: ______/______/________

Laboratory Name: ____________________________

Equipment Model: ____________________________

Load Cell

Nominal Load Level (kN)	Dial Gauge Reading	Proving Ring Load Level, (kN)	Laboratory Load Cell, (kN)	Ratio of Proving Ring to Load Cell Readings
2.67	___	__.__	__.__	_.___
5.34	___	__.__	__.__	_.___
8.01	___	__.__	__.__	_.___
10.7	___	__.__	__.__	_.___
13.3	___	__.__	__.__	_.___
16.0	___	__.__	__.__	_.___
18.7	___	__.__	__.__	_.___
20.0	___	__.__	__.__	_.___

Plot values for each nominal load. All points should fall within the ± 5 percent lines shown in figure 7.

Figure 15. Form 4 - resilient modulus testing process load cell check.

Inspection Date: ______/______/________

Laboratory Name: ________________________

Equipment Model: ________________________

Load versus Deformation

Nominal Target Load[1] (kN)	Mean Applied Load (kN)	Mean Measured Deformation, mm			$R_v=Y_{max}/Y_{min}$ 1.1	Point within ±5% ?
		LVDT #1 (mm)	LVDT #2 (mm)	Mean LVDT Reading		
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No
__.__	__.__	_.______	_.______	_.______	Yes / No	Yes / No

---

[1] Load levels are dependent on the type of load cell and proving ring used to conduct the testing.

Plot mean applied load versus mean deformation using a chart similar to that provided on figures 8 and 9. Check that the deformation/load results fall within the ± 5 percent limits shown.

Figure 16. Form 5 - resilient modulus testing process load versus deformation check.

Inspection Date: ______/______/________

Laboratory Name: ____________________

Equipment Model: ____________________

Triaxial Chamber: Type 1/Type 2 (circle one)

Triaxial Chamber

Time, min.	Pressure Level 1 (kPa)		Pressure Level 2 (kPa)		Pressure Level 3 (kPa)		Pressure Level 4 (kPa)		Pressure Level 5 (kPa)	
	Syst	Gauge	Syst	Gauge	Syst	Gauge	Syst	Gauge	Syst	Gauge
0	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
1	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
2	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
3	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
4	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
5	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
6	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
7	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
8	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
9	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._
10	___._	___._	___._	___._	___._	___._	___._	___._	___._	___._

All system and gauge readings should be within ±2.5 percent of the target readings.

Figure 17. Form 6 - resilient modulus testing process triaxial cell check.

Equipment Availability

Check that the following items are ready prior to beginning the QC procedure.

____. Latest version of Protocol P46.
____. Computer with sufficient hardware/software for data analysis.
____. Pressure gauge.
____. Triaxial cell and pressure system.
____. Loading device.
____. Electronic load cell.
____. Spring-loaded LVDT's.
____. Signal excitation, conditioning, and recording equipment.
____. All other miscellaneous equipment needed for preparing samples.
____. Bulk material splitter.
____. 152 mm diameter split mold, minimum height of 381 mm.
____. 71 mm diameter mold, minimum height of 152 mm.
____. Vibratory compaction device.
____. Spacer plugs for compaction of material lifts.

Electronic Systems Performance Verification Check

____. The Electronic Systems Performance Verification Check has been successfully completed.

Calibration Check and Overall System Performance Verification Procedure

____. Calibration Check and Overall System Performance Verification Procedure has been successfully completed

Type 1 (Base/Subbase) Proficiency

____. Sample preparation is performed satisfactorily.
____. Moisture content within ±1 percent of specified.
____. Dry density within ±3 percent of specified.
____. Specimen is compacted according to Appendix B procedure.
____. Porous stone and sample cap in-place.
____. Specimen is placed in triaxial chamber, with all lines hooked up, and no leakage is noted.
____. Triaxial chamber checked for levelness.
____. Initial pressure of 14 kPa applied to specimen in chamber.
____. Apply confining pressure of 103 kPa.
____. Load cell and LVDT's ready to begin testing.
____. Sample is not decreasing in height after preconditioning.
____. The Type 1 (subgrade) test sequence has been performed.
____. Remove specimen and determine moisture content.
____. Triaxial pressure maintained within tolerance throughout testing.
____. LVDT ratios are within acceptable tolerances.
____. Specimen was handled appropriately throughout the test procedure.

Figure 18. Form 7 - checklist for P46 proficiency procedure.

Type 2 (Subgrade) Proficiency

____. Sample preparation is performed satisfactorily.
____. Moisture content within ±0.5 percent of specified.
____. Dry density within ±3 percent of specified.
____. Specimen is compacted according to Appendix C procedure.
____. Porous stone and sample cap in-place.
____. Specimen is placed in triaxial chamber, with all lines hooked up, and no leakage is noted.
____. Triaxial chamber checked for levelness.
____. Initial pressure of 14 kPa applied to specimen in chamber.
____. Apply confining pressure of 41 kPa.
____. Load cell and LVDT's ready to begin testing.
____. Sample is not decreasing in height after preconditioning.
____. The Type 2 (subgrade) test sequence has been performed.
____. Remove specimen and determine moisture content.
____. Triaxial pressure maintained within tolerance throughout testing.
____. LVDT ratios are within acceptable tolerances.
____. Specimen was handled appropriately throughout the test procedure.

Figure 18. Form 7 - checklist for P46 proficiency procedure, (continued).

*********************** SPS LABORATORY TESTING DATA SHEET *************************

LABORATORY MATERIAL HANDLING AND TESTING SHEET NO ____ OF ____
LABORATORY MATERIAL TEST DATA
RESILIENT MODULUS OF UNBOUND GRANULAR BASE/SUBBASE
MATERIALS AND SUBGRADE SOILS
LABORATORY DATA SHEET T46A - RECOMPACTED SAMPLES

UNBOUND GRANULAR BASE/SUBBASE LAYERS AND SUBGRADE SOILS
SHRP TEST DESIGNATION UG07, SS07/SHRP PROTOCOL P46

LABORATORY PERFORMING TEST: ________________________________
LABORATORY IDENTIFICATION CODE: __ __ __ __
SAMPLES FROM: SHRP REGION __________ STATE ______ **STATE CODE:** __ __
LTPP EXPT. NO.: __________ **SHRP SECTION ID.:** __ __ __ __ __ __
SAMPLED BY: ______________________________ **FIELD SET NO.:** __
DRILLING AND SAMPLING CONTRACTOR/AGENCY
SAMPLING DATE: __ __ - __ __ -19 __ __

1. **LAYER NUMBER** (FROM LAB SHEET L04) __
2. **LAYER TYPE** (1 = subgrade, 2 = base/subbase) __
3. **SAMPLING AREA NO.** (SA-) __ __
4. **SHRP LABORATORY TEST NUMBER** __
5. **LOCATION NUMBER** __ __ __
6. **SHRP SAMPLE NUMBER** __ __ __ __
7. **MATERIAL TYPE** (Type 1 or Type 2) __
8. **TEST INFORMATION**
   PRECONDITIONING - GREATER THAN 5% PERM. STRAIN? (Y = YES OR N = NO) __
   TESTING - GREATER THAN 5% PERM. STRAIN? (Y = YES OR N = NO) __
   TESTING - NUMBER OF LOAD SEQUENCES COMPLETED (0 - 15) __ __
9. **SPECIMEN INFO.:**
   SPEC. DIAM., mm
      TOP __ __ __ . __
      MIDDLE __ __ __ . __
      BOTTOM __ __ __ . __
      AVERAGE __ __ __ . __
      MEMBRANE THICKNESS(1), mm __ . __ __
      MEMBRANE THICKNESS(2), mm __ . __ __
   NET DIAM, mm __ __ __ . __
   HEIGHT OF SPECIMEN, CAP AND BASE, mm __ __ __ . __
   HEIGHT OF CAP AND BASE, mm __ __ __ . __
   INITIAL LENGTH L_o, mm __ __ __ . __
   INITIAL AREA, A_o, mm^2 __ __ __ __ __ .
   INITIAL VOLUME, A_oL_o, mm^3 __ __ __ __ __ __ __ .
10. **SOIL SPECIMEN WEIGHT:**
   INITIAL WEIGHT OF CONTAINER AND WET SOIL, grams __ __ __ __ __ . __ __
   FINAL WEIGHT OF CONTAINER AND WET SOIL, grams __ __ __ __ __ . __ __
   WEIGHT OF WET SOIL USED, grams __ __ __ __ __ . __ __
11. **SOIL PROPERTIES:**
   IN SITU MOISTURE CONTENT (NUCLEAR), % __ __ . __
   IN SITU WET DENSITY (NUCLEAR), kg/m^3 __ __ __ __ . __
   or
   OPTIMUM MOISTURE CONTENT, % __ __ . __
   MAX. DRY DENSITY, kg/m^3 __ __ __ __ . __
   95% MAX. DRY DENSITY, kg/m^3 __ __ __ __ . __
12. **SPECIMEN PROPERTIES:**
   COMPACTION MOISTURE CONTENT, % __ __ . __
   MOISTURE CONTENT AFTER RESILIENT MODULUS TESTING, % __ __ . __
   COMPACTION DRY DENSITY, γ_d, kg/m^3 __ __ __ __ . __
13. **QUICK SHEAR TEST**
   STRESS-STRAIN PLOT ATTACHED (Y = YES OR N = NO) __
   TRIAXIAL SHEAR MAXIMUM STRENGTH, kPa __ __ __ __.
   SPECIMEN FAIL DURING TRIAXIAL SHEAR? (Y = YES, N = NO) __
14. **COMMENTS** (Section 10.4 of Protocol P46)
   (a) **CODE** __ __, __ __, __ __, __ __, __ __, __ __
   (b) **NOTE** ______________________________
15. **TEST DATE** __ __ - __ __ - __ __

GENERAL REMARKS: ______________________________
SUBMITTED BY, DATE CHECKED AND APPROVED, DATE

______________________ ______________________
LABORATORY CHIEF
Affiliation______________ Affiliation______________

Figure 19. Form T46A.

******************** SPS LABORATORY TESTING DATA SHEET **********************

LABORATORY MATERIAL HANDLING AND TESTING SHEET NO ____ OF ____
LABORATORY MATERIAL TEST DATA
RESILIENT MODULUS OF UNBOUND GRANULAR BASE/SUBBASE
MATERIALS AND SUBGRADE SOILS
LABORATORY DATA SHEET T46B - THINWALL TUBE SAMPLES

UNBOUND GRANULAR BASE/SUBBASE LAYERS AND SUBGRADE SOILS
SHRP TEST DESIGNATION UG07, SS07/SHRP PROTOCOL P46

LABORATORY PERFORMING TEST: ______________________________
LABORATORY IDENTIFICATION CODE: _ _ _ _
SAMPLES FROM: SHRP REGION __________ STATE ______ ***STATE CODE***: _ _
LTPP EXPT. NO.: __________ ***SHRP SECTION ID***.: _ _ _ _
SAMPLED BY: ______________________________ ***FIELD SET NO***.: _
DRILLING AND SAMPLING CONTRACTOR/AGENCY
SAMPLING DATE: _ _-_ _-19 _ _

1. ***LAYER NUMBER*** (FROM LAB SHEET L04) _
2. ***LAYER TYPE*** (1 = subgrade, 2 = base/subbase) _
3. ***SAMPLING AREA NO.*** (SA-) _ _
4. ***SHRP LABORATORY TEST NUMBER*** _
5. ***LOCATION NUMBER*** _ _ _
6. ***SHRP SAMPLE NUMBER*** _ _ _ _
7. ***MATERIAL TYPE*** (Type 1 or Type 2) _
8. ***APPROX. DISTANCE FROM TOP OF SUBGRADE TO SAMPLE***, m _ . _ _
9. ***TEST INFORMATION***
   PRECONDITIONING - GREATER THAN 5% PERM. STRAIN? (Y = YES OR N = NO) _
   TESTING - GREATER THAN 5% PERM. STRAIN? (Y = YES OR N = NO) _
   TESTING - NUMBER OF LOAD SEQUENCES COMPLETED (0 - 15) _ _
10. ***SPECIMEN INFO.***:
    SPEC. DIAM., mm
        TOP _ _ _ . _
        MIDDLE _ _ _ . _
        BOTTOM _ _ _ . _
        AVERAGE _ _ _ . _
        MEMBRANE THICKNESS(1), mm _ . _ _
        MEMBRANE THICKNESS(2), mm _ . _ _
    NET DIAM, mm _ _ _ . _
    INITIAL LENGTH L_o, mm _ _ _ . _
    INITIAL AREA, A_o, mm² _ _ _ _ _ .
    INITIAL VOLUME, A_oL_o, mm³ _ _ _ _ _ _ _ .
    INITIAL WEIGHT, grams _ _ _ _ _ . _
11. ***SOIL PROPERTIES***:
    IN SITU MOISTURE CONTENT, % _ _ . _
    MOISTURE CONTENT AFTER RESILIENT MODULUS TESTING, % _ _ . _
    WET DENSITY, γ_w, kg/m³ _ _ _ _ . _
    DRY DENSITY, γ_d, kg/m³ _ _ _ _ . _
12. ***QUICK SHEAR TEST***
    STRESS-STRAIN PLOT ATTACHED (Y = YES OR N = NO) _
    TRIAXIAL SHEAR MAXIMUM STRENGTH, kPa _ _ _ _.
    SPECIMEN FAIL DURING TRIAXIAL SHEAR? (Y = YES, N = NO) _
13. ***COMMENTS*** (Section 10.4 of Protocol P46)
    (a) ***CODE*** _ _, _ _, _ _, _ _, _ _, _ _
    (b) ***NOTE*** ______________________________
14. ***TEST DATE*** _ _ - _ _ - _ _

GENERAL REMARKS: ______________________________

SUBMITTED BY, DATE CHECKED AND APPROVED, DATE

______________ ______________

LABORATORY CHIEF Affiliation______________
Affiliation______________

Figure 20. Form T46B.

1. ***LABORATORY IDENTIFICATION CODE*** _ _ _ _
2. ***STATE CODE*** _ _
3. ***SHRP SECTION ID*** _ _ _ _ _ _
4. ***FIELD SET NO.*** _
5. ***LAYER NUMBER*** _
6. ***LAYER TYPE*** (1 = subgrade, 2 = base/subbase) _
7. ***SAMPLING AREA NO.*** (SA-) _ _
8. ***SHRP LABORATORY TEST NUMBER*** _
9. ***LOCATION NUMBER*** _ _ _
10. ***SHRP SAMPLE NUMBER*** _ _ _ _
11. ***MATERIAL TYPE*** _
12. ***TEST DATE*** _ _ - _ _ - _ _
13. ***RESILIENT MODULUS TESTING***

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PARAMETER	*Chamber Confining Pressure*	*Nominal Maximum Axial Stress*	*Cycle No.*	*Actual Applied Max. Axial Load*	*Actual Applied Cyclic Load*	*Actual Applied Contact Load*	*Actual Applied Max. Axial Stress*	*Actual Applied Cyclic Stress*	*Actual Applied Contact Stress*	*Recov Def. LVDT #1 Reading*	*Recov Def. LVDT #2 Reading*	*Average Recov Def. LVDT 1 and 2*	*Resilient Strain*	*Resilient Modulus*
DESIGNATION	S	$S_{cyclic\ 3}$	c_i	P_{max}	P_{cyclic}	$P_{contact}$	S_{max}	S_{cyclic}	$S_{contact}$	H_1	H_2	H_{avg}	ϵ_r	M_r
UNIT	kPa	kPa	---	N	N	N	kPa	kPa	kPa	mm	mm	mm	mm/mm	MPa
PRECISION	_ _ _ . _	_ _ _ . _	_	_ _ _ _ . _	_ _ _ _ . _	_ _ _ . _	_ _ _ . _	_ _ _ . _	_ _ _	_ . _ _ _ _	_ . _ _ _ _	_ . _ _ _ _	_ . _ _ _ _ _ _	_ _ _
SEQUENCE 1			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

1. ***LABORATORY IDENTIFICATION CODE*** _ _ _ _
2. ***STATE CODE*** _ _
3. ***SHRP SECTION ID*** _ _ _ _ _ _
4. ***FIELD SET NO.*** _

Figure 21. Worksheet P46 - Page 1.

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 2			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 3			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 4			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

Figure 22. Worksheet P46 - Page 2.

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 5			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 6			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 7			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

Figure 23. Worksheet T46 - Page 3.

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 8			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 9			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 10			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

Figure 24. Worksheet T46 - Page 4.

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 11			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 12			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 13			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

Figure 25. Worksheet T46 - Page 5.

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 14			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

COLUMN #	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SEQUENCE 15			1											
			2											
			3											
			4											
			5											
	COLUMN AVERAGE													
	STANDARD DEV.													

SUBMITTED BY, DATE

DATE

____

LABORATORY CHIEF

Affiliation ____________________

CHECKED AND APPROVED,

____

Affiliation ____________________

Figure 26. Worksheet T46 - Page 6.

APPENDIX B
COMPACTION OF TYPE 1 MATERIAL

Type 1 soils will be recompacted using a 152 mm split mold and vibratory compaction. 152 mm (inside diameter) split molds shall be used to prepare 305 mm high test samples for all Type 1 materials with nominal particle sizes less than or equal to 32 mm. If samples contain more than 5 percent by volume of plus 32 mm material, the plus 32 mm material shall be removed prior to sample preparation and this condition shall be noted in the data reporting for this test.

Cohesionless soils shall be compacted in 6 lifts in a split mold mounted on the base of the triaxial cell as shown in figure 5 of Protocol P46. Compaction forces are generated by a vibratory impact hammer powered by air or electricity and of sufficient size to provide the required laboratory densities while minimizing damage to the sample membrane.

1. SCOPE

This method covers the compaction of Type 1 soils for use in resilient modulus testing.

2. APPARATUS

2.1 152.4 mm diameter split mold, having a minimum height of 381 mm or a sufficient height to allow guidance of the compaction head for the final lift.

2.2 Vibratory compaction device.

3. PROCEDURE

3.1 For removable platens, tighten the bottom platen into place on the triaxial cell base. It is essential that an airtight seal is obtained and that the bottom platen interface constitutes a rigid body since calculations of strain assume zero movement of the bottom platen under load.

3.2 Place the two porous stones and the top platen on the bottom platen. Determine the total height of the top and bottom platens and stones to the nearest .3 mm.

3.3 Remove the top platen and upper porous stone if used. Measure the thickness of the rubber membrane with a micrometer.

3.4 Place the rubber membrane over the bottom platen and lower porous stone. Secure the membrane to the bottom platen using an O-ring or other means to obtain an airtight seal.

3.5 Place the split mold around the bottom platen and draw the membrane up through the mold. Tighten the split mold firmly in place. Exercise care to avoid pinching the membrane.

3.6 Stretch the membrane tightly over the rim of the mold. Apply a vacuum to the mold sufficient to draw the membrane in contact. If wrinkles are present in the membrane, release the vacuum, adjust the membrane and reapply the vacuum. The use of a porous plastic forming jacket line helps to ensure that the membrane fits smoothly inside the mold. The vacuum is maintained throughout the compaction procedure.

3.7 Measure, to the nearest .3 mm, the inside diameter of the membrane lined mold and the distance between the top of the lower porous stone and the top of the mold.

3.8 Determine the volume, V, of the specimen to be prepared using the diameter determined in step 3.7 and a value of height between 305 and 318 mm.

3.9 Determine the weight of material, at the prepared water content, to be compacted into the volume, V, to obtain the desired density.

3.10 For 152 mm diameter specimens (specimen height of 305 mm) 6 layers of 51 mm per layer are required for the compaction process. Determine the weight of wet soil, W_L required for each layer.

$$W_L = W_t/N$$

where:

W_t = total weight of test specimen to produce appropriate density,
N = number of layers to be compacted.

3.11 Place the total required mass of soil for all lifts, W_{ad} into a mixing pan. Add the required amount of water, W_{aw} and mix thoroughly.

3.12 Determine the weight of wet soil and the mixing pan.

3.13 Place the amount of wet soil, W_L, into the mold. Avoid spillage. Using a spatula, draw soil away from the inside edge of the mold to form a small mound at the center.

3.14 Insert the vibrator head and vibrate the soil until the distance from the surface of the compacted layer to the rim of the mold is equal to the distance measured in step 3.7 minus the thickness of the layer selected in step 3.10. This may require removal and reinsertion of the vibrator several times until experience is gained in gaging the vibration time which is required.

3.15 Repeat steps 3.13 and 3.14 for each new layer after first scarifying the top surface of the previous layer to a depth of 6.5 mm. The measured distance from the surface of the compacted layer to the rim of the mold is successively reduced by the layer thickness selected in step 3.10. The final surface shall be a smooth horizontal plane. As a recommended final step where porous bronze end plates are used, the top plate shall be placed on the sample and seated with the vibrator head.

3.16 When the compaction process is completed, weigh the mixing pan and the excess soil. This weight subtracted from the weight determined in step 3.12 is the weight of the wet soil used (weight of specimen). Verify the compaction water, W_c of the excess soil using care in covering the pan of wetted soil during compaction to avoid drying and loss of moisture. The moisture content of this sample shall be conducted using LTPP Protocol P49 (Determination of Moisture Content).

APPENDIX C
COMPACTION OF TYPE 2 MATERIAL

The general method of compaction of Type 2 soils will be that of static loading (a modified version of the double plunger method). If testable thin-walled tubes are available, specimens shall not be recompacted.

Specimens shall be recompacted in a 71 mm diameter mold. The process is one of compacting a known weight of soil to a volume that is fixed by the dimensions of the mold assembly (mold shall be of a sufficient size to produce specimens 71 mm in diameter and 152 mm in height). A typical mold assembly is shown in figure 6 of Protocol P46. As an alternative for soils lacking in cohesion, a mold with the membrane installed and held by vacuum, as in Attachment B of Protocol P46, may be used. Several steps are required for static compaction as follows in the procedures section of this appendix and as illustrated in figures 7-11 of Protocol P46.

1. SCOPE

This method covers the compaction of Type 2 soils for use in resilient modulus testing.

2. APPARATUS

As shown in figure 6 of Protocol P46.

As an alternative for soils lacking in cohesion, a mold with the membrane installed and held by vacuum may be used.

3. PROCEDURE

3.1 Five layers of equal mass shall be used to compact the specimens using this procedure. Determine the mass of wet soil, W_L to be used per layer where $W_L = W_t/5$.

3.2 Place one of the spacer plugs into the specimen mold.

3.3 Place the mass of soil, W_L determined in step 3.1 into the specimen mold. Using a spatula, draw the soil away from the edge of the mold to form a slight mound in the center.

3.4 Insert the second plug and place the assembly in the static loading machine. Apply a small load. Adjust the position of the mold with respect to the soil mass, so that the distances from the mold ends to the respective spacer plug are equal. Soil pressure developed by the initial loading will serve to hold the mold in place. By having both spacer plugs reach the zero volume change simultaneously, more uniform layer densities are obtained.

3.5 Slowly increase the load until the plugs rest firmly against the mold ends. Maintain this load for a period of not less than one minute. The amount of soil rebound depends on the rate of loading and load duration. The slower the rate of loading and the longer the load is maintained, the less the rebound (see figure 7 of Protocol P46).

To obtain uniform densities, extreme care must be taken to center the first soil layer exactly between the ends of the specimen mold. Checks and any necessary adjustments should be made after completion of steps 4 and 5.

Use of compaction by measuring the plunge movements to determine that the desired volume has been reached for each layer is an acceptable alternative to the use of the spacer plugs.

3.6 Decrease the load to zero and remove the assembly from the loading machine.

3.7 Remove the loading ram. Scarify the top surface of the compacted layer to a depth of 3 mm and put the weight of wet soil W_L for the second layer in place and form a mound. Add a spacer plug of the height shown in figure 8 of Protocol P46.

3.8 Slowly increase the load until the plugs rest firmly against the top of the mold end. Maintain load for a period of not less than one minute (see figure 8 of Protocol P46).

3.9 Remove the load and flip the mold over and remove the bottom plug keeping the top plug in place. Scarify the bottom surface of layer 1 and put the weight of wet soil W_L for the third layer in place and form a mound. Add a spacer ring of the height shown in figure 9 of Protocol P46.

3.10 Place the assembly in the loading machine. Increase the load slowly until the spacer plugs firmly contact the ends of the specimen mold. Maintain this load for a period of not less than one minute.

3.11 Follow the steps presented in figure 9 and 10 of Protocol P46 to compact the remaining two layers.

3.12 After compaction is completed, determine the moisture content of the remaining soil using LTPP Protocol P49 (Determination of Moisture Content). Record this value on LTPP Worksheet T46 in Appendix A.

3.13 Using the extrusion ram, press the compacted soil out of the specimen mold and into the extrusion mold. Extrusion should be done slowly to avoid impact loading the specimen.

3.14 Using the extrusion mold, carefully slide the specimen off the ram, onto a solid end platen. The platen should be circular with a diameter equal to that of the specimen and have a minimum thickness of 13 mm. Platens shall be of a material which will not absorb soil moisture.

3.15 Determine the weight of the compacted specimen to the nearest gram. Measure the height and diameter to the nearest .3 mm. Record these values on Worksheet T46 in Appendix A.

3.16 Place a platen similar to the one used in step 3.13 on top of the specimen.

3.17 Using a vacuum membrane expander, place the membrane over the specimen. Carefully pull the ends of the membrane over the end platens. Secure the membrane to each platen using O-rings or other means to provide an airtight seal.

APPENDIX D
DETERMINATION OF PHASE ANGLE

This appendix provides **one** method with which to calculate phase angles for the sinusoidal dynamic response checks performed as part of the P46 QC program. Other methods may be used to perform this calculation and this procedure is included herein only as an example and not necessarily as the preferred or "best" approach. This calculation is based upon the LINEST function utilized in Microsoft Excel.

1. THEORY

The sinusoidal frequency and phase angle response tests produces time-history data for each data channel. The data should have four columns: time, load, LVDT #1 and LVDT #2. It is desired to derive from this data the phase angle between load and LVDT #1 and load and LVDT #2. A linear regression algorithm using the method of Least Squares can produce amplitude and phase data if given an estimate for frequency.

The reference (load) and channel (LVDT #1 or LVDT #2) data is in the form of:

$y = A\cos(2\pi Ft + \Theta) + b$

where,

A = amplitude,
F = the frequency,
t = time,
Θ = phase shift with respect to the time data,
b = offset.

The above equation can be rearranged as follows:

$y = m_1\sin(2\pi Ft) + m_2\cos(2\pi Ft) + b$

where,

$A = SQRT(m_1^2 + m_2^2)$

and $\Theta = -\arctan(m_1/m_2)$

let $x_1 = \sin(2\pi Ft)$

let $x_2 = \cos(2\pi Ft)$, therefore,

$y = m_1x_1 + m_2x_2 + b$.

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2. PROCEDURE

LINEST uses the "least squares" method to calculate a straight line that best fits the data and returns an array that describes the line. With a column in Excel generated for x_1 and x_2, the LINEST function can be utilized given an estimate for **F**. It will return an array with m_2, m_1 and b.[24] In addition it will return the R^2 value.[25] Using the m_2, m_1 and b coefficients to describe the properties of the load and displacement data, the phase angle between the channels can be determined. It has been found that this procedure works best with only a few cycles of data.

In Excel, import the raw data file acquired from the data acquisition system for the given test. For this example, it is assumed that time will be in column A, load in column B, LVDT #1 in column C and LVDT #2 in column D and that the first row is header information and that the data starts in row 2.

Insert six columns between the load and LVDT #1 and four columns between LVDT #1 and LVDT #2. LVDT #1 should now be in column I and LVDT #2 should be in column N.

Label column C "sine" and perform the following calculation in cell C2: SIN(2*PI()*H2*A2). Copy this calculation for all values of time. Similarly, label column D "cosine" and perform the following calculation in cell D2: COS(2*PI()*H2*A2). Copy this calculation for all values of time.

Label column E "m2cosine", column F "m1sine", column G "b-offset", and column H "Frequency". In cell H2 input the frequency for the particular test under analysis. Select block E2:G6. Type the formula "=LINEST(B2:B502, C2:D502, TRUE, TRUE)" and press ENTER while holding the CONTROL and SHIFT keys down. In this ***example*** formula, B2:B502 equals the known y's and C2:D502 equals the known x's. Please note that this is only an example formula. The true range for known x's and known y's must be input in the formula.

In cell E10, perform the calculation (-ATAN(F2/E2))*180/PI(). In cell F10 perform the calculation SQRT((E2*E2)+(F2*F2)). Label cell E9 "phase-load" and cell F9 "amp-load".

Proceed to cell J2 and select block J2:L6. Input the LINEST formula again as previously discussed. Input the range of load values for "known y's" (example - I2:I502), the range of values in columns C and D under "known x's" (example - C2:D502) and input "TRUE" for "const" and "stats". This will return a similar matrix as before.

In cell J10, perform the calculation (-ATAN(K2/J2))*180/PI(). In cell K10 perform the calculation SQRT((J2*J2)+(K2*K2)). Label cell J9 "phase-lvdt1" and cell K9 "amp-lvdt1".

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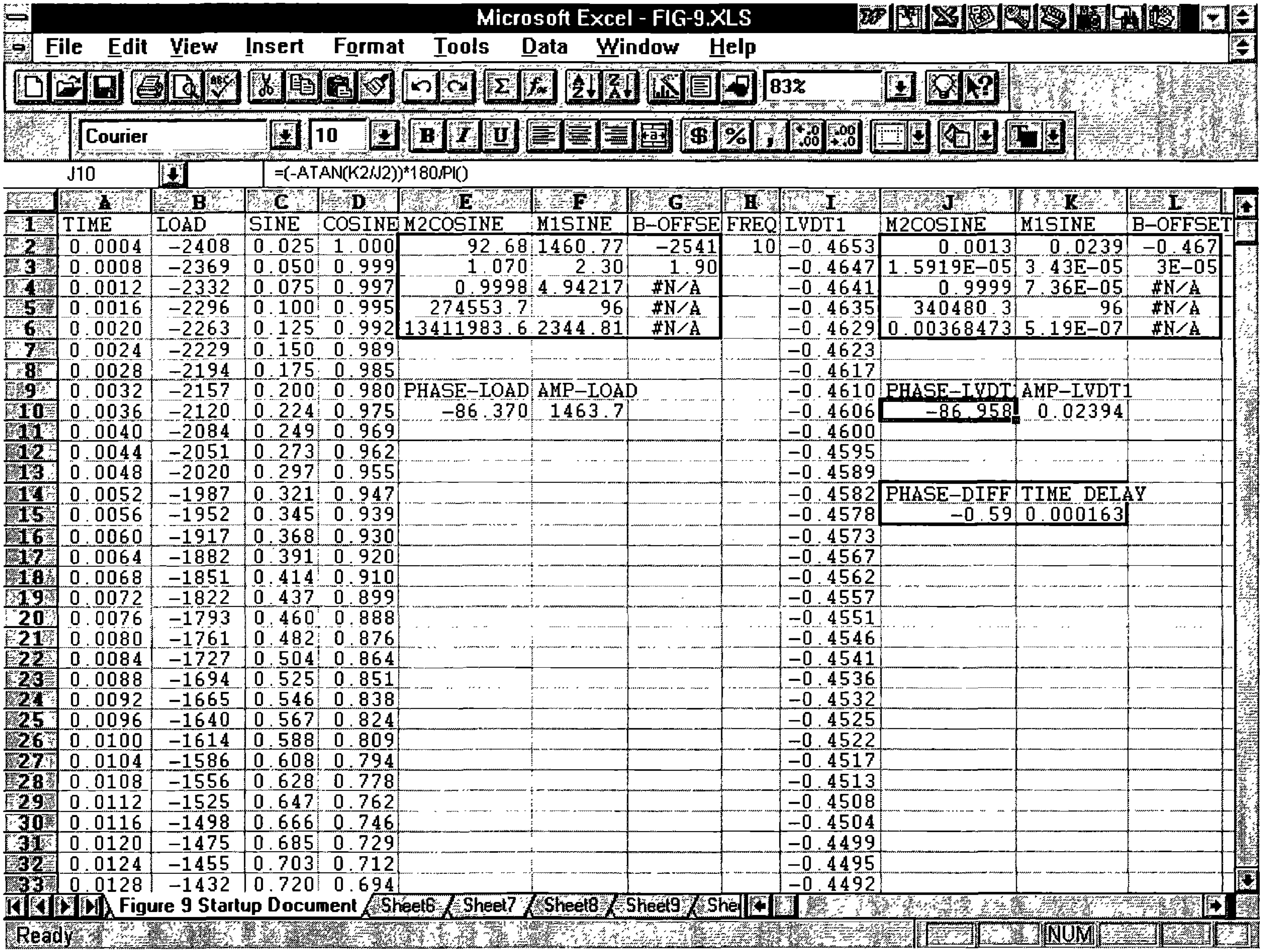
[24] For a detailed description of the LINEST function, go to the Excel "Help" dialog box and search for "LINEST."

[25] If the frequency is imbedded as a variable in the sin and cos column data, it can be varied to optimize R^2.

In cell J15, perform the calculation J10-E10 to determine the Phase Difference (degrees) between LVDT #1 and the load. In cell K15, perform the calculation ABS((J10-E10/360)*(1/H2) to determine the Time Delay (seconds) between LVDT #1 and the load.

Perform the same sequence of calculations for LVDT #2.

An example of a partial Excel spreadsheet illustrating the calculations for load and LVDT #1 is contained in figure 27.



J10 =(-ATAN(K2/J2))*180/PI()

	A	B	C	D	E	F	G	H	I	J	K	L
1	TIME	LOAD	SINE	COSINE	M2COSINE	M1SINE	B-OFFSE	FREQ	LVDT1	M2COSINE	M1SINE	B-OFFSET
2	0.0004	-2408	0.025	1.000	92.68	1460.77	-2541	10	-0.4653	0.0013	0.0239	-0.467
3	0.0008	-2369	0.050	0.999	1.070	2.30	1.90		-0.4647	1.5919E-05	3.43E-05	3E-05
4	0.0012	-2332	0.075	0.997	0.9998	4.94217	#N/A		-0.4641	0.9999	7.36E-05	#N/A
5	0.0016	-2296	0.100	0.995	274553.7	96	#N/A		-0.4635	340480.3	96	#N/A
6	0.0020	-2263	0.125	0.992	13411983.6	2344.81	#N/A		-0.4629	0.00368473	5.19E-07	#N/A
7	0.0024	-2229	0.150	0.989					-0.4623			
8	0.0028	-2194	0.175	0.985					-0.4617			
9	0.0032	-2157	0.200	0.980	PHASE-LOAD	AMP-LOAD			-0.4610	PHASE-LVDT	AMP-LVDT1	
10	0.0036	-2120	0.224	0.975	-86.370	1463.7			-0.4606	-86.958	0.02394	
11	0.0040	-2084	0.249	0.969					-0.4600			
12	0.0044	-2051	0.273	0.962					-0.4595			
13	0.0048	-2020	0.297	0.955					-0.4589			
14	0.0052	-1987	0.321	0.947					-0.4582	PHASE-DIFF	TIME DELAY	
15	0.0056	-1952	0.345	0.939					-0.4578	-0.59	0.000163	
16	0.0060	-1917	0.368	0.930					-0.4573			
17	0.0064	-1882	0.391	0.920					-0.4567			
18	0.0068	-1851	0.414	0.910					-0.4562			
19	0.0072	-1822	0.437	0.899					-0.4557			
20	0.0076	-1793	0.460	0.888					-0.4551			
21	0.0080	-1761	0.482	0.876					-0.4546			
22	0.0084	-1727	0.504	0.864					-0.4541			
23	0.0088	-1694	0.525	0.851					-0.4536			
24	0.0092	-1665	0.546	0.838					-0.4532			
25	0.0096	-1640	0.567	0.824					-0.4525			
26	0.0100	-1614	0.588	0.809					-0.4522			
27	0.0104	-1586	0.608	0.794					-0.4517			
28	0.0108	-1556	0.628	0.778					-0.4513			
29	0.0112	-1525	0.647	0.762					-0.4508			
30	0.0116	-1498	0.666	0.746					-0.4504			
31	0.0120	-1475	0.685	0.729					-0.4499			
32	0.0124	-1455	0.703	0.712					-0.4495			
33	0.0128	-1432	0.720	0.694					-0.4492			

Figure 27. Example Excel spreadsheet for calculation of phase angle.