Long-Term Pavement Performance Materials Characterization Program: Verification of Dynamic Test Systems With an Emphasis on Resilient Modulus

FHWA-RD-02-034

U.S. Department of Transportation
Federal Highway Administration

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 (LTPP) program materials characterization effort, a quality control/quality assurance (QC/QA) procedure was developed to verify the ability of the laboratory equipment and personnel to perform LTPP Protocol P46 resilient modulus testing. This effort is documented in report FHWA-RD-96-176, *Resilient Modulus of Unbound Materials (LTPP Protocol P46) Laboratory Startup and Quality Control Procedure*s.

Since the issuance of that report in February 1997, a great deal of experience has been gathered in using the procedure. The purpose of this document is to further expand the concepts introduced in FHWA-RD-96-176 and incorporate the lessons learned in the past few years. In addition, the procedures documented in this report have been written in a more generic sense so that their use can be more broadly applied in the materials characterization industry. While the procedures outlined herein are principally designed to verify resilient modulus testing operations within a laboratory, extension of these concepts to other test procedures can be made with little or no modification.

The implementation of FHWA-RD-96-176 has had a great impact on achieving repeatable, reliable, high-quality resilient modulus data for the LTPP program. It is envisioned that the broader application of these procedures and processes in other test programs may bring a benefit to a broader community interested in the acquisition of accurate, repeatable test results from dynamic test systems.

Gary L. Henderson
Director, Office of Infrastructure
Research and Development

NOTICE

QUALITY ASSURANCE STATEMENT

Technical Report Documentation Page

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16. Abstract This document describes a procedure for verifying a dynamic testing system (closed-loop servohydraulic). 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. This procedure may be used to evaluate a wide range of equipment and has applications to many test procedures. Implementation of this procedure in the Federal Highway Administration contractor laboratories has greatly reduced the within- and between-lab variability associated with the Long-Term Pavement Performance resilient modulus test procedures.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^{o}C	Celsius	1.8C+32	Fahrenheit	^{o}F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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I. INTRODUCTION

GENERAL

The Long-Term Pavement Performance (LTPP) program resilient modulus test protocols were developed to ascertain the stiffness of pavement surface (asphalt concrete), base, subbase, and subgrade materials. 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 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 resilient modulus testing for the LTPP program.

The original procedure was documented in FHWA-RD-96-176, *LTPP Materials Characterization Program: Resilient Modulus of Unbound Materials (LTPP Protocol P46) Laboratory Startup and Quality Control Procedures.* It was developed primarily for the verification of base, subbase, and subgrade resilient modulus procedures. Since issuance of that report, many lessons have been learned and procedures have been added in an ongoing process-improvement cycle. As a result of these improvements and enhancements, this document has been prepared to present a more comprehensive test system evaluation. It should be noted that this document is a revision and expansion of FHWA-RD-96-176, and some portions are not necessarily the original work of the authors of this report. It is intended to be used as a generic dynamic (primarily closed-loop, servohydraulic) test system evaluation procedure; however, the user will notice the strong emphasis on resilient modulus procedures resulting from the development history of the procedures.

The primary reasons for the development of this document were to:

- Revise the procedure to reflect lessons learned since the issuance of the original document.
- Incorporate enhanced and expanded instructions.
- Add examples to illustrate the processes.
- Expand the data-analysis procedures.
- Make the process as generic as possible to increase the use of the procedure in the dynamic testing community.

The procedures outlined here have been modified to reflect the lessons learned from numerous implementations of the procedure and to address the most frequently asked questions concerning the use and conduct of the processes. This document does not supercede FHWA-RD-96-176; most of those processes and acceptance criteria are still valid. Rather, this document expands, clarifies, and enhances FHWA-RD-96-176.

These procedures are meant to be used for verification of system performance and not calibration of the system. Calibration of the system should be performed by the manufacturer or other trained personnel.

These procedures were developed to ensure the accuracy and reliability of the raw measurements produced while testing materials using closed-loop servohydraulic systems. They are based on the premise that any engineering analysis requires reliable raw data, and the prerequisite for reliable raw data is properly configured equipment. The procedures were designed to verify the operating accuracy of all 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 parts work together properly. 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 (LVDTs)) 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. After the system has been evaluated, the proficiency phase of the procedure will address the competence of the laboratory personnel to prepare and test samples. Through the use of this procedure, all components necessary to obtain repeatable, accurate test results are verified.

The procedure enables laboratories to verify their testing systems and procedures before starting production testing by using a comprehensive and logical process. The procedure also can be used to perform ongoing quality control checks of the laboratory’s equipment and testing processes during the production testing process.

The equipment required to conduct the procedure was specifically chosen to be readily available in the market at reasonable costs. This equipment includes instruments such as an oscilloscope, function generator, and a computer, which are available in most testing laboratories. This procedure has been successfully implemented at Federal Highway Administration (FHWA) facilities in McLean, VA, State departments of transportation, universities, and in two commercial laboratories under contract to FHWA. Although originally intended for the resilient modulus program, this procedure can be implemented to verify most closed-loop servohydraulic 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 characterizes 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 electronic parts of the test system remain the same, this procedure does not necessarily need to be repeated on a continuing basis (e.g., monthly). However, the procedure should be conducted at least annually to verify that 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 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 hours to complete (including data analysis). If problems are found with the system, troubleshooting intended to isolate the problem usually has been found to take 24 hours, but is wholly dependent on system configuration, complexity, access to manufacturer's specifications, and other factors.

In this document, the electronics verification procedure has been described to allow as much flexibility as possible; two methods are discussed. The first is an electrical approach that is accomplished by using electrical instruments to simulate load cells and deformation devices. The second is a mechanical approach in which the load cells and deformation devices are actually stimulated by a mechanical device. Either method can be used to evaluate the system electronics.

Dynamic testing procedures require a system made up of many different pieces of equipment: load frame, load cells, hydraulic system, deformation devices, triaxial pressure chamber, temperature chambers, computer, etc. For the calibration check and overall system performance verification procedure, individual elements of the test equipment are checked first, followed by the overall test setup. This verifies that the test system is producing the expected responses. When the individual components of the test system are checked first, many problems that would be encountered during actual dynamic testing likely can be identified and eliminated prior to an overall system check. This procedure is generally used prior to initiation of a testing program and subsequently on a continuing basis (e.g., monthly) to verify the system response. On average, the procedure requires approximately 16 hours to complete.

The ability of laboratory personnel to conduct dynamic testing is evaluated in the proficiency procedure. Again, while this procedure has been developed primarily for resilient modulus testing, the concepts introduced here can be applied to many test programs. This procedure is generally used prior to initiation of a testing program and subsequently on a continuing basis (e.g., quarterly) to verify the operator's ability to conduct resilient modulus testing. The procedure requires approximately 2 days to complete.

The two primary goals of this process are to: (1) ensure that the test system and technicians are capable of performing a test procedure, and (2) develop a benchmark performance standard against which the laboratory can be evaluated on an ongoing basis. This is a very important part of any quality control/quality assurance system.

Certain procedures outlined here may not be necessary to verify a system. For example, if the user is performing resilient modulus testing of soils, a temperature chamber is not used, so this procedure is not necessary. Users should use engineering judgment to select the processes and experiments that best meet their objectives.

WHO SHOULD USE THE PROCEDURE

This procedure can be used by any organization performing dynamic testing procedures. It is primarily designed to be used on closed-loop, servohydraulic test systems, but potentially the concepts can be used for other test equipment. Historically, the procedure has been used by departments of transportation, universities, and consultant laboratories to verify equipment for testing resilient modulus, creep compliance, and indirect tensile strength.

WHEN THE PROCEDURE SHOULD BE USED

The procedure should be used prior to starting a testing program, every year during production testing, and after periods of system inactivity (e.g., 6 weeks of downtime). It can also be used when equipment is replaced, moved, or whenever a suspected overload or malfunction occurs. Another important use is to verify the operation of new machines delivered by a manufacturer. Conversely, the procedure can be used to verify the ability of older machines to perform new applications.

BENEFITS OF USE

Using the procedure detailed here has several obvious benefits. The procedure provides guidelines for standardization of an entire test process. It also provides a benchmark performance standard for equipment. If implemented correctly, it can minimize equipment and operator variability and thus provide greater confidence in the test results and their application in research or design.

DISCLAIMER

This procedure was designed based on three criteria: effectiveness, simplicity, and low cost. It was formulated to be as general as possible so it could be implemented by a variety of testing laboratories. Its growing implementation by laboratories nationwide is an indication of the procedure’s 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 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 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 implementation of 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 FHWA nor the contractor team is responsible for any personal injury or property damage due to the use of this procedure.

II. GENERAL EQUIPMENT REQUIREMENTS

To perform the complete dynamic test system evaluation, it is necessary to have available certain pieces of equipment. The equipment should be selected based upon the experiments to be conducted. This equipment includes:

- Computer with sufficient hardware/software for data analysis.
- Oscilloscope (two or more channels).
- Sine wave generator.
- Digital voltmeter with resistance-reading capabilities.
- Mechanical oscillator (to simulate deformation device movement)—this is generally a custom built apparatus.
- Strain indicator, in this case, Measurements Group P-3500 (or similar).
  - One micro strain 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.
- National Institute of Standards and Technology (NIST)-traceable proving ring(s).
- Independent LVDT with power source and signal conditioning.
- A micrometer head-based calibrator with .001 millimeter (mm) resolution (for ±2.5 mm 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 kilopascals (kPa).
- Independent calibrated temperature gauge.
- All applicable equipment required by the test procedure.

These pieces of equipment will be used to verify the operating accuracy of all essential system components in a logical manner.

III. ELECTRONIC SYSTEMS PERFORMANCE VERIFICATION PROCEDURE

INTRODUCTION

Based on multiple system evaluations, it has been found that the electronics verification procedure is by far the most complex and difficult portion of the evaluation procedure. Because of the inherent complexity of this task, this section of the document provides an expanded discussion of the theory and rationale behind the procedure.

Many different types of test systems are on the market today. Generally, each of these systems contains its own vendor-proprietary method for signal conditioning. Because of the wide variety of system configurations, this section of the document has been developed to present the general approaches to electronics evaluation. Users are advised to select the most applicable method for their system and apply the concepts presented here to characterize and verify the system.

It is strongly recommended that personnel with a background in electronics and mechanical systems perform these procedures. Performance of these procedures by unsuitably qualified personnel may result in system damage, physical injury, or other undesirable consequences. The entire system—software, data-acquisition system, control electronics, hydraulics, and mechanical aspects of the test system—needs to be operating in a controlled and safe manner before the verification procedure can be completed successfully.

BACKGROUND

When performing a test, it is generally accepted that the test transducers be calibrated. In this procedure, the output of the transducer is compared to a known test value (e.g., a load, pressure, or displacement), and a relationship (usually linear) is developed between the transducer output and the known applied test values. The resulting curve is the transducer calibration. This calibration procedure is a required element if the user is to know the test values being applied to a sample under test. But this calibration is by no means the only factor that influences the test readings. The calibration procedure may not account for the system electronics, and it certainly does not account for time-varying test conditions. If the test system electronics are improperly configured, the test readings may be quite wrong, even if the transducers are calibrated.

The purpose of this verification procedure is to assess the dynamic system performance of the data-acquisition system (DAS) so that the user is confident that the values measured by the computer are in fact the loads, displacements, and pressures being applied to the sample. To perform this verification test on the DAS, known signals (known in time and magnitude) are applied to each conditioned channel in succession, and the response of each channel is compared to the known applied signal. These verification tests are performed “in-system” to as great an extent as possible so that the entire transducer/conditioning/acquisition system is incorporated in the verification test.

An additional benefit of performing these verification tests is that the test system is exercised and the operators become more familiar with both system software and hardware. If an open mind is used to analyze the sources of error and aberrations that are exhibited during these tests, then other interrelated shortcomings of the system can often be deduced and rectified, resulting in a more robust and properly operating system. Therefore, the procedure should not be used in a cookbook manner. Instead, the objective of each task and the response of the system should also be understood, rather than applying a "go/no-go" mentality.

An attempt has been made to compartmentalize the various tasks of the verification procedure, but as the user works with the system, the user realizes that each component contributes to the proper functioning of the whole system. The interactions between the system components sometimes make it difficult to troubleshoot a system without understanding all of the subcomponents and the interactions among these subcomponents.

This procedure has been developed to evaluate the filter settings of the signal conditioners. When a signal passes through a filter, the signal is delayed by a constant amount (the delay of which is for the most part independent of the frequencies used in these tests). In addition, the signal is attenuated as the signal frequency increases past the cutoff frequency of the filter. If the input to the conditioner is compared to the output signal over a range of frequencies, the user can identify the type of filter and the cutoff frequency of the filter. More important, the user can evaluate whether the conditioned signal closely duplicates (both in magnitude and in time) the physical processes being monitored.

The procedure used to evaluate the filter settings was initially developed using a wholly electrical approach in which the transducers were electrically simulated. This approach works well for direct current (DC) type signal conditioners, but has serious drawbacks for transducers that rely on alternating current (AC) excitation (e.g., LVDTs). For these AC-excited transducers, a new simulation interface circuit has to be designed, built, and tested for each type of AC signal conditioner. The new construction and testing of the test circuit is in itself a task that is quite labor intensive, and the final test circuit could introduce noise. In addition, any errors introduced by the circuit need to be quantified. Another issue with this approach is that the new circuit needs to be tested in the system before it is deemed acceptable. This approach is very time consuming.

To work around these shortcomings, a mechanical approach was developed to actuate the system LVDTs and test the AC conditioning system by comparing the movement of a reference LVDT to the displacement of the system LVDT being tested. (This mechanical LVDT actuator could be further modified to include a strain-gauged member that would be mechanically flexed and result in a Wheatstone bridge output that could be used to simulate a load cell. Thus, with this mechanical actuator, no electrical simulations would be required to perform the verification tests.)

An alternative procedure to the electrical simulation has been developed for evaluating the load cell channels. In this approach, the load cell is physically actuated using the hydraulic loading system. The hydraulic loading ram applies a sinusoidal load at frequencies up to 50 hertz (Hz). Generally, most systems encountered to date seem to be limited to a frequency of about 20 Hz (although this may be software limited rather than being limited by the hardware). Due to this inability to reach 50 Hz, the DC conditioners will have to be electrically simulated unless this limitation can be overcome.

A note concerning filter settings is warranted: Low-pass filters are an integral part of most signal-conditioning systems. They are used to smooth out the desired signals and to block high-frequency noise that may be superimposed on the desired signal. In the case of AC conditioning systems, they also filter out any residual noise resulting from the carrier frequency. With such benefits to be gained from filters, it is tempting to add as much filtering as possible. The problem with this approach is that the filters also introduce a time delay and tend to attenuate the desired signal as the frequency of the designed signal starts to approach the cutoff frequency of the filter. It is best to set these low-pass filters as high as possible and yet still obtain a smooth signal. These filter settings should be recorded and tests performed with these filter settings. Before settling on these filter settings, the user should operate the test system under various conditions, for various periods of time, and at various times of day to ascertain the settings when a variety of operating environments are encountered. Starting and stopping of large inductive motors creates a particularly large amount of electrical interference. To account for these potential sources of electrical noise, air conditioners, compressors, hydraulic pumps, and other large motors should be started and stopped when taking data in an attempt to identify sources of noise that might impact the system. Filter cutoff frequencies should be set to reduce this noise to a tolerable level. If reducing the filter settings does not reduce the noise sufficiently, the test system should be isolated from the source of the electrical noise.

Typically, a test system uses filters of the same type on each of its channels. In this instance, it might be a good policy to set the cutoff frequencies of the filters to the same values. Thus, even though the filters might introduce a delay to each of the channels, the relative delay between channels would be nearly zero, and would still result in a satisfactory channel-to-channel delay (as long as there is no appreciable attenuation).

Because frequencies of 20 Hz are anticipated, in no event should the filters be set anywhere close to this level. As a guideline, the user would not want the filter cutoff frequencies to be set any lower than about 50 to 100 Hz, and higher cutoff frequencies would be preferred. Often, 60 Hz filters are used to reduce 120-volt (V) power hum. If such noise is superimposed upon a signal, it indicates a system problem, which needs to be rectified other than with filters. The power supplies should be well enough shielded and filtered to prevent this 60 Hz hum from entering into the signal-conditioning system.

Filters can be set using software or by physically changing components in the filter section of the signal conditioner. Usually filters are not physically modified due to a natural hesitation on the part of a technician to physically enter into the computer or signal-conditioning system and modify the system. Because it requires a knowledgeable effort to modify a filter, once the physical filters are set they are not usually modified (although they may be unintentionally changed when a signal-conditioning module is changed). On the other hand, software filters may be easily modified, whether intentionally or not, simply with a few keystrokes at the keyboard. Diligence is therefore required on the part of the test operator to be aware of what the filter settings are, how to change them, and what they should be for each test. The test procedures discussed below should be performed using the filter settings for which it is anticipated the test will be normally run. Any filters set with different cutoff frequencies than those used in the verification procedure would possibly invalidate any test performed with these filter settings.

DYNAMIC SYSTEM TEST CONFIGURATION

A number of possible test configurations can be used to verify the proper operation of the system channels, all of which depend on the type and configuration of the DAS. There are essentially two main concerns: whether to actuate or simulate the transducer under test, and how to access an unconditioned channel in the DAS so that the channel under test can be compared to the reference signal.

For a purely electrical evaluation, the hydraulic system can be turned off. For a mechanical evaluation, which relies on the hydraulic system, all test systems should be turned on and the machine should be warmed up according to manufacturer specifications.

APPROACH

DC Transducer (Load Cell) Simulation

If a transducer is to be simulated, the user needs to determine the magnitude of the electrical signal that will simulate the transducer. In the case of a DC load cell channel, the load cell forms a Wheatstone bridge. A constant DC voltage (usually about 10 V—see the system manual for the DC signal conditioner to determine the transducer supply voltage) is imposed across the bridge. The output of the bridge (the other two arms opposed to the power side of the bridge) is monitored and amplified by the signal conditioner. If the load cell is loaded, the bridge balance is upset, and a small millivolt (mV) reading is measured across the output of the bridge. The relationship between the mV reading and the load is as follows. The load cell has a calibration factor of, say, 2.069 mV/V. This means that for every volt of supply voltage applied to the load cell bridge, the load cell output will indicate 2.069 mV at the rated capacity of the load cell. Thus, if a 10V DC supply voltage is used, and the user has a 8.9 kilonewton (kN) load cell with a calibration factor of 2.069 mV/V, the load cell will have an output voltage of 20.69 mV (10V times 2.069 mV/V) at a load of 8.9 kN. So for this example of a load cell and applied voltage, if the user wants to simulate a ±0.2225 kN sinusoidal load, the user needs to supply a sinusoidal voltage of ±0.259 mV (20.69mV times 0.2225 kN/8.9 kN), or 0.517 mV_{pp} (V_{pp} is voltage measured peak-to-peak).

To simulate a load cell subjected to a sinusoidal load the user would use a sine wave generator, which has the capability of outputting a bipolar sinusoidal millivolt signal. It is important that the output of the sine wave generator be isolated from ground (or in other words, floating with respect to ground). If the output is referenced to ground, then the signal conditioner may have problems with being shorted to ground through the signal input. Whether this is a problem or not depends on the design of the DC signal conditioner.

Thus, in the example above, if the user wanted to simulate a ±0.222 kN sinusoidal load, the user would need to set up the signal generator for a ±0.259 mV sinusoidal signal.

This sine generator output thus takes care of the input to the signal conditioner. But the problem is how to monitor this reference signal. If the signals are to be compared on an oscilloscope (this is the most convenient configuration for trouble shooting), then a BNC tee is used to direct the millivolt signal to both the oscilloscope and the signal conditioner. In this event, the output of the signal conditioner (after filtering) would then be fed into the second channel of the oscilloscope and the signal conditioner input (millivolt range) can be compared to the signal conditioner output (with an amplitude of volts).

After a suitable response has been obtained using the oscilloscope, the signals need to be acquired on the DAS. No effort is required to monitor the channel being tested, as this is the normal manner of connecting the channel, but the reference signal needs to be monitored by an unfiltered and unconditioned available channel. The topic of how to find an unconditioned and unfiltered channel is addressed in a later section of this document.

The reference signal must be of an amplitude that the analog-digital (A/D) converter can handle. Typically, this voltage should be in the range of ±5 V. If the voltage is too small, then there may not be enough digital bits to result in a meaningful conversion with sufficient resolution to evaluate the attenuation of the signal. As a rule of thumb, the reference voltage should be of the same order of magnitude as the conditioned signal being monitored. Therefore two requirements are imposed on the signal generator; it must provide a low-millivolt signal for the conditioned channel input, and must also provide a high-voltage signal to be monitored by the unconditioned channel.

The required amplitude of the reference signal can be handled in two ways, depending on the type of signal generator used. If the generator has a high-voltage output (less than 5 V_{pp}) that follows the millivolt output, then the user can simply monitor this generator output with the unconditioned DAS input. It is more common, however, for the generator to have only the user output. In this event the user needs to make a resistive voltage divider and use this to obtain both the millivolt output as well as the large amplitude output, hook up the divider to the output of the generator, take the high-amplitude output from the top of the resistor divider, and take the low amplitude output near the bottom of the divider (figure 1).

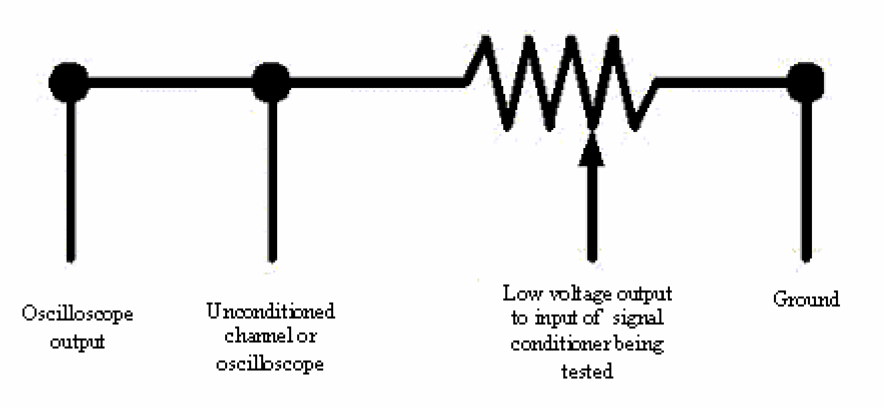

Figure 1. Graph. Sample electrical schematic of voltage divider.

DC Transducer (Load Cell) Actuation

If the loading system being tested is functioning properly, another method of characterizing the load channels is possible. In this approach, one uses the loading system to apply a sinusoidal load to the load cell. Limitations to this approach include a limited range of frequency (possibly not being able to perform a test at 50 Hz), and a loading function departing from a smooth sinusoidal shape (i.e., the loading system is not really functioning properly).

In this approach, one uses an LVDT mounted in a proving ring to provide the reference load measurement. Since a proving ring is an inherently linear device, the only time delay introduced in the reference signal is due to the LVDT conditioning system. This LVDT can either be one of the system LVDTs that has already been characterized, or a reference LVDT system with known delay and attenuation characteristics.

This approach has the added advantage that the delay between a pair of AC and DC conditioned system channels can be directly monitored. All other approaches compare the channel under test to a known reference displacement or load. These measurements result in “absolute” measurements of time delay. However, the more important characteristic is the relative time delay between channels. The absolute measurements are of help in identifying problems with filter settings and other peculiarities of the system, but the relative time delay between test channels is what is most relevant for a test (i.e., that the test measurements are synchronous and can unambiguously relate a load to a displacement).

In evaluating the load cell, a high-quality proving ring should be used. A proving ring with a single-piece design can help eliminate out-of-axis movements that can develop in a multi-component ring. In this test, the dial gauge holder of the proving ring is replaced with an LVDT holder. To monitor loads with the proving ring, the user needs to calibrate the ring with the LVDT in place. Otherwise, there is no need for proving ring calibration, as the displacements are linearly proportional to the load.

If this approach is used to monitor absolute load cell channel time delays, the user still needs to find a way of monitoring the LVDT with an unconditioned channel (in the case where a well-characterized conditioned reference LVDT is used), or the user needs to use an already well-characterized system LVDT, along with its dedicated signal-conditioning channel.

AC Transducer (LVDT) Simulation

AC transducer simulation is a bit more involved than DC simulation, and is not generally recommended due to its complexity. The method of simulating an LVDT depends on the design of the AC signal conditioner. In one traditional design, the carrier wave (typically a 2 to 10 kilohertz (kHz) sinusoidal wave) is amplitude modulated by the LVDT. The modulated wave is demodulated in the signal conditioner, with the help of the original carrier wave. The amplitude of the demodulated wave is linearly proportional to the displacement amplitude, and the phase of the modulated wave (compared to the carrier wave) is used to determine the direction of the displacement. For an AC signal conditioner of this type, the job of the transducer simulator is to receive the carrier wave, modulate it with a known wave (a sinusoid from 2 to 50 Hz that represents the LVDT displacement), and output both the modulated wave that is fed back into the AC signal conditioner and the modulating wave (the 2 to 50 Hz reference signal), which is used as the reference signal and compared to the output of the LVDT signal conditioner. Such a system can be built from readily available integrated circuits, or a signal generator (which can modulate a signal with a known sinusoid) may be modified. For an indepth description of this approach, which it should be noted is not the currently preferred approach, the reader is referred to section 3 of FHWA-RD-96-176.

AC Transducer (LVDT) Mechanical Actuation

Due to the variety of AC signal conditioner designs and the complexity of fabricating a special piece of electronic equipment for each design, it was easier to physically actuate the LVDT and its respective channel than to simulate the LVDT.

The purpose of this system is to sinusoidally move the core of the LVDT from 2 to 50 Hz with a constant amplitude. The mechanical device consists of a DC motor that operates smoothly between 120 revolutions per minute (rpm) (2 Hz) and 3000 rpm (50 Hz), a bearing mounted eccentrically to the end of the motor shaft, a connecting rod that connects that bearing to a linear slide bearing, and holders for two LVDTs, the cores of which bear against the linear slide. The motor, linear slide bearing, and LVDT holders are all mounted to one rigid plate. As the motor rotates, the eccentrically mounted bearing transmits a displacement to the slide bearing via the connecting rod. If the eccentricity is small (on the order of 0.635 mm), and the connecting rod is long (on the order of 100 mm), then the deviation from a sinusoidal motion that the slide follows is quite small. Therefore, except for this small error, the slide translates back and forth in a sinusoidal manner with a peak-to-peak amplitude of twice the eccentricity of the bearing (1.27 mm in this example). The cores of the two LVDTs are then mounted to (or bear against, in the case of spring-loaded LVDTs) the linear slide and translate in and out of their respective bodies. Of the two LVDTs, one is the reference LVDT with its dedicated signal conditioner; the other is the LVDT being tested.

Before this system can be used, the reference LVDT must be characterized over the range of frequencies being used. The attenuation of the reference LVDT must be checked (i.e., that the signal is not attenuated over the frequency range of interest), and any delay must be measured. This delay can be measured either using the electronic simulation approach referred to above, or by comparing the LVDT response to that of a linear slide potentiometer. Comparing the reference LVDT output to a rectilinear potentiometer output is preferred as it requires less equipment and is easier to perform. (One might think that a potentiometer might be the preferred reference device for the verification procedure, but wear of the resistive surface would limit its life in such a high-frequency application.) If a potentiometer were used as a reference device, a 10V DC signal would be applied across the linear potentiometer and the slider voltage would be proportional to the potentiometer displacement.

One concern when fabricating an LVDT actuator is that the motor operate smoothly without pulsing though the range of speeds required. A brushed DC motor with a DC power supply works well. Another major concern is that the LVDT conditioner must not filter the signal excessively. Of the many conditioners investigated, a Macro Sensors LPC2000 was found to be satisfactory with no attenuation over the frequency range of interest and with about a 0.7 millisecond (ms) signal delay. Many LVDT conditioning systems are designed to measure essentially static or slow processes, and so may incorporate too much filtering for dynamic applications.

To use this actuator, the test LVDT (which is connected in its normal manner to its conditioning system) is mounted in its holder and adjusted to operate approximately about a mean of zero voltage. If an oscilloscope is used to evaluate the conditioner under test, the output of the conditioner is fed into one oscilloscope channel. The reference LVDT output is then fed into the other oscilloscope channel. The behavior of the channel under test can then be compared to the reference LVDT, keeping in mind the delay introduced by the reference LVDT conditioner. To record the channel under test to the reference channel, the user needs to connect the output of the reference LVDT conditioner to an unconditioned and unfiltered input to the DAS. The computer can then be used to monitor and record the reference channel and the LVDT under test (again, remembering to account for the delay introduced by the reference LVDT conditioner).

Accessing a Conditioned Data-Acquisition Channel

In the beginning stages of evaluating a system, it is convenient to use an oscilloscope for comparing the conditioned signal to the reference signal. In this case, the user needs to monitor the conditioned signal being tested from a point after the filtering and amplification sections of the signal conditioning module, but before the A/D converter. Some systems have analog output test points on the front of the signal conditioning module. In others, the user might need to disconnect a cable that connects the signal-conditioning section to the DAS and take the required signal from the output of the back of the signal-conditioning module. In yet other systems, the user may need to open the computer and monitor a test point on the signal-conditioning/digitization printed circuit card. This last approach is not generally recommended because the test probe could slip, shorting out some other pins and potentially ruining the circuit board. The point one uses to monitor, and the ability to monitor any point at all, depends completely on the design and configuration of the data-acquisition/signal-conditioning system.

Accessing a Free Unconditioned A/D Converter

The ability to access the input to the A/D converter is a function of the system design and the cabling configuration of the system. In some systems, signal conditioners and filters are housed in a separate unit and the conditioned voltages are passed to the A/D converter with shielded cables. In this instance, the user needs to unplug the chosen channel and connect the simulator/actuator output to the A/D input with a suitable connector and cable. To do so, the user needs to know the gender and number of the connector as well as the pin-outs so that the signal can be connected to the proper connector pins.

Other systems combine the signal-conditioning and A/D converter on the same printed circuit card. In this event, it is likely to be difficult to find the appropriate point to insert the reference signal (and may prove detrimental to the integrated circuits on the board due to overloading the upstream circuits); and in any case the user would likely need to monitor trace voltages on the printed circuit card. Since this approach is fraught with possible problems that could ruin the card, it is not generally suitable for this general procedure. In this event, the only other approach available is to characterize one of the channels using the oscilloscope, and use this well-characterized channel as the reference channel.

A third possibility is that the signal-conditioning and A/D circuits are on separate circuit cards or modules, but are contained in the same physical housing. In this case, it still may be possible to identify the connections (given that a back plane is not used) between the conditioner and the A/D converter, and hardwire the reference signal to the input of the A/D converter.

Developing a Reference Channel

If the user cannot access the input of an A/D converter (or identify an unconditioned channel), another approach is possible in which one channel, slated to be the reference channel, is characterized using an oscilloscope, and this channel’s attenuations and time delay are incorporated into the analyses when developing the characteristics of the other channels being tested. This approach is the less desirable one, as it entails an indirect comparison. Also, an oscilloscope does not yield as accurate a measurement as the digitally recorded results. But for the purpose of finding significant shortcomings of the test system, or if there are no other alternatives, the approach is likely to be quite satisfactory.

To use this approach, the user needs to have access to the conditioned and filtered output of the chosen reference channel so that it can be monitored with the oscilloscope. If the only possible point of accessing the output is on a printed circuit card, then it might be acceptable as the procedure only needs to be performed once, although there is still a risk of damaging the card (the alternative is to not perform the tests). In this event, the risk of damaging the card (not too great if care is taken) might be considered to outweigh the possibility of not evaluating the system.

Having identified the output of the conditioned and filtered signal, the user monitors this output on one channel of the oscilloscope. The second oscilloscope channel is used to monitor the reference signal. The actuator/simulator is taken from 2 to 50 Hz, while the user records the attenuation and time delay at each frequency. If the time delay or attenuation are sizable, then it might be appropriate to increase the filter cutoff frequency for this channel in an attempt to reduce these errors. (This filter cutoff frequency must be maintained when evaluating the other channels.) Once the attenuation and time delays have been recorded for each test frequency, the channel can be considered as characterized and subsequently be used as a reference channel. Other channels can now be compared to this one using the computer DAS, and absolute attenuations and delays can be calculated by adding the attenuations and delays recorded during this oscilloscope comparison to the actuator/simulator signal.

Choice of Test Frequencies

Questions often arise regarding the choice of frequencies used in this verification procedure. A tester’s focus is generally the test being performed. However, the concern with this portion of the verification procedure is not the performance of the ultimate test being performed, but rather the characterization of the electronics system. To this end, the user must measure the response of the electrical system. The user performs the verification at low frequencies to evaluate the low-frequency response of the system. Unless the signal conditioners are improperly configured, this low-frequency test will measure the unattenuated signal throughput. The highest frequency of 50 Hz is used to measure the signal delay through the signal-conditioning/filtering modules. The filtering section introduces a constant time delay that is fairly independent of frequency. This small time delay is observed with better resolution if a high frequency is used. Therefore, a verification test at 50 Hz is used to accurately characterize the signal delay due to the filtering/conditioning module. Tests at the intermediate frequencies of 10 and 20 Hz are done to more thoroughly characterize the frequency/attenuation of the channel being tested.

Test Performance

The objective of the verification test is to compare a known reference sinusoidal signal to the same signal that has passed through the signal conditioner and DAS. These two signals can be viewed on an oscilloscope for troubleshooting purposes or recorded on the DAS computer for a permanent record of the channel response.

The time delay and attenuation of the signals with respect to the reference signal characterizes the DAS and indicates whether filters are set correctly, and may indicate other problems with the system.

Two test systems must be developed and assembled: one for testing the LVDT system, and a second for testing the DC load cell system. If a simulation approach is taken, then cables must be prepared to connect the transducer simulator to the signal conditioner. If a transducer actuator approach is taken, a cable between the reference signal conditioner must be fabricated to connect the conditioner to the A/D converter input. In addition, suitable LVDT holders need to be fabricated. After the test components are assembled, the test procedure is fairly straightforward.

1. Assemble the test system as dictated by the actuation/simulation approach.

2. Connect the system to a two-channel (minimum) oscilloscope to perform an initial evaluation. It is helpful if there is a storage capability for low-frequency monitoring. This initial step is useful for troubleshooting. An analog oscilloscope is good for most applications, but for a higher level of accuracy a digital oscilloscope or one with digital readouts might be useful.

3. Perform comparisons between the reference and conditioned signals at 2, 10, 20, and 50 Hz. If the time delay and attenuations are acceptable, then proceed to step 4. Otherwise, identify the source of the unacceptable delay or attenuation, rectify the problem, and repeat the test.

4. Connect the reference and test channels to the DAS and record both channels simultaneously at 2, 10, 20, and 50 Hz for a permanent record. These data files will be used to calculate the time delay and the channel attenuation for the specified filter setting.

If there seems to be a problem with attenuation that cannot be easily rectified during the verification procedure, the next step is to record the system response at 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, and 50 Hz. The set of the attenuations measured at these frequencies can be used to better characterize the filter response and be a basis for identifying the type of filter (e.g., Bessel, Butterworth, Chebyshev) being encountered in the system. The identification of the filter type is beyond the scope of this document, but this can be accomplished by an electronics engineer versed in filter design. This backup information should also be of some assistance to the designers of the filtering module in evaluating the module.

It is usually of some help to monitor the signal with the oscilloscope during the acquisition mode to ensure that all signals are as the user might expect. The use of the oscilloscope in this portion of the testing also is helpful in setting the desired test frequency.

When taking data on the computer, the user needs to take enough data points per loading or displacement cycle so that the full waveform is reasonably well represented. This means that the peak of the sine wave and the zero crossing point (i.e., the intersection of the sine wave and the sine wave mean) are easy to identify. Generally, the user does not want to use less than about 20 points per complete sine wave. When testing at 50 Hz, this means taking 1,000 samples per second (s). A higher acquisition rate would be even better. Only a few cycles of data need be recorded, but for troubleshooting purposes it may be helpful to take a dataset over a long period of time as well.

Data Analysis

The objective of these tests is twofold: to find the time delay between the actual process and the recorded process, and to observe any attenuation in the input-to-output signal. The easiest way of measuring the time delay is to subtract the average of the sine signal (this means an average over integral cycles, and not any partial cycles) from the sine wave form. This mathematical operation will result in a curve that is symmetrical about the zero axis. If the input and output curves are translated to the same axis in this manner and they are plotted on the same graph, the time offset between the two modified curves is the time delay between the input and output signals. This delay is most easily identified by the zero crossing points of the two plots. Because the delay is almost independent of frequency, one can obtain a more accurate measure of the delay at higher frequencies. Therefore, the user needs only calculate the time delay for the 50 Hz signal. If desired, this delay can also be expressed as a function of phase angle as: 360^o x delay/period.

The amplitude attenuation is best evaluated by assessing the peak-to-peak amplitude of each signal. The V_{max} minus V_{min} values for each trace are calculated and compared. The user first must evaluate the ratio between the two at the lowest frequency of 2 Hz. At this low frequency, the signal conditioners should not attenuate the signal at all. (If they do, the attenuation will be evident as the frequency increases.) This baseline ratio between V_{out}/V_{in} can be considered as the unattenuated ratio. This ratio is compared to the high-frequency ratio; a high-frequency amplitude ratio of V_{out}/V_{in} less than the low-frequency voltage ratio indicates a filtering problem.

Generally, the time delay is much more noticeable than the amplitude attenuation, and therefore is a better indication of improper filter settings. The delay may not be important in its own right (given that all of the channels are delayed about the same amount), but rather as an indicator that there may be a problem with the data-acquisition and conditioning system.

ACCEPTANCE CRITERIA

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

- 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 preceding 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.[1] Filter characteristics should not cause excessive amplitude or phase errors in the signals. Error tolerances are specified in the acceptance criteria. Filter settings should remain unchanged after the electronics system has passed the acceptance criteria.

DISCUSSION

The starting point from which these steps were developed was the previous verification procedure document. Typically, because each testing system is unique, the user needs to keep an open mind, and work around problems posed by each new system.

The very first obstacle encountered was one of electronics compatibility. The signal generator specified in FHWA-RD-96-176 is no longer available, and the design of the currently available model is such that the modifications suggested in the original document are no longer applicable. This problem, along with the variety of signal-conditioning system designs, necessitated a more universally applicable approach, which spawned the development of the mechanical LVDT actuator. Other approaches may also be found, and be equally suitable. If the user can get a known signal (a sine signal with set frequencies of 2 to 50 Hz) into the signal-conditioner/filter system, and monitor the input as well as the conditioner output, then all the requirements are met for testing the channel.

Electrically interfacing to the DAS can generate problems of signal ground. The polarity of the signal may be wrong and thereby ground the signal. A possible fix for this situation may be to place resistors in the signal input line so that both input and signal generator see a range of resistance that matches their respective impedances. The resistors can also be used to prevent a short to ground.

In all of these procedures, the user needs to be able to access at least one unconditioned, unfiltered channel for recording the reference signal. This search for a suitable reference channel is usually a challenge. Some systems are composed of discrete components, making it easy to inject a signal at will into the input of the A/D converter. In other systems, there is no possibility of doing so, in which case the user might be able to work around the problem by setting the filter of the “reference channel” to a high cutoff frequency, and reducing the gain to a suitable value so the input of the signal conditioner is sufficiently amplified to produce adequate amplitude when it arrives at the A/D converter to result in a reasonably large number of non-zero bits. If there is no possibility of modifying such a “reference channel,” then the user must assume that it is really the relative time offset between channels that is important. In this instance, there should be very little relative offset between the channels. Such a comparison can be performed using a combination of a load cell, proving ring, and LVDT. For such a comparison, there is no reference amplitude, so the user needs to compare the amplitude of a very slow test to the amplitude of a fast test. During this approach, however, a problem can develop. If the load cell being monitored is used to control the load (by the hydraulic control system), and yet is attenuated, the actual applied load will be higher than the desired load and there will be no way of evaluating this condition. If possible, some other means of evaluating the load or displacement is desirable.

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[1] It should be noted that these requirements were developed for detection of gross errors in the system and are based on the performance of specific equipment used in previous implementations of this procedure.

Early on in developing these procedures, the authors attempted to bypass some of these problematic systems by opening the computer, identifying the monitoring pins on the data acquisition card, and monitoring these voltages. This is certainly still possible, but comes with the hazard that if the probe slips, the user might short out the DAS circuit boards and ruin the system. The authors have tried to move away from this approach and attempt to perform all system tests externally (although troubleshooting may still require monitoring some internal voltages).

This procedure has often uncovered improper filter settings and, in one recent test, uncovered a large delay between two signals, not due to filtering but because there were two separate data-acquisition subsystems in the one test system, resulting in a large delay between signals, which was likely due to software polling problems.

If there is a noticeable signal attenuation, then the filter cutoff settings are generally set too low and need to be modified. It is very instructive for the person performing the test to experiment with the filter settings and set them to sequentially lower and lower values. The output signal will be seen to get smaller and smaller even though the input signal remains the same. This exercise demonstrates the importance of proper filter settings, and how improper filter settings can result in useless data.

There are no easy rules to use in choosing the best verification test configuration. The electronic simulation of the LVDTs can be difficult to understand, whereas the mechanical actuation is quite easy to comprehend. In the end, the choice of configuration depends on the equipment that the user has available and the design of the DAS, as well as the approach with which the user feels comfortable.

EXAMPLE

The following example, for illustrative purposes only, is derived from an actual laboratory evaluation. This example illustrates the use of the electrical approach for load cell channel (DC channel) characterization and the mechanical approach for LVDT (AC) characterization.

Results of the Load Cell Verification Tests

The initial approach of characterizing the load cell channels was to use an oscillator to simulate the load cell. The signal from the oscillator was split into two legs: one remained as a large amplitude signal (about 1 V_{pp}) and the other was reduced in amplitude using a resistor-dividing network to a magnitude on the order of 1 mV_{pp}. The large signal was directly fed into the DAS (the data acquisition card that was used to acquire all of the LVDT channels), whereas the small signal was fed into the load cell connector. This low voltage signal was then amplified by the load cell conditioning card and acquired by the proprietary acquisition card. Thus both channels would be recorded by the computer and analyzed later. The justification for using this configuration was that the signal being monitored by the DAS would not be conditioned, and thus not be subject to any filtering, and could serve as a non-delayed and non-attenuated reference against which the load cell channel could be compared. When this approach was taken, the load cell channels were both very stable and exhibited no attenuation. However, the "reference" signal being monitored directly by the DAS was significantly attenuated at 50 Hz, and arrived much later than the load cell channel readings. This behavior was exactly contrary to the expected behavior. If the “reference” channel was truly a reference measurement, then its amplitude would not have changed with frequency, and the load cell channel would have arrived after the reference signal. Thus some filtering must have been occurring on the LVDT channels, after the signal conditioning and somewhere within the computer. Clearly, this approach could not be used for evaluating the attenuation and time delay of the conditioned signals, so another approach was taken.

In the second approach, the signal from the oscillator was divided down to a millivolt level as in the first approach, and then applied to the load cell connector. The conditioned signal was then monitored with an oscilloscope on one of two test pins on the edge of the conditioning and acquisition card. (This entailed opening the computer and plugging a lead into the two test points.) The large amplitude (1 V_{pp}) signal from the oscillator was used as the reference signal and was monitored by the oscilloscope. The frequency of the oscillator was then varied from 2 to 50 Hz, while the amplitude of the reference and conditioned signals was recorded (from the oscilloscope traces). The time delay between the two signals was measured at the 50 Hz frequency. Attenuations and delays for these two load cell channels are summarized in table 1.

Table 1. Example load cell channel attenuation and time delay.

Channel Name	Load (400 Hz, 2-pole Butterworth filter)			Trxload (400 Hz, 2-pole Butterworth filter)		
Frequency (Hz)	V_{in} (V_{p-p})	V_{out} (V_{p-p})	Time Delay (ms)	V_{in} (V_{p-p})	V_{out} (V_{p-p})	Time Delay (ms)
2	0.80	0.67		0.80	0.48	
4	0.80	0.67		0.80	0.48	
6	0.80	0.67		0.80	0.48	
8	0.80	0.67		0.80	0.48	
10	0.80	0.67		0.80	0.48	
12	0.80	0.67		0.80	0.48	
14	0.80	0.67		0.80	0.48	
16	0.80	0.67		0.80	0.48	
18	0.80	0.67		0.80	0.48	
20	0.80	0.67		0.80	0.48	
50	0.80	0.67	0.60	0.80	0.48	0.6

Shaded cells: No data taken.

From these tests, it appears that there is no measurable attenuation, and that the absolute time delay is quite small and of an acceptable level. (The absolute time delay is not a critical factor, although it does give the user an idea of the filter settings. The relative time delays between the channels, however, are of great importance.) It should also be noted that a quick check was made to see if the 0.6 ms delay was in fact due to the filter. The filter cutoff frequency was switched to 4 kHz and the reference signal was compared to the conditioned and filtered signal. The signals overlapped with no measurable offset between the two signals. Thus it was verified that the time delays measured in these tests were in fact due to the 400 Hz 2-pole Butterworth filters (theoretically about 0.63 ms).

Results of the LVDT Verification Tests

During the first effort to measure the load cell channel behavior, it was determined that for some unknown reason the acquisition system introduced a large delay and attenuation on all channels being acquired through the DAS (i.e., all of the LVDT channels). Therefore, the first objective was to get some idea of the response of the conditioners used to condition and filter the LVDTs. In this cursory investigation, only one conditioner (used for the LVDT1) was evaluated. It was assumed that the others were similar (because they consisted of the same modules and same filter settings). The evaluation of this one conditioner would give some idea of the contribution of these conditioners to the total channel delay and attenuation.

To perform this test, a mechanical oscillator was used to move two LVDTs simultaneously in a sinusoidal manner. One LVDT and its corresponding channel was the one under test; the other was a reference LVDT that was conditioned with a stand-alone reference signal. The conditioned signal of the reference LVDT was viewed on the oscilloscope along with the output of the conditioned test LVDT. The frequency of the mechanical oscillator was varied from 2 to 40 Hz while both signal amplitudes were recorded (table 2). In addition, the time delay was measured at 40 Hz. In this case, the test LVDT signal arrived before the reference LVDT, implying that the time delay of the reference signal (1.6 ms) was greater than that of the test LVDT, and thus had to be subtracted from the test value.

Table 2. Example of LVDT conditioner attenuation and time delay.

Channel Name	LVDT Channel (500 Hz filter)		
Frequency (Hz)	V_{in} (V_{p-p})	V_{out} (V_{p-p})	Time Delay Raw/Corrected (ms)
2	4.8	8.0	▨
4	4.8	8.0	▨
6	4.8	8.0	▨
8	4.8	8.0	▨
10	4.8	8.0	▨
12	4.8	8.0	▨
14	4.8	8.0	▨
16	4.8	8.0	▨
18	4.8	8.0	▨
20	4.8	8.0	▨
40	4.8	8.0	-0.8/+0.8

Shaded cells: No data taken.

After the conditioner was evaluated, the complete LVDT conditioning system was evaluated. In this second configuration, all readings were recorded using the DAS. The mechanical oscillator was used to actuate both the LVDT under test as well as the reference LVDT. The test LVDT was conditioned in its conventional configuration using the conditioner to feed the data acquisition card, the output of which was recorded by the acquisition program. The reference LVDT was conditioned using its own stand-alone conditioner (introducing a delay of 1.6 ms of the reference channel). The signal was then reduced to a millivolt level with a resistor voltage divider and then fed into the “Load” channel load cell connector. The filter of this channel was set to 4 kHz so that there would be no delay or attenuation, as proven in the last step of the load cell verification procedure, mentioned earlier. Thus, except for the delay introduced by the conditioner, the “Load” channel provides a good reference signal. The recorded data files developed from these two channels were then used to evaluate the attenuation and time delay between the two channels. Due to the large number of LVDTs, the tests were performed at only four frequencies (2, 5, 10, and 40 Hz); the time delay was calculated at 40 Hz.

After completing this suite of tests, the time delays were found to be quite significant, on the order of 4.0 ms (a reading of -2.4 ms minus the 1.6 ms delay introduced by the reference signal conditioner, with negative sign indicating that the test LVDT signal occurred after the reference signal), along with significant attenuation of about 25 percent at the highest frequency. The delay and attenuation was discussed with a manufacturer’s representative, who said that the program incorporates a software filter on the LVDT channels that is controlled by the "smoothing" parameter in the channel configuration file. This parameter was set to 10 and it was recommended that it be set to 1 or 2. These parameters were changed to 1 and the tests repeated. There appeared to be no attenuation, and the time delay reversed sign and was roughly 0.5 ms (a +2.1 ms reading minus the 1.6 ms delay introduced by the reference signal conditioner) with the LVDT signals recorded prior to the reference signals. A third set of tests was then performed in which the smoothing parameters were set to 3. In this case, the LVDT occurred after the reference channel by about 0.5 ms (a reading of +1.1 ms minus the 1.6 ms delay introduced by the reference signal conditioner). In this case, slight attenuation at the highest frequency was noticeable. These test results are summarized in table 3 for a smoothing function of 1 or 10. The data for a smoothing function of 3 were only visually documented.

Table 3. Example of summary results for electronics check.

LVDT Channel	Internal/ External	Smoothing	Attenuation 10 Hz		Attenuation 40 Hz		Time Delay, ms
			%	Pass?	%	Pass?	
1	Internal	1	-0.1	Yes	0.1	No	0.5
2	Internal	1	-0.1	Yes	0.1	No	0.5
3	Internal	1	0	Yes	0.8	No	0.6
1	External	1	0.1	Yes	0.9	No	0.7
2	External	1	-0.1	Yes	0.9	No	0.7
1	Internal	10	-1.6	No	-24	No	-3.7
2	Internal	10	-1.5	No	-23	No	-3.7
3	Internal	10	-1.6	No	-24	No	-3.7
1	External	10	No Data	N/A	No Data	No	-3.7
2	External	10	No Data	N/A	No Data	No	-3.7

These tests highlight the asynchronous nature of the DAS. It appears that the channels on the conditioners are being acquired significantly before the load channels. Thus a very large time offset, which is not a function of any filtering, is introduced into the system. Additionally, software filters are included in the acquisition program that greatly affect the attenuation and time delay of the LVDT channels.

Conclusion

The load cell channels appear to be in good working order and result in satisfactorily small time delays and attenuations.

The electrical architecture used to incorporate the LVDT channels in this system causes problems. Two or more data acquisition cards of differing designs are used in this system. Not only does the processor need to poll each card separately (which, due to the serial nature of the process, requires a delay between each polling process), but the times to sample and hold a channel of data are different due to the two different designs of the cards. Thus there are two possible sources of time lag between the two cards. It is likely that the DAS is polled first, data recorded, and then the proprietary card is polled and its data acquired. This sequence could explain the large time delay encountered in this verification procedure.

The second objection is in the manner of incorporating a software filter. This undocumented filter is not accessible from the user interface. Such filters most definitely need to be documented and characterized so that the user of the system can evaluate the need for the filter.

To arrive at an acceptable configuration, the time delay between the load and displacement channels needs to be eliminated and the reason for the software “smoothing” filters needs to be eliminated or reduced to the extent that the signal attenuation is less severe.

IV. CALIBRATION CHECK AND OVERALL SYSTEM PERFORMANCE VERIFICATION PROCEDURE

INTRODUCTION

A typical dynamic testing procedure requires many pieces of equipment, including: load frame, load cells, hydraulic system, deformation devices, triaxial pressure chamber, computer, signal processor. For the testing procedure, elements of the overall test setup are first checked to verify that their operation produces the expected responses. Checking the individual components first helps ensure that many problems that would be encountered during actual testing can be identified and eliminated prior to checking the system's proficiency.

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

1. Deformation measurement device.
2. Load cell zero.
3. Load cell calibration.
4. Verification of load cell calibration (static).
5. Load versus deformation response check (dynamic).
6. System dynamic response check.
7. Triaxial pressure chamber.
8. Environmental chamber.

DEFORMATION MEASUREMENT DEVICES

Background

One of the most critical aspects of a dynamic materials testing system is the strain (or deformation) transducers used to measure movement of the sample. These can consist of LVDTs, extensometers, strain gauges, and other devices. The purpose of this experiment is to verify that the deformation measurement device is properly calibrated and performing acceptably. This procedure has primarily been developed for LDVTs or extensometers; however, a similar approach can be used for other types of deformation measurement equipment.

For deformation measurement devices that are internal to the dynamic testing apparatus or practically inaccessible to the user (such as an LVDT used to measure movement of the loading piston), other techniques for verifying deformation response can be used as explained in subsequent portions of this document.

The deformation measurement device must be matched to the application. For a more detailed explanation of the types of deformation measurement devices and their application, the user is referred to the dynamic test system manufacturer or various deformation measurement device manufacturers. Much of this information can be obtained from the manufacturer's Web site.

Dynamic System Configuration

The test system should be turned on and warmed up according to the manufacturer's specifications. The hydraulic system does not need to be turned on for these experiments.

Approach

Inspect the deformation device to ensure it is in good working order and not damaged in any manner. If possible, the deformation device should be manually exercised (do not exceed full-scale travel) to ensure proper working condition. For example, an LVDT can be moved to determine whether any components stick, or to check for excessive friction in the housing. If the deformation device is in satisfactory condition, the procedure may proceed. If it is not in proper working order, it should be repaired or replaced.

Verification of the deformation measurement transducers is performed using a micrometer head-based calibrator capable of accurate calibration of ±2.5 mm deformation movement. The calibration should be performed for all ranges required for the test being performed. A minimum of a nine-point calibration should be conducted starting with the zero offset (0 V = 0 mm). Begin by reading the zero measurement. Proceed in equal increments to the full upper range of the deformation device, then proceed to the full lower range of the device in equal increments to the zero point. For each increment, register the values of the micrometer reading and the voltage reading (or, alternatively, read the deformation output by the system). Be careful not to extend the deformation device past its normal operating range.

For a deformation device with a maximum stroke of ±2.54 mm, the calibration verification is performed as in table 4.

Table 4. Sample of deformation calibration verification dataset.

Micrometer Reading, mm	Deformation Device Reading, mm	Difference, mm	Deformation Difference ≤ ± 1% full scale?
0.000	0.000	0.000	Yes
0.635	0.635	0.000	Yes
1.270	1.295	-0.025	Yes
1.905	1.880	0.025	Yes
2.540	2.489	0.051	No
1.905	1.880	0.025	Yes
1.270	1.321	-0.051	No
0.635	0.635	0.000	Yes

Table 4. Sample of deformation calibration verification dataset—*Continued*

Micrometer Reading, mm	Deformation Device Reading, mm	Difference, mm	Deformation Difference ≤ ± 1% full scale?
0.000	0.000	0.000	Yes
-0.635	-0.610	-0.025	Yes
-1.270	-1.270	0.000	Yes
-1.905	-1.829	-0.076	No
-2.540	-2.540	0.000	Yes
-1.905	-1.905	0.000	Yes
-1.270	-1.321	0.051	
-0.635	-0.635	0.000	Yes
0.000	0.000	0.000	Yes

Data Analysis

Divide the total positive travel of the deformation transducer by 100. This value will be used as one of the acceptance criteria. Subtract the deformation device reading from the micrometer reading to determine the difference in the readings.

Plot the deformation device displacement readings versus the micrometer displacement readings. If voltage is used, the deformation voltage readout must be multiplied by the proper calibration factor for the deformation device to obtain deformation in the appropriate units. Perform a linear regression of the data to obtain the zero intercept and coefficient of determination (R^2). This is easily performed in a spreadsheet computer program.

If the deformation device fails any of the acceptance criteria, a second verification must be performed. If it fails both tests, the device should be repaired or replaced.

Acceptance Criteria

- The best-fit curve must have a zero intercept (±0.0254 mm) and a R^2 value of at least 0.99.

- The maximum difference in the readings between the micrometer and the deformation device cannot exceed 1 percent of the device’s full-scale travel. For example, for a deformation device with a full-scale range of 2.54 mm, the micrometer versus deformation device readings should be within ±0.0254 mm.

- The deformation device shall be free of visual defects and should operate in an acceptable manner (e.g., no visible damage and no sticking).

Discussion

In a production testing mode, it is recommended that the LVDTs be verified every 2 weeks or after every 50 resilient modulus tests, whichever comes first. In addition, it is highly recommended that the micrometer used to check the calibration be NIST calibrated or calibrated using NIST traceable gauge blocks.

Example

The deformation device (in this case an LVDT) was manually exercised. It was visually inspected and found to be in good working order with no obvious signs of damage. The spring-mounted device was manually exercised and no sticking was found.

Using the previous example, the total travel of the deformation device is 2.54 mm. Therefore the 1 percent criterion would be 2.54 mm / 100 = 0.0254 mm. Referring to table 4, the difference between the two readings is calculated.

Referring to figure 2, a plot of micrometer deformation versus deformation device readings is displayed. The results of the linear regression are also shown on this figure. The calculated y-intercept is 0.0015 mm and the R^2 value is 0.999.

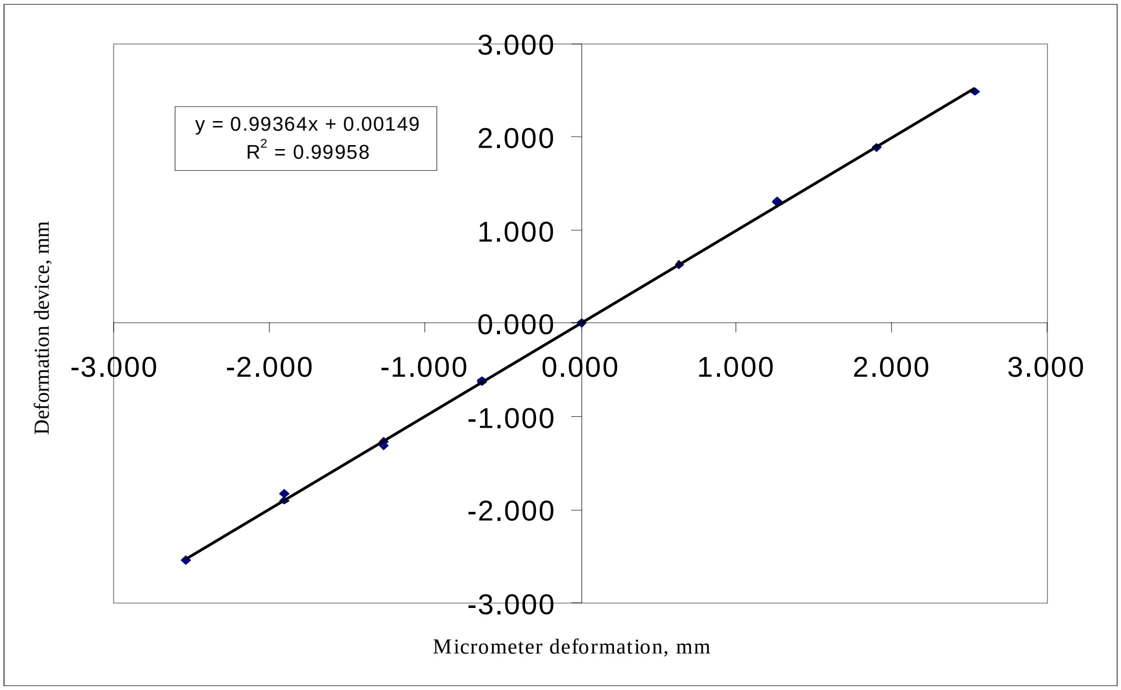

Figure 2. Chart. Example of micrometer reading versus displacement.

Using the acceptance criteria, this example transducer would pass both manual inspection and linear regression criteria. The y-intercept is 0.0015 mm, well within the tolerance of zero ±0.0254 mm, and the R^2 value is 0.999, which is greater than the 0.99 requirement. However, the device does not pass the micrometer-versus-deformation check. As shown in table 4, this check fails at four locations. Depending on the necessary accuracy of the contemplated test procedure, this can cause substantial errors.

In this example, the transducer is marginal for use in certain applications and consideration would need to be given to replacing the device.

LOAD CELL ZERO

Background

It is not uncommon in a laboratory to overload a load cell. Overloading can occur by accidentally exceeding the rated capacity of the load cell, or by dropping it. In addition, if a cell is loaded to near its rated capacity, and the sample fails, then the dynamic stress wave that passes through the device can also overstress the cell. Such overloading needs to be evaluated periodically. It is often erroneously thought that the cell need only be recalibrated in the event of an overload. In some cases of mild overloading, this approach may be acceptable, but often the only recourse is to dispose of the load cell.

An overloaded load cell can acquire some very undesirable characteristics. The zero of the load cell will usually shift due to the overloading. This is the most obvious sign of an overloaded cell. Again, it is commonly believed that one can just re-zero the cell and continue testing. Unfortunately, by overloading the cell, a portion of the sensing membrane in the cell has gone into plasticity. This permanent deformation changes the elastic behavior of the sensing member in the cell. In addition to the zero offset, the cell may now have a different calibration factor and, more important, it may well exhibit hysteresis and creep. Thus the loading curve (of load cell voltage versus known load) will not follow the unloading curve. The creep behavior is manifested by not returning to zero after being unloaded, and then gradually settling down to a zero reading. Or after a large load is applied, the cell will slowly drift to a steady reading. These traits are unacceptable for any transducer, and such an overloaded cell should be repaired or replaced.

When a load cell is fabricated and set up at the factory, the Wheatstone bridge is balanced, either using laser-trimmed strain gauges or additional resistors, to read near-zero volts when the bridge is excited. When the cell is overloaded, this balance is destroyed.

This state of balance can be evaluated either with a precision voltmeter or a strain gauge box. For a precision voltmeter, one applies a supply voltage to the cell, and simply reads the output voltage. A strain gauge box is essentially the same device, but with a built-in power supply, and is read in micro strain instead of voltage. For purposes of this procedure, it is assumed a strain gauge box is used, as they are usually readily available in the laboratory.

This procedure should be used for all load cells that will be used in the testing process.

Dynamic System Configuration

The dynamic test system is not used for this verification. In fact, machine may be turned off. To perform this procedure, the load cell is removed from the machine. For obvious reasons, it is extremely important that no load be applied to the cell during conduct of this procedure.

Approach

1. Connect the 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.
4. Set the strain indicator to full bridge mode.
5. Read the resultant strain.

Record the results on the load cell zero reading check form (figure 15 in appendix A) .

Data Analysis

1. Determine the sensitivity of the load cell. This value is in millivolts/volt (mV/V) and is usually shown on the manufacturer's calibration data sheet as the "full-scale" output. If the sensitivity of the load cell cannot be determined, contact the manufacturer, who should be able to provide this information.
2. Multiply this value by 0.015. This will yield the maximum zero value allowed in mV/V.
3. Use the zero value determined from the test in mV/V.
4. Convert the initial strain to units of mV/V by dividing the indicated micro strain by 2000. Record the measured mV/V on the form (figure 15 in appendix A) provided in the column labeled "measured zero."
5. Remember that the strain indicator has an associated error that must be accounted for in this analysis.
6. Compare the measured zero value to the allowable maximum zero (remember to include the strain indicator box error).
7. Determine acceptance or rejection.

Acceptance Criterion

The load cell zero reading should be within 1.5 percent of its full-scale, factory-indicated sensitivity.

Discussion

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 manufacturers 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.

It is recommended that the load cell zero check be conducted on all load cells at least yearly or whenever a suspected overload has occurred.

Example

Table 5 contains several examples of this procedure. Note that load cell example 1 fails based on the raw zero value reading; however, when the strain box error is applied, the load cell meets the criterion.

Table 5. Load cell zero example.

Load Cell	Example 1	Example 2	Example 3
Vendor	XYZ, Inc.	XYZ, Inc.	XYZ, Inc.
Model number	123	456	789
Serial number	123321	456654	789987
Capacity	4.4 kN	4.4 kN	1.3 kN
Sensitivity	1.999	1.991	2.012
Max. zero value	±0.030 mV/V	±0.030 mV/V	±0.030 mV/V
Strain indicator error	±5 micro strain	±5 micro strain	±5 micro strain
Gauge factor on strain indicator	2	2	2
Balance range	0	0	0
Balance pot	500	500	500
Raw measured zero value	+64 micro strain	+32 micro strain	+215 micro strain
Calculated zero value (with strain indicator error)	0.032 ±0.025 mV/V	0.016 ±0.025 mV/V	+0.108 ±0.25 mV/V
Load cell zero within tolerance?	Yes (marginal)	Yes	No

LOAD CELL CALIBRATION

Background

Load cell calibration is equally important as the load cell zero check. As part of any standard laboratory QC plan, load cells should be evaluated at least yearly either in-house, by trained staff using NIST traceable standards, or using a calibration service with an NIST traceable cell. In either case, the calibration should be conducted using the latest version of the American Society for Testing and Materials (ASTM) E4 standard. The calibration should be performed for the entire load cell operating range. 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.

During this portion of the procedure, the load cell calibration certificates are simply reviewed to determine if this calibration has occurred within the past 12 months.

Dynamic System Configuration

The dynamic test system is not used for this verification.

Approach

The reviewer should view the load cell calibration certificate for each load cell used for dynamic testing and note the date of the last calibration.

Data Analysis

No data analysis (except for a simple date comparison) is needed for this procedure.

Acceptance Criterion

The load cell must have been calibrated within one year of the inspection. A missing certificate is cause for rejection of the load cell for testing until the necessary calibration has taken place.

VERIFICATION OF LOAD CELL CALIBRATION (STATIC)

Background

The verification of the load cell static calibration is conducted with the system fully assembled as if a production test were going to be performed. In this experiment, a proving ring (specimen with known properties), or other suitable device, is used. This procedure does not take the place of the NIST traceable calibration mentioned previously. It is simply a check of the entire system versus a specimen of known properties.

The load cell calibration is verified for two reasons: (1) to ensure that the load cell is performing as expected in the system, and (2) to check for unwanted deformations in the system.

Two methods may be used to perform this procedure depending on the user's test requirements. If verification of the static calibration is all that is required, then a proving ring or external load cell can be used. If, as in the case of LTPP Protocol P46, the deformation transducers are mounted outside the test chamber, then the user would want to measure the difference between the deformation measured inside the system versus that measured outside the system to check for unwanted friction or deformations in the system. In this case, a proving ring with an internally mounted dial gauge or digital readout is preferred for the deformation comparisons. Several types of equipment and/or procedures can be used to accomplish these objectives; for this procedure, the proving ring approach will be emphasized.

Many proving rings are on the market today. If the aim is to perform an inside deformation versus outside deformation check using a proving ring, a high-quality proving ring that consists of one solid piece of metal is recommended, rather than the type that has separate units for the top boss, ring, and bottom boss. Experience has shown that these multipiece rings are unsuitable for this application as they contain many metal-to-metal interfaces that can add to the measured outside deformation, thus making the results difficult to interpret. Single-piece rings do not have these extra interfaces, which minimizes errors due to the extraneous ring deformations. If only load verification is desired, a multipiece proving ring is adequate. The equipment used to accomplish this procedure depends entirely on the user's goals.

To perform this procedure, the proving ring or other load measurement device must be matched to the application. Many proving rings are only guaranteed to be linear from 10 to 100 percent of their rated capacity. Therefore, if the test procedure contemplated results in loads up to 4.5 kN, the proving ring should be matched to this requirement. The user should verify the load cell calibration for all loads anticipated for a particular test application.

For this experiment, specially machined proving ring mounting blocks are usually required. The proving ring should be rigidly mounted in the test apparatus to ensure proper seating of the ring and to minimize lateral movement of the proving ring while under test. This procedure is based on the LTPP Protocol P46 and Protocol P07 tests but it can be modified for other test procedures as applicable.

Dynamic System Configuration

All test systems should be turned on and the machine should be warmed up according to the manufacturer's specifications.

Approach

The steps for checking the load cell are described below:

1. Position the proving ring in the test system 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 test apparatus (e.g., triaxial cell), 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 or otherwise rigidly attached to the test apparatus to perform the test. Furthermore, the bottom of the test apparatus must be bolted down (or tightly fastened) to the bottom loading platen of the load frame.[1, 2, 3]

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[1] Before 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.

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

2. If applicable, place the deformation devices in their appropriate positions.

3. Using the system controls, apply a slow ramp load from 0 to 10 percent of proving ring capacity. Hold this load for 15 s or long enough to record the readings. Record the proving ring dial indicator or internally mounted LVDT value and register the load cell and (if applicable) system deformation device readings using the DAS.

4. Apply a slow ramp load to 20 percent of load cell capacity and hold this load for an appropriate time interval (allow ample time to read the appropriate devices, usually about 15 s). Again, using a slow ramp load, decrease the load to 10 percent of proving ring capacity. Repeat this procedure at 10 percent loading increments up to 90 percent of proving ring loading capacity (but do not exceed the load cell capacity).[3] It should take about 10 s to proceed from the 10 percent value to the desired value. Take readings at every stopping point.

5. Convert proving ring dial gauge values into load values using the proving ring load-dial gauge equation (provided with each proving ring). If a calibrated load cell is used, record the load values directly.

A sample loading specification is shown in table 6.

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[3] 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.

Table 6. Sample static loading parameters.

Seating Load (%)	Seating Load Holding Period (s)	Ramp Rate (%/s)	Final Load Level (%)	Load Holding Period (s)	De-ramp Rate (%/s)	Data Acquisition Rate (points/s)
1	10	10	10		10	2
10			20			
			30			
			40			
			50			
			60			
			70			
			80			
			90			

Note 1: Ramp and de-ramp rate is expressed in percent difference in load per second. Therefore, if proceeding between 45 N and 223 N, the ramp rate would equal 17.8 kN per second (223–45 = 178; 178*0.1 = 17.8).
Note 2: The final load level column is expressed as percent of full range capacity of the proving ring, assuming that this range does not exceed the load cell capacity.

Data Analysis

1. Using the calibration curve provided with the proving ring, or the standard load cell load values, determine the registered load at each interval.

2. Subtract the maximum load from the seating load for all load levels to determine the net difference in load.

3. Compare the machine loads versus the reference standard load readings.

4. If inside versus outside deformations are being compared, convert the proving ring dial indicator value (or use the deformations registered on the deformation device mounted in the proving ring) to displacement measurement at a given load (by using the dial gauge displacement conversion factor).

5. Subtract the maximum deformation from the seating deformation for all loads to determine the net difference in deformation.

6. Compare the proving ring displacement measurement with the average system deformation measurement. If multiple deformation measurement devices are used to measure outside deformation, these values should be averaged before being compared with the proving ring deformation.

Acceptance Criteria

1. The test system load must be within ±5 percent of the proving ring load.

2. The test system deformation must be within ±5 percent of the proving ring deformation.

Discussion

If, using the acceptance criteria, the system fails this check, repeat the procedure. If the system fails the second test, the system fails the check. If the system passes the second test, then a third test should be run to determine acceptance or failure. The apparatus should be disassembled and re-assembled between each test.

If the system fails this check, the load cell should be recalibrated, or a new load cell should be installed on the test system and the process repeated.

If the system does not pass the deformation criteria, check the system for friction in the triaxial piston, misalignment, loose triaxial cell, loose deformation devices, etc.[4]

This process can be modified depending on the test procedure. For example, if verifying a machine for a creep type test, the user may want to hold the load constant for 100 s to ensure that the system is stable at the desired load. Similar acceptance criteria (e.g., load must be held for 100 s and remain within 5 percent of the target load) can be used for this test.

Example

A user is interested in performing this procedure for LTPP Protocol P46 for a type 2 (thinwall tube) sample. The anticipated load range for this test is from 45 N to 267 N. The user has a test system with a 445 N load cell and is performing displacement measurements outside the triaxial chamber. Therefore, the user has decided to use a proving ring with an internally mounted dial gauge so that inside and outside deformations can be measured.

The user selects a 445 N proving ring to perform the verification. The proving ring is only guaranteed to be linear from 45 to 445 N; however, this is within the testing tolerance and thus a good choice.

To perform the test, the user then develops a loading scheme based on the requirements stated herein. The loading patterns are shown in table 7 and figure 3.

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[4] The dial gauge readings can also be used to perform a very general verification of the stroke measurement for the ram, or piston, of the LVDT. This would only detect gross errors in the LVDT calibration.

Table 7. Sample loading specification for 445 N proving ring.

Seating Load (N)	Seating Load Holding Period (s)	Ramp Rate (N/s)	Final Load Level (N)	Load Holding Period (s)	De-ramp Rate (N/s)	Data Acquisition Rate (points/s)
4.5	10	4.5	45	15	0	2
45		4.5	90		4.5	
		9.0	134		9.0	
		13.4	178		13.4	
		17.8	222		17.8	
		22.3	267		22.3	
		26.7	312		26.7	
		31.2	356		31.2	
		35.6	401		35.6	
		40.0	445		40.0	

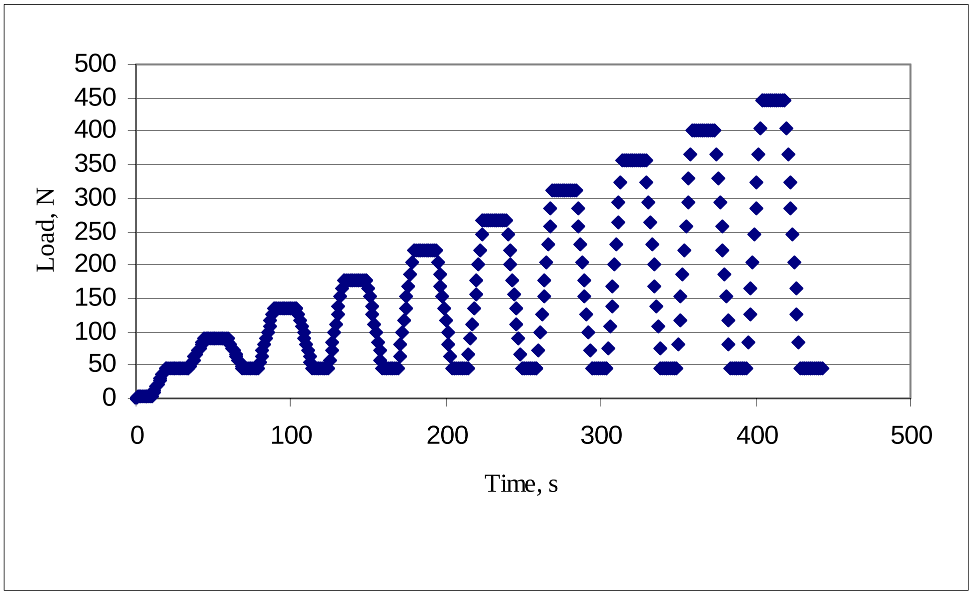

Figure 3. Graph. Sample 445 N proving ring loading pattern.

Tables 8 and 9 and figures 4 and 5 contain the results from this test. In this particular example, the system passes both sets of checks.

Table 8. Sample results of static load testing of 445 N load cell.

Total Nominal Load, N	Nominal Load Differential, N	Proving Ring Load, N	Load Cell Reading, N	% Difference Proving Ring to Load Cell Load
90	45	44.5	45	0.0
134	89	86.3	89	-3.2
178	134	130.4	134	-2.3
223	178	174.4	178	-2.0
267	223	218.5	223	-1.8
312	267	263.0	267	-1.5
356	312	307.9	312	-1.0
401	356	352.9	356	-0.8

Table 9. Example of inside versus outside deformation readings.

Total Nominal Load, N	Nominal Load Differential, N	Proving Ring Deformation, mm	Average Outside Deformation Reading, mm	% Difference Inside versus Outside
90	45	0.2590	0.2642	-1.9
134	89	0.5258	0.5309	-0.9
178	134	0.7899	0.8001	-1.3
223	178	1.0566	1.0744	-1.7
267	223	1.3260	1.3487	-1.8
312	267	1.5926	1.6256	-2.1
356	312	1.8669	1.9025	-1.9
401	356	2.1412	2.1819	-1.9

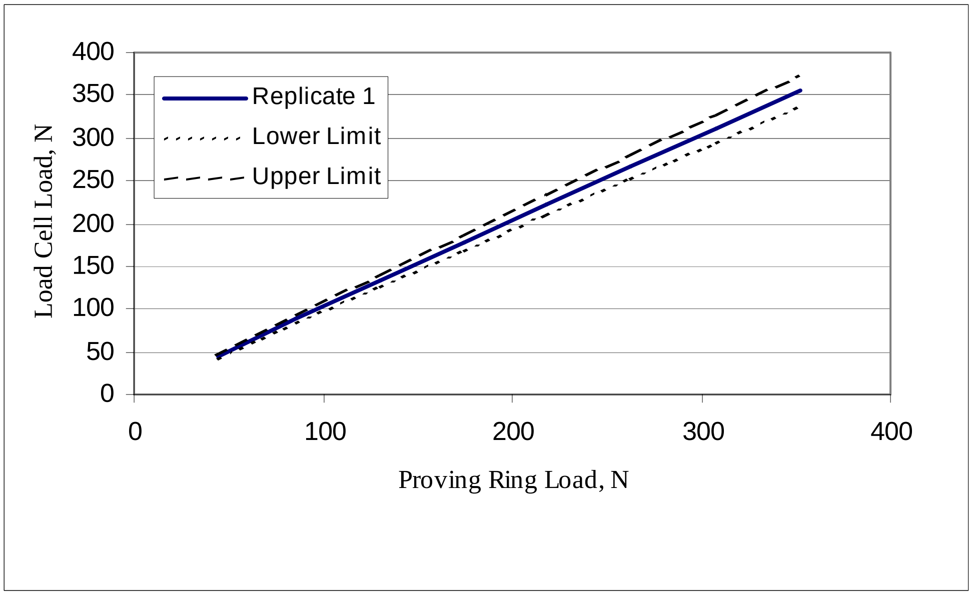

Figure 4. Graph. Example of proving ring versus load cell check.

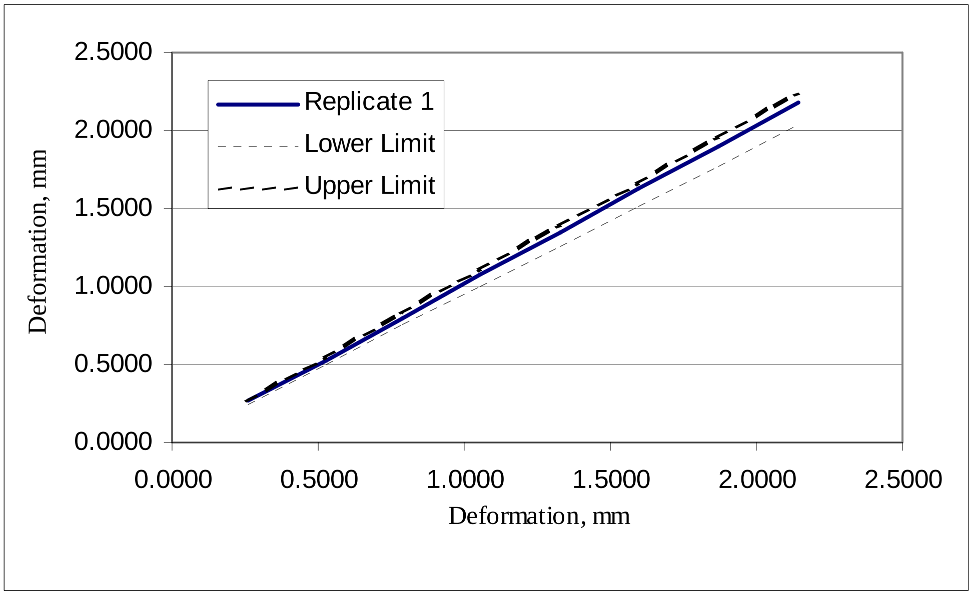

Figure 5. Graph. Example of proving ring versus LVDT check.

LOAD VERSUS DEFORMATION RESPONSE CHECK (DYNAMIC)

Background

To properly evaluate the suitability of a particular test system to a given application, it is essential that the machine be compared against a specimen of known properties. This comparison will allow the user to assess the performance of the equipment in near-test conditions without the repeatability and accuracy limitations imposed by testing a real sample. Therefore, the purpose of this experiment is to simulate an actual test as closely as possible and ensure system performance meets the anticipated needs of the user. This experiment is designed to provide a benchmark performance standard that can be repeated in the future to ensure the system is performing in a consistent manner.

The conduct of this experiment depends entirely on the test procedure. Because of the wide variety of potential applications, it is impractical to include all variations here. This procedure will focus primarily on the resilient modulus test. The fundamentals of this experiment can be applied to other test procedures in a similar manner.

To perform this procedure, a proving ring with an internally mounted deformation device is required. Alternatively, if measuring deformation on the outside of a triaxial cell (for a soils resilient modulus test), the deformation can be monitored using the external deformation devices (assuming the system has passed the external versus internal deformation test presented previously). Similar requirements regarding proving rings as presented earlier apply to this test. It is assumed that the proving rings used for this test have the capacity to perform testing in a similar manner as the test requires. Never overload the proving ring or load cells when performing these procedures.

Dynamic System Configuration

All test systems should be turned on and the machine should be warmed up per the manufacturer's specifications.

Approach

1. Position the proving ring in the test system 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 test apparatus (e.g., triaxial cell), 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 or otherwise rigidly attached to the test apparatus to perform the test. Furthermore, the bottom of the test apparatus must be bolted down (or tightly fastened) to the bottom loading platen of the load frame.[5, 6]

2. Place the deformation devices in their appropriate positions. If outside deformation devices are used, then it is not necessary to use a deformation device mounted in the proving ring.

3. Using the system controls, apply a load in a similar manner as required by the test procedure. For LTPP resilient modulus tests, this consists of applying a haversine-shaped load pulse of 0.1s duration and 0.9s rest period with a seating load of 10 percent of maximum load. The reader is referred to LTPP Protocol P46 (American Association of State Highway and Transportation Officials (AASHTO) T 307) for the definition of haversine waveform.

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[5] Before 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 5 times to minimize the hysteresis of the proving ring.

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

4. For testing procedures in which the exact load levels are known, use the test load levels as the experiment loadings. If the loads used in the test procedure vary, then perform this procedure using 10 percent increments in a similar manner as the static testing procedure described previously. A maximum of 100 load repetitions should be used at each load level. This will allow the operator to fine tune the loading shape prior to collecting data. A fewer number of load cycles may be used if the operator is confident about adjusting the system adequately to produce a suitable waveform.

   For example, for a subgrade specimen with a 71 mm diameter, the loading pattern in table 10 is used. Using this test sequence, the user would select target loads of 49.4, 98.8, 148.2, 197.1, and 246.5 N for this analysis (only use unique loads). The seating load used for the test should be as per protocol specifications, or 10 percent of the total load. This would result in the loading specifications of table 11. For a base/subbase specimen, 152 mm diameter, the loading sequence of table 12 is used. Because several of the loads of table 12 are repeated, the user would select only unique loads as target loads. This would result in the loading specifications of table 13.

Table 10. Example of subgrade loading parameters.

Sequence	Maximum Load, N
1	49.4
2	98.8
3	148.2
4	197.1
5	246.5
6	49.4
7	98.8
8	148.2
9	197.1
10	246.5
11	49.4
12	98.8
13	148.2
14	197.1
15	246.5

Table 11. Example of subgrade dynamic loading parameters.

Seating Load $P_{contact}$ (N)	Final Load Level P_{max} (N)	Cyclic Load (N)	Load Pulse (s)	Rest Period (s)	Cycles	Data Acquisition Rate (points/s)
4.9	49.4	44.5	0.1	0.9	100	500
9.9	98.8	88.9				
14.8	148.2	133.4				
19.7	197.1	177.4				
24.6	246.5	221.9				

Table 12. Example base/subbase loading parameters.

Sequence	Maximum Load, kN
1	0.34
2	0.68
3	1.02
4	0.56
5	1.13
6	1.70
7	1.13
8	2.26
9	3.40
10	1.13
11	1.70
12	3.40
13	1.70
14	2.27
15	4.53

Table 13. Example of subgrade dynamic loading parameters.

Seating Load $P_{contact}$ (kN)	Final Load Level P_{max} (kN)	Cyclic Load (kN)	Load Pulse (s)	Rest Period (s)	Cycles	Data Acquisition Rate (points/s)
0.034	0.338	0.304	0.1	0.9	100	500
0.057	0.565	0.508				
0.068	0.681	0.613				
0.102	1.019	0.917				
0.113	1.135	0.022				
0.170	1.700	1.530				
0.227	2.265	2.038				
0.340	3.395	3.055				
0.454	4.530	4.076				

For LTPP Protocol P07 resilient modulus testing, the loading depends upon the test sample; therefore, no pre-set loading parameters are defined. In this case, the total capacity of the load cell is determined, and nine loading parameters are defined equally spaced throughout the loading range. Because this is a dynamic test, the user should not test to the maximum capacity of the load cell/proving ring and the maximum load achieved should be around 90 percent of the load cell capacity. This will minimize the chance that an over-range event can occur. For example, if a 13.3 kN load cell is being used, the loading parameters shown in table 14 would be used.

5. Record data at a similar interval as required for the test procedure. Record time, load, and all deformations using the DAS.

6. Collect data for the last five load cycles at each load level.

Table 14. Example of asphalt concrete dynamic testing parameters.

Seating Load $P_{contact}$ (kN)	Final Load Level P_{max} (kN)	Cyclic Load (kN)	Load Pulse (s)	Rest Period (s)	Cycles	Data Acquisition Rate (points/s)
0.134	1.34	1.21	0.1	0.9	100	500
0.267	2.67	2.40				
0.401	4.00	3.60				
0.534	5.34	4.81				
0.668	6.68	6.01				
0.801	7.47	6.67				
0.935	9.35	8.42				
1.068	10.68	9.61				
1.202	12.02	10.82				

Data Analysis

Data analysis for this experiment is a very involved process. The user first analyzes the “raw” data to determine acceptability. Raw data are the load and deformation traces recorded by the system. The raw data are reduced to determine the overall acceptability of the system to perform these tests. The following analyses are discussed in more detail in following sections:

- Raw data analyses:
  - Load response.
  - Deformation response.
  - Load versus deformation time lag.

- Calculated data analyses:
  - Load value (maximum, contact, cyclic).
  - Deformation response.
  - Load versus deformation comparison.

Raw Data Analysis

Load

Plot the load values (readings from the load cell) versus time for a representative cycle(s) at each load. Superimpose an ideal load over this typical load pulse. Compare the actual load pulse with the ideal load pulse. For resilient modulus testing, this criterion is as follows:

Construct a theoretical ideal loading pulse for each load sequence from the maximum load and the 0.1 s loading duration specified in the LTPP P07 or P46 protocol. The peak theoretical load is matched in time with the peak recorded load of a given sequence. An acceptance tolerance band is then created around the theoretical load pulse, which is used to flag suspect data falling outside of the band. The development of the minimum and maximum values of the acceptance band are based on the following considerations:

- *Acceptance tolerance range*. A ±10 percent variation from the theoretical load is judged to be acceptable. In combination with the other checks, this range is effective at higher load levels and those near the peak. However, at low load levels this range may create an unreasonably tight tolerance.
- *Servovalve response time*. A ±0.006 s time shift in load from the theoretical load pulse is reasonable to allow for the physical limitations on the response time of the servohydraulic system. This will provide a reasonable tolerance band that will be effective at intermediate loading and unloading portions of the load cycle.
- *Resolution of the electronic load cell*. The resolution of the electronic load cell generally used in resilient modulus testing for these materials is ±4.4 N. Therefore, a range of twice the minimum resolution of the load cell is used (i.e., ±8.8 N). This range provides acceptable tolerances for testing at low load levels.
- *Logic*. The minimum load allowed is 0 N.

For each time step in the load curve, the tolerance range from all of these components is computed. The maximum value of these three components is selected as the upper tolerance limit, while the minimum value is used for the lower limit at each time step. Over the entire range of loading, five points are allowed to be out of tolerance before the load cycle is considered failed. If pulse duration and shape are not improved within a reasonable number of iterations, problems such as friction in the servoram piston, inadequate servovalve size, problems with software controlling the load, etc., should be investigated.

Also, review the time history data for each load pulse. Ensure that one load cycle consists of 500 points. If the load cycle does not have 500 points, the system fails this check. The experiment should be repeated using a data acquisition rate of 500 points per second.

Deformation

Plot the deformation values (readings from the deformation device) versus time for a representative cycle(s) at each load level. Superimpose an ideal deformation response over this typical deformation pulse. Compare the actual deformation pulse with the ideal deformation pulse. For resilient modulus testing, this criterion is as follows:

Construct a theoretical ideal deformation pulse for each load sequence from the maximum deformation and the 0.1 s loading duration specified in the protocol. The peak theoretical deformation is matched in time with the peak recorded deformation of a given sequence.

An acceptance tolerance band is then created around the theoretical deformation pulse, which is used to flag suspect data falling outside of the band. The development of the minimum and maximum values of the acceptance band are based on the following considerations:

- *Acceptable tolerance range*. A ±10 percent variation from the theoretical deformation is judged to be acceptable. The theoretical deformation is established by finding the maximum deformation and applying the following checks to it using the equation for a haversine waveform. It should be noted that for a real specimen, the deformation response is specimen specific and may not follow a haversine waveform. However, because it is assumed we are using a proving ring, the deformation response should be very close to a haversine waveform.

- *Logic*. The minimum deformation allowed is 0.

For each step in the deformation curve, the tolerance range from these components is computed based upon the maximum deformation point for the cycle. The maximum value of these checks is selected as the upper tolerance; the minimum value is selected as the lower limit for each time step. The actual deformation is then compared with the tolerances at each time step to determine conformance. Over the entire range of loading, 5 points are allowed to be out of tolerance before the deformation cycle is considered failed. If the system fails this check, then problems with system response and deformation response should be evaluated in a similar fashion as if the load pulse failed the check.

Perform this test for all deformation devices.

Load versus Deformation Time Lag

Determine the maximum load point for a given cycle and extract the corresponding time stamp. Determine the maximum deformation for the same cycle and extract the corresponding time stamp. Subtract the maximum deformation point time stamp from the maximum load point time stamp. This value should be positive and less than 0.008 s.

If the time delay is greater than 0.008 s, most likely there is a problem with the system electronics or software. If the time delay is negative, it means that the maximum deformation is occurring before the maximum load, a practical impossibility. This again would lead to the suspicion that there is a problem with the system electronics or software.

Perform this analysis for each deformation device used for this experiment.

Calculated Data Analysis

Load Value

For a given load cycle, extract the maximum load value. Average the load from point 125 to 500 (last 75 percent of the cycle). This is the contact load. Subtract the maximum value from this minimum value.

The maximum and cyclic values must be within 5 percent of the target values. The contact load must be within 10 percent of the target value.

If the system fails this check, the operator should try to adjust the machine settings to achieve the proper load. Also, the load cell should be checked to ensure that it is compatible with the desired loading regime. For example, a load cell with a very large capacity should generally not be used for a test that requires a very low load unless the load cell can be scaled to an appropriate range.

Deformation Response

This test is only conducted if more than one deformation device is mounted on the system. All deformation devices used for this comparison should be mounted in approximately the same location in the system, such as on top of the triaxial chamber or on either side of the test specimen. In this analysis, the balance of the deformation devices is evaluated. If deformation devices are mounted in approximately the same location on the sample or in the system, it can be reasonably expected that the devices would experience similar deformation measurements.

For a given deformation cycle, extract the maximum deformation value. Average the deformation from point 125 to 500 (last 75 percent of the cycle). This is the minimum deformation. Subtract the maximum value from this minimum value. Perform this analysis for each deformation transducer.

The collected deformation readings will be checked to ensure that acceptable vertical deformation ratios are being measured. 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. This analysis should be performed for each deformation device in order. If more than one deformation device is used, deformation transducer 1 should be used as the reference deformation value.

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 deformation holders should be investigated and alleviated.

Load versus Deformation Comparison

Plot the mean applied load versus mean applied deformation for each load level. Using the static load/deformation calibration equation (usually supplied with the proving ring), it is possible to determine the ring deformation for a given load. Plot the theoretical load versus displacement line using the ring calibration equation. Calculate and plot +5 percent and -5 percent of the theoretical load versus deformation. Plot the actual average load versus average deformation results derived from the deformation device(s). The deformation device readings should be within the ±5 percent lines at all load levels. Calculate the R^2 of the best fit line connecting the actual data points. This value should be greater than 0.99.

Acceptance Criteria

For this experiment, the user is looking for the following eight criteria:

1. Generated haversine waveform is close to ideal haversine waveform.
2. Load and deformation consists of 500 points per cycle.
3. Generated deformation output is close to ideal haversine waveform.
4. Time lag between load peak and deformation peak is less than 0.008 s and deformation is occurring after load.
5. Maximum and cyclic loads within 5 percent of target; contact load within 10 percent of target.
6. Deformation devices measuring within 10 percent of each other (only used for certain test configurations).
7. Mean deformation values versus mean applied load within ±5 percent lines.
8. The R^2 of the best fit line should be greater than 0.99.

Discussion

If, using the acceptance criteria, the system fails this test, repeat the procedure. If the system fails the second test, the system fails the check. If the system passes the second test, then a third test should be run to determine acceptance or failure. The apparatus should be disassembled and re-assembled between each test.

- If the system fails the loading or deformation check, the operator should adjust the machine settings to obtain a better waveform. If this does not correct the problem, the manufacturer should be contacted to assist in problem resolution.
- If the system fails the time lag check, the system electronics and software should be evaluated to determine the cause of the time delay. Also, check the system for friction in the triaxial piston, misalignment, loose connections, loose deformation devices, etc.

Example

A laboratory is interested in performing the dynamic verification for LTPP Protocol P46, type 2 testing. The specimen diameter is 71 mm and the deformation devices are mounted on the top of the triaxial chamber. A 445 N load cell are used.

To perform this test, the same 445 N proving ring as used in the static verification is procured to match the capacity of the load cell. An LVDT deformation device is mounted in the proving ring to measure deformation.

Using the table presented previously for P46 type 2 testing (table 7), the loading is established. The test is conducted and raw load and deformation data are obtained from the system.

The first step in the analysis procedure is to analyze the data file for the last five load cycles at each load level. For each cycle, the user would plot the loading curve and visually examine the output. One cycle should be exactly 500 points of data. Therefore, for 5 cycles, the data file should contain 2,500 points.

Next the user would develop the load acceptance bands described previously. An example of the outcome of this analysis is shown in figure 6. A similar analysis should be conducted for each load cycle at each load level.

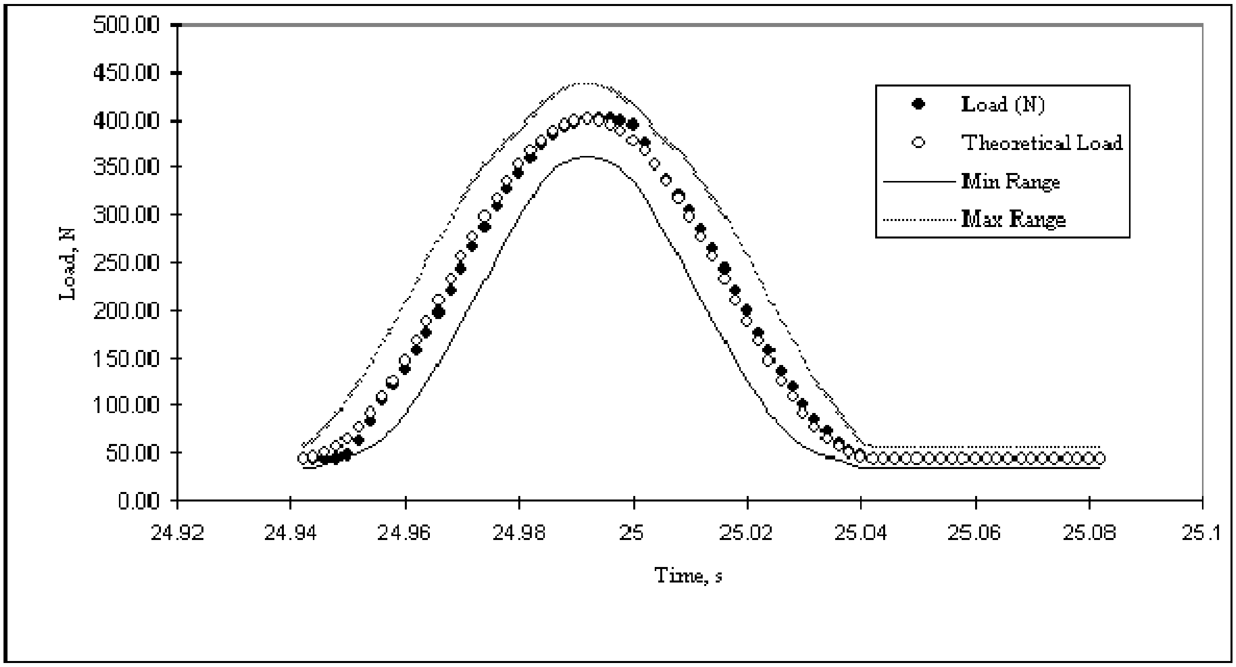

Figure 6. Graph. Example of load pulse analysis.

The user would then develop the deformation acceptance bands described previously. An example of the outcome of this analysis is shown in figure 7. A similar analysis should be conducted for each deformation trace at each load level and for each deformation device.

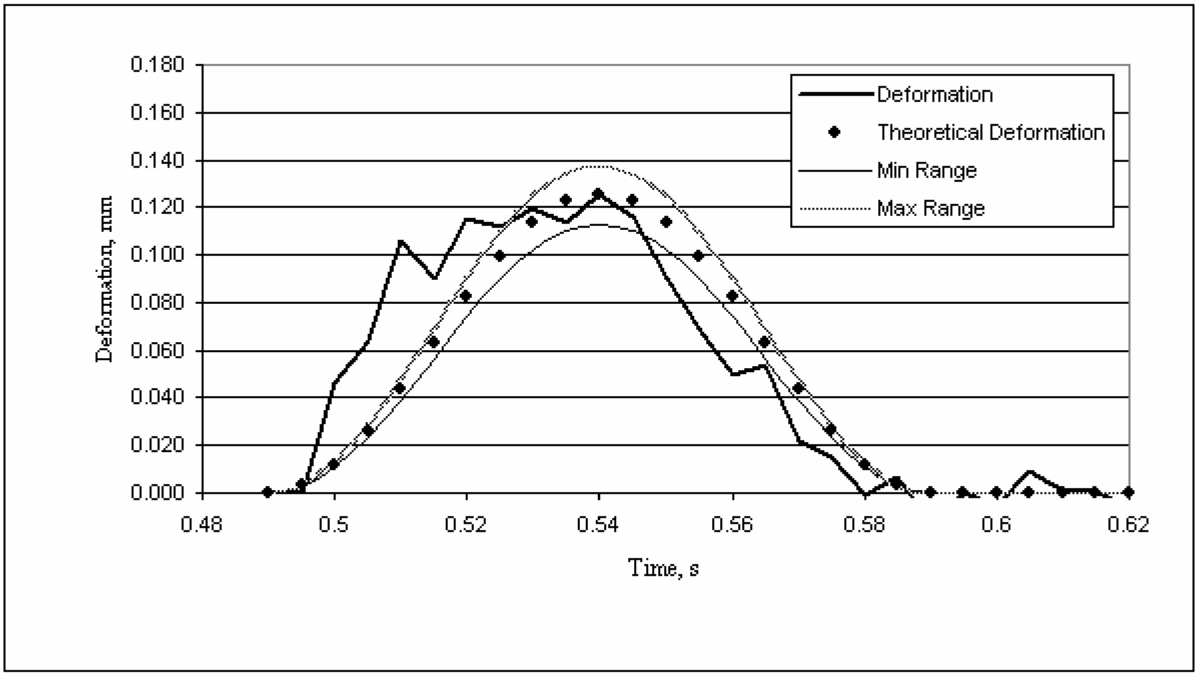

Figure 7. Graph. Example of deformation response analysis.

At this point in the analysis, the user should review the results. If the load and deformation pulses do not pass the criteria, a decision must be made as to the validity of proceeding further. It is recommended that if the system does not pass these checks, then adjustments should be made to the system to rectify the problems encountered.

The user then conducts the load versus deformation time lag test. To perform this test, the user selects the maximum load point for a given load cycle. The time at this point is read by the user. The user then selects the maximum deformation value for the same load cycle and reads the time that this event occurs. Subtract the maximum load time from the maximum deformation time. Compare it to the acceptance criteria. This function can be performed manually using the raw data, or the data can be imported into a spreadsheet and the process conducted using a simple macro. In this analysis, the user scales the spreadsheet so that the peaks of the load and deformation are clear. The user then manually picks the points and performs the analysis. In this case, the maximum load occurs at time, t = 1.000 s; the maximum deformation occurs at t = 1.004s. Performing a simple calculation, the user determines that the deformation peak is occurring 0.004 s after the load peak. Also, because the number is positive, it is obvious that the peak deformation is occurring after the peak load (this would also be obvious from the graph). These values are well within the acceptance criteria. This check is subsequently conducted for all load/deformation combinations.

A summary of the results for this experiment is shown in table 15.

Next, the user analyzes the load results to determine the maximum, contact, and cyclic loads. Table 16 contains the results of this analysis.

As can be seen from this analysis, the maximum and cyclic loads all meet the 5 percent criterion. The contact loads, on the other hand, are out of tolerance by a substantial margin. This is actually a common occurrence at the lower contact loads due to the system's inability to control to a very tight low load. In this case, the operator should adjust the settings to attempt to make the system respond at the lower loads.

To perform the deformation analysis, the maximum, contact, and cyclic deformations are calculated in a similar manner as the load. These values will be used in a subsequent analysis as well. Perform this calculation for all deformation cycles. For each load and deformation cycle, the user calculates the balance of the deformation devices per the procedure. For this example, the following results are contained in table 17. Note in the table that the deformations for all 5 cycles are averaged prior to performing the comparison.

In this example, the deformation devices appear to be well balanced with respect to each other.

Table 15. Example of load versus deformation time delay results.

Load Sequence	Cycle	Load versus LVDT 1 Time Delay, s	Load versus LVDT 2 Time Delay, s
1	1	0.004	0.006
1	2	0.004	0.006
1	3	0.006	0.008
1	4	0.006	0.006
1	5	0.006	0.006
2	1	0.004	0.006
2	2	0.004	0.006
2	3	0.006	0.008
2	4	0.006	0.006
2	5	0.006	0.006
3	1	0.004	0.006
3	2	0.004	0.006
3	3	0.006	0.008
3	4	0.006	0.006
3	5	0.006	0.006
4	1	0.004	0.006
4	2	0.004	0.006
4	3	0.006	0.008
4	4	0.006	0.006
4	5	0.006	0.006
5	1	0.004	0.006
5	2	0.004	0.006
5	3	0.006	0.008
5	4	0.006	0.006
5	5	0.006	0.006

Table 16. Example of summary dynamic loading results.

Sequence	Target Max Load Level (N)	Actual Max Load (N)	% Difference	Target Contact Load (N)	Actual Contact Load (N)	% Difference	Target Cyclic Load (N)	Actual Cyclic Load (N)	% Difference
1	49.4	49.0	0.9	4.9	6.2	-27.3	42.7	42.72	0.0
2	98.8	97.9	0.9	9.8	12.5	-13.6	89.0	86.80	2.5
3	148.2	153.5	-3.6	14.7	16.9	-12.2	133.5	136.60	-2.3
4	197.1	199.3	-1.1	19.1	20.0	-4.7	178.0	179.30	-0.8
5	246.5	246.5	0.0	24.0	24.0	0.0	222.5	222.50	0.0

Table 17. Example of deformation balance check results.

Load Sequence	Average Cyclic Deformation 1, mm	Average Cyclic Deformation 2, mm	Balance
1	0.0734	0.0812	1.10
2	0.1470	0.1575	1.07
3	0.2184	0.2337	1.07
4	0.2946	0.3150	1.07
5	0.3708	0.4013	1.08

The final check of the results of this experiment is the load versus deformation check. For this check, the proving ring calibration equation is needed and is given as follows:

$$\text{Deformation} = \text{Load x } 0.000256 \qquad (1)$$

Using this equation, and the cyclic loads calculated from the previous analysis, the theoretical deformation response shown in table 18 is calculated.

Table 18. Example of dynamic response acceptance results.

Average Load, N	Theoretical Deformation, mm	+5 Percent	-5 Percent	Actual Average Deformation, mm
49.0	0.071	0.076	0.069	0.079
97.9	0.142	0.150	0.137	0.152
153.5	0.213	0.226	0.203	0.226
199.4	0.287	0.300	0.272	0.305
246.5	0.358	0.376	0.340	0.386

Using these values, a graph such as that shown in figure 8 can be generated to determine the acceptability of the load versus deformation curve. By evaluating these results, it can be determined that the outside deformation transducers are measuring a greater deformation than allowed. In this case, the entire system should be investigated to determine the cause for the extraneous deformations. Also, one can determine that the internal LVDT is measuring deformations within the ±5 percent criterion. This is another indication that the system is performing as expected; however, there is an extraneous deformation occurring between the proving ring and the top of the triaxial cell. This example would fail the acceptance criteria, and a subsequent investigation would need to be conducted to determine the cause of the problem.

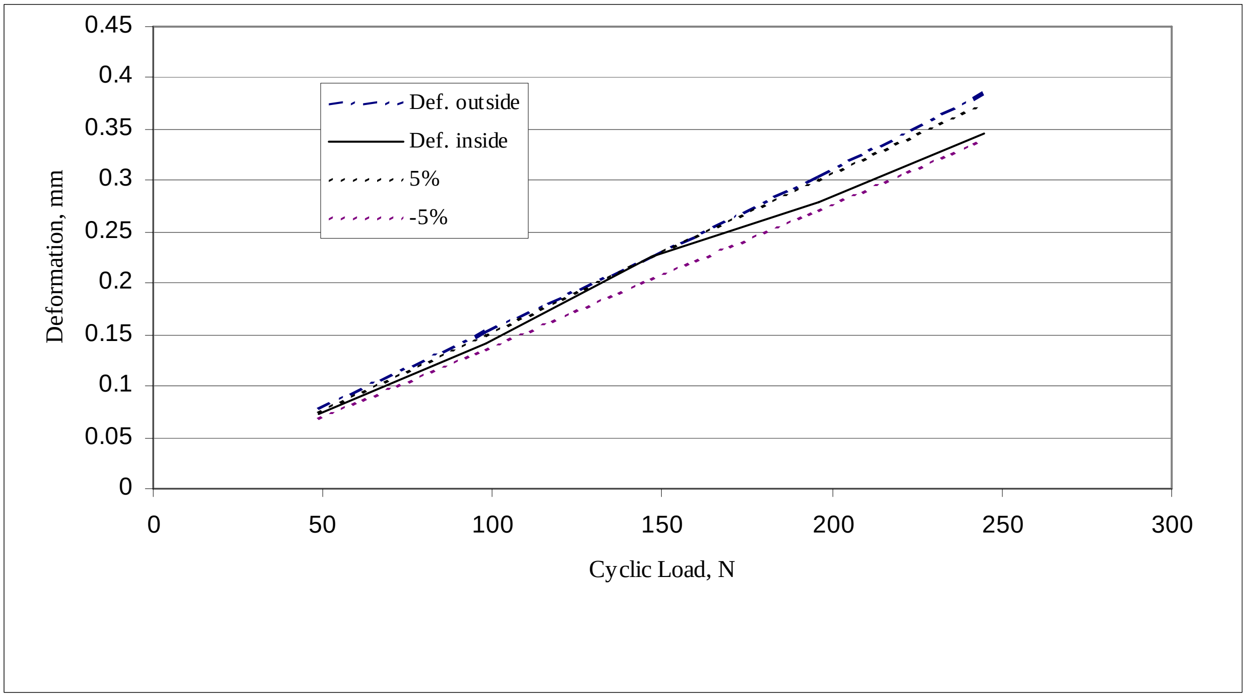

Figure 8. Graph. Sample results of dynamic haversine check, 445 N load cell.

SYSTEM DYNAMIC RESPONSE CHECK

Background

To 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, a series of frequency sweep sinusoidal dynamic loading experiments is conducted. To perform this test, cyclic load and deformation readings are acquired from the DAS using the load cell and the deformation device mounted on the proving ring. The deformation can also be obtained from deformation devices located elsewhere on the system, such as on the top of the triaxial cell.

The purpose of this test is to ascertain the time delay between the load and deformation device channel(s) and to check for attenuation of the load and deformation values over a range of loading frequencies. This check not only re-verifies the electronics checks, but it also identifies friction in the system, misalignment, and overall system function. This experiment cannot take the place of the electronics checks, as it does not fully characterize the electronics system. However, it can be used as a rough check of the system electronics. Caution is advised if this process is used to check the electronics of the system; other causal factors such as friction and misalignment can cause the results to fail this check. Therefore, a more indepth evaluation would have to be undertaken to determine the cause of failure than if the electronics procedure and the system dynamic response check were run independently.

Dynamic System Configuration

All test systems should be turned on and the machine should be warmed up per the manufacturer’s specifications.

Approach

Position the proving ring in the test system 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 test apparatus (e.g., triaxial cell), 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 or otherwise rigidly attached to the test apparatus to perform the test. Furthermore, the bottom of the test apparatus must be bolted down (or tightly fastened) to the bottom loading platen of the load frame.[7] A similar configuration as used for the load versus deformation response check can be used for this procedure.

Place the deformation devices in their appropriate positions. Generally, a deformation device is mounted inside the proving ring as in previous test procedures. If outside deformation devices are used, then it is not necessary to use a deformation device mounted in the proving ring unless the user prefers that.

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[7] Before 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. 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.

To conduct this test properly, the deformation device used should be connected to the appropriate deformation data channel of the system. This test is conducted using the same proving ring as used for previous checks. Using the system controls, apply 100 cycles of a sinusoidal dynamic load with a peak-to-peak amplitude between 25 percent and 75 percent of proving ring capacity and a mean compression load of 50 percent of proving ring capacity at 1 Hz, 5 Hz, and 10 Hz frequencies. Record load and deformation measurements for the last five cycles at: 200 data points per period at 1 Hz (200 points/s) and 200 data points per period at 5 Hz (1,000 points/s). At 10 Hz, collect 200 data points per period (2,000 points/s) if possible; otherwise collect 100 data points per period (1,000 points/s).

Repeat the procedure so that all deformation device channels are represented.

Data Analysis

Calculate the phase angle between load and displacement using the digitized data (a sample method to calculate the phase angle is contained in appendix B of this document). The phase angle measurement should remain consistent for all 5 periods at a given frequency (within ±0.5 degree). The maximum average 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). Then the dynamic experiments should be repeated.

The 2.8-degree 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 uncertainty.

Acceptance Criteria

- The phase angle measurement should remain consistent for all five periods at a given frequency (within ±0.5 degree).

- The phase angle measurement should be less than 2.8 degrees.

Discussion

If, using the acceptance criteria, the system fails this test, repeat the procedure. If the system fails the second test, the system fails the check. If the system passes the second test, then a third test should be run to determine acceptance or failure. The apparatus should be disassembled and re-assembled between each test.

If the system fails this check, the system electronics and software should be evaluated to determine the cause of the time delay. Also, check the system for such problems as friction in the triaxial piston, misalignment, loose connections, and loose deformation devices.

Example

Using a similar example as before, a 445 N proving ring is used to conduct the experiment. Therefore, the sinusoidal loading pattern is determined by the following:

- 25 percent of capacity = 111 N = minimum peak load.
- 50 percent of capacity = 223 N = mean compression load.
- 75 percent of capacity = 334 N = maximum peak load.

The loading waveform would be similar to that shown in figure 9.

The test is conducted and the raw load and deformation data are obtained from the system. In this example, two deformation devices are used on the outside of the triaxial chamber. Therefore the test is performed twice, once for each deformation device channel.

The results are analyzed using the process described in appendix B. Table 19 contains the results from this example test procedure.

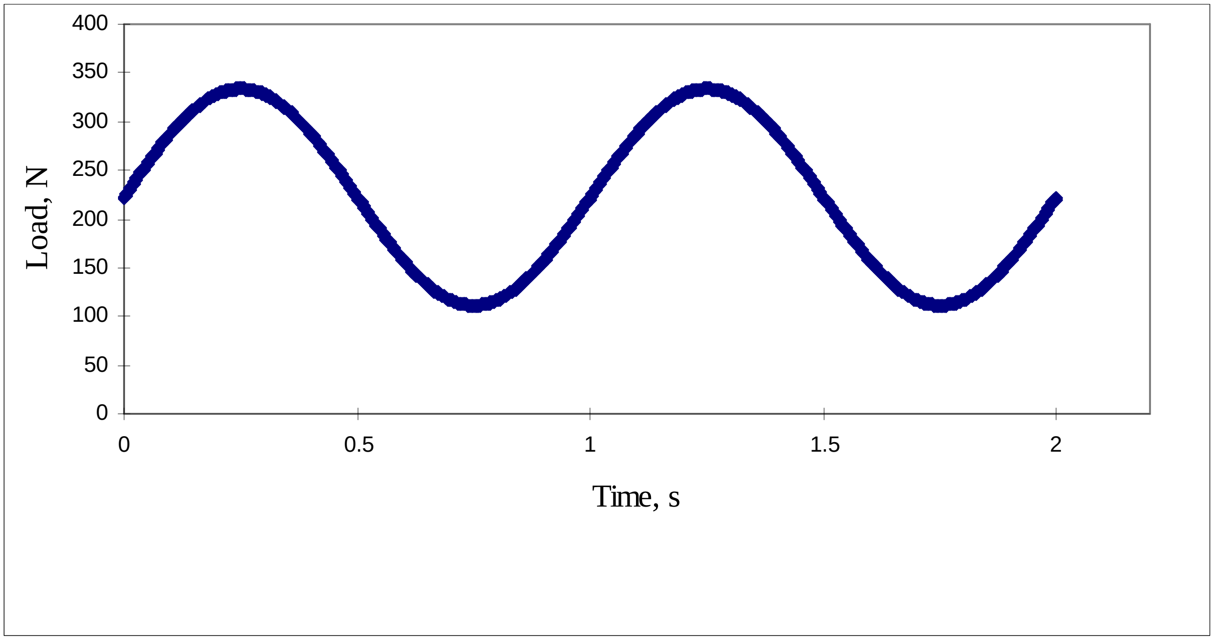

Figure 9. Graph. Example of system dynamic response check of 445 N proving ring, 1 Hz.

Table 19. Sample phase angle test results.

Frequency	LVDT Channel	Test	Phase Angle, degrees
1 Hz	1	1	-1.9
		2	-1.9
	2	1	-2.8
		2	-2.7
5 Hz	1	1	-10.1
		2	-10.1
	2	1	-10.6
		2	-10.6
10 Hz	1	1	-20.3
		2	-20.3
	2	1	-21.0
		2	-21.0

As can be seen from these results, the device passed the check at 1 Hz but failed the checks at 5 and 10 Hz (acceptance criteria = 2.8 degrees). As shown, the test was repeated a second time to ensure that the results were accurate. In this example, the problem was caused by faulty system electronics. The filter settings were of a design that imparted a large time delay in the deformation channel. In this example, after a complete and thorough trouble-shooting session, a complete electronic system upgrade was recommended.

TRIAXIAL PRESSURE CHAMBER

Background

Each triaxial pressure chamber to be used for testing should be able to maintain pressure in accordance with testing parameters. It is also very important that test results report the actual pressure used for the test. In several instances, it has been found that users report the nominal pressure, or the pressure that was programmed for the test. For some test systems, the pressure used for the test may vary from that specified. In this case, use of the nominal pressure can cause errors in the test results when compared with other test results.

To perform this test procedure, a separate NIST traceable pressure gauge or transducer is necessary to perform an independent check of the system. Also, it is very important that the cell pressure be zero before applying the system command to pressurize the chamber.

The pressures used for this experiment should be similar to those used for the actual test procedure. This experiment can be conducted during proficiency testing as well if that is deemed more efficient than running the experiment independently.

Dynamic System Configuration

All test systems should be turned on and the machine should be warmed up per the manufacturer's specifications.

Approach

The pressure should remain constant for a period of 5 minutes 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.[8] 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 and hold for 5 minutes. The pressure must be the same as that used for the test procedure. For a type 1 triaxial cell, pressures should be maintained at 5 levels (21, 34, 69, 103, and 138 kPa). For a type 2 triaxial cell, pressures should be maintained at 3 levels (14, 28, and 41 kPa).

3. Determine the time required for the system to achieve the target pressure. This is defined as the time it takes for the system to achieve the target pressure within 3.4 kPa and remain within 3.4 kPa of the target pressure (if the system cannot control the pressure to 3.4 kPa psi of target, it will more than likely fail the check).

4. Check the pressure readings for both the system controls and the pressure gauge every minute for the 5-minute observation period.

Data Analysis

- Average the readings for each pressure level.

- Determine the percent difference between the system pressure transducer and the target pressure.

- Determine the percent difference between the NIST traceable pressure device and the target pressure.

- Determine the percent difference between the system pressure transducer and the NIST traceable pressure device.

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[8] 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 is sufficient to monitor the pressure on the primary pressure outlet using a second (nonsystem) calibrated pressure gauge. Repeat the experiment using the system pressure gauge and compare the results with the results from the second (nonsystem) calibrated pressure gauge (refer to the acceptance criteria above).

Acceptance Criteria

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

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

- All system and gauge readings should be within ±2.5 percent of each other for the duration of the test procedure.

- The target pressure must be achieved within 30 s.

Discussion

This check is critically important to the achievement of repeatable, accurate test values. The seals used in the triaxial chamber should be clean and free of grit, dirt, etc. Due to the dusty conditions in a soils laboratory, it is very important that foreign matter on the triaxial seals be kept to a minimum.

As with other portions of a servohydraulic system, selection of a system pressure system is extremely important. If a pressure transducer is used, it is very important that the transducer be matched to the test system as closely as possible. It may not be advisable to use a 1034 kPa pressure transducer to perform LTPP Protocol P46 testing unless it can be scaled to a suitable range without loss of accuracy. Contact the system manufacturer for assistance in selecting a suitable pressure transducer for use in a particular test procedure.

If, using the acceptance criteria, the system fails this test, repeat the procedure. If the system fails the second test, the system fails the check. If the system passes the second test, then a third test should be run to determine acceptance or failure. The apparatus should be disassembled and reassembled between each test.

If problems are found with the system pressure, the manufacturer should be contacted to assist in determining probable causes and efficient solutions.

Example

A user is interested in determining the ability of his or her triaxial cells to perform LTPP Protocol P46 type 1 and type 2 testing. Therefore, the user reviews the test procedure and finds that 8 different pressure settings are used for the procedure: 13.8, 20.7, 27.6, 34.5, 41.3, 68.9, 103.4, and 137.8 kPa. The user conducts the test procedure using these pressure settings and an independent NIST traceable pressure gauge. Table 20 contains the results.

Table 20. Example of pressure test results.

Target Pressure, kPa	Time to Achieve Target, s	Average System Reading, kPa	Average Reference Reading, kPa	System to Target, %	Reference to Target, %	System to Reference, %
13.8	25	13.8	14.5	0.0	5.0	4.8
20.7	35	20.7	21.3	0.0	3.3	3.2
27.6	35	26.9	28.2	2.5	2.5	4.9
34.5	29	33.8	35.1	2.0	2.0	3.9
41.3	5	40.7	42.0	1.7	1.7	3.3
68.9	5	68.2	69.6	1.0	1.0	2.0
103.4	5	102.7	104.0	0.7	0.7	1.3
137.8	5	136.4	138.4	1.0	0.5	1.5

Shaded cells: Out-of-specification or otherwise undesirable results.

In reviewing these results, it can be seen that the system was slow to respond to the command to pressurize to 20.7 and 27.6 kPa, respectively. In this case, the solution was to scale the pressure transducer to a lower pressure range—from 103.4 kPa full range to 172.2 kPa full range. This allowed the system to achieve more stable pressure readings. The system to target readings (comparison of the system monitored pressure reading versus the target pressure) were all within specifications. This is an indication that the system is achieving pressure readings very close to those specified by the controller. The reference to target values (comparison of secondary NIST pressure cell to target reading) were out of specification for 13.8 and 20.7 kPa, respectively. A result like this usually means that the calibration of the pressure transducer should be checked because, although the system is coming very close to the target pressures, it is still not reading close to the “true” pressure. Finally, the system to reference (comparison of pressure transducer to secondary NIST traceable gauge) check illustrates that the system gauge is not measuring pressures very close to the secondary NIST traceable gauge. This is usually the result of poor calibration of the system pressure device.

In this example, several troubleshooting activities would be conducted as the results do not meet the acceptance tolerances for this procedure.

ENVIRONMENTAL CHAMBER

Background

Some test procedures, such as LTPP Protocol P07, utilize an environmental chamber to control the temperature of the test specimen. This experiment has been developed to ensure that the chamber can maintain temperature in accordance with testing parameters. In this test procedure, the temperature should remain constant for a period of 10 minutes for each temperature.

To perform this test procedure, a separate NIST traceable temperature measuring device is necessary. This gauge is used to perform an independent check of the system. The temperatures used for this procedure should be comparable to those used for the testing process. This experiment can be conducted during proficiency testing as well if it is deemed more efficient than running the experiment independently.

Dynamic System Configuration

All test systems should be turned on and the machine should be warmed up per the manufacturer's specifications.

Approach

Checking the environmental chamber should follow the steps listed below:

1. Position the temperature gauge sensor as close as possible to the center of the chamber.[9] Seal the chamber so that the temperature can be regulated.

2. Using the test system controls, bring to the prescribed temperature and hold for 10 minutes. For example, for LTPP Protocol P07 testing, the temperature should be maintained at three levels: 5, 25, and 40 °C.

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

Data Analysis

- Average the readings for each temperature level.

- Determine the percent difference between the system temperature reading and the target temperature.

- Determine the percent difference between the NIST traceable temperature device and the target temperature.

- Determine the percent difference between the system temperature transducer and the NIST traceable temperature device.

Acceptance Criteria

- All system temperature readings should be within ±0.5 °C of the target values for the duration of the test procedure.

- All NIST traceable device temperature readings should be within ±0.5 °C of the target values for the duration of the test procedure.

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[9] The temperature must be checked using an autonomous calibrated temperature gauge.

- All system and gauge readings should be within ±0.5 °C of each other for the duration of the test procedure.

Discussion

This check is critically important to the achievement of repeatable, accurate test values. As with other portions of a servohydraulic system, selection of a system temperature control system is extremely important. It is very important that the temperature control system be matched to the test system as closely as possible. Contact the system manufacturer for assistance in selecting a suitable temperature control system for use in a particular test procedure.

If, using the acceptance criteria, the system fails this test, repeat the procedure. If the system fails the second test, the system fails the check. If the system passes the second test, then a third test should be run to determine acceptance or failure.

If problems are found with temperature control, the manufacturer should be contacted to assist in determining probable cause(s) and efficient solutions.

Example

A user is interested in determining the ability to control the temperature to perform LTPP Protocol P07 testing. The user conducts the test procedure using the three temperature settings required for the test procedure and an independent temperature gauge. The results are contained in table 21.

The results show that the system was performing as expected. The difference between the target and the system readings were within specifications at all temperatures. In addition, the difference between the reference and target values was zero. This response is indicative of a well-calibrated, well-controlled test system.

Table 21. Example of environmental chamber test results.

Target Temp., °C	Average System Reading, °C	Average Reference Reading, °C	System to Target, °C	Reference to Target, °C	System to Reference, °C
5	4.7	4.7	0.3	0.3	0.0
25	25.0	25.0	0.0	0.0	0.0
40	40.0	40.0	0.0	0.0	0.0

V. PROFICIENCY PROCEDURE

BACKGROUND

To perform a complete analysis of a laboratory's ability to perform a particular test, all facets of the test process must be reviewed. A person with adequate experience in performing the test must be enlisted to do this review. The proficiency procedure brings together all of the experiments mentioned previously to ensure that accurate, repeatable test values are determined.

A large number of tests could be evaluated, but it is not practical to enumerate processes for each. The following section describes the general methodology to be used and provides three examples of screening criteria that could be used. Similar to previous sections of this document, the examples are based on LTPP Protocols P07 and P46. Similar procedures could be adopted for other test procedures as well.

Proficiency procedures should not be conducted until all mechanical and electrical system evaluation processes have been completed to the satisfaction of the evaluation team. Moreover, a well-written comprehensive test procedure must be available to document the test processes.

Several fundamental procedures should be evaluated during a proficiency testing review as follows:

- Material preparation.
- Test performance.
- Calculations.
- Data reporting.
- Data reasonableness.

The entire test procedure should be observed by personnel who are very familiar with the testing process. This should commence with sample preparation all the way through to data analysis and reporting. It should be noted that some acceptance criteria noted here are subjective, thus the necessity for a knowledgeable individual to perform this procedure.

Appendix A contains a checklist of items to look for in asphalt and soils/aggregate resilient modulus testing (figures 20 and 21).

DYNAMIC SYSTEM CONFIGURATION

All test systems should be turned on and the machine should be warmed up according to the manufacturer's specifications.

APPROACH

Material Preparation

Inspection personnel should review material preparation activities, whether they be sample compaction (soils and aggregate) or sawing the specimen to size (asphalt). (See checklists, figures 20 and 21 in appendix A). Sample preparation worksheets should be reviewed to determine whether all applicable information is complete and accurate.

All sample/specimen preparation activities should be conducted according to applicable test procedures.

Test Performance

The inspector should view a test procedure being performed and perform a review of laboratory conformance with the test procedures.

Some items of special note that should be evaluated are as follows:

- Load pulse reasonableness.
- Deformation response reasonableness.
- Load versus deformation time lag.
- Review of data-computation process.
- Conformance to test parameters.
- Deformation device variation.
- Deformation balance.
- Reasonableness of test results.

For a resilient modulus test, the following items should be analyzed.

Load Pulse Reasonableness

Plot the load values (readings from the load cell) versus time for a representative cycle(s) at each load. Superimpose an ideal load over this typical load pulse. Compare the actual load pulse with the ideal load pulse. For resilient modulus testing, the procedure is set forth in the following paragraphs.

Construct a theoretical ideal loading pulse for each load sequence from the maximum load and the 0.1 s loading duration specified in the resilient modulus protocol. The peak theoretical load is matched in time with the peak recorded load of a given sequence. An acceptance tolerance band is then created around the theoretical load pulse and used to flag suspect data falling outside of the band. The development of the minimum and maximum values of the acceptance band is based on the following considerations:

- *Acceptance tolerance range*. A ±10 percent variation from the theoretical load is judged to be acceptable. In combination with the other checks, this range is effective at higher load levels and those near the peak. However, at low load levels, this range may create an unreasonably tight tolerance.

- *Servovalve response time*. A ±0.006 s time shift in load from the theoretical load pulse is reasonable to allow for the physical limitations on the response time of the servohydraulic system. This will provide a reasonable tolerance band that will be effective at intermediate loading and unloading portions of the load cycle.

- *Resolution of the electronic load cell*. The resolution of the electronic load cell generally used in resilient modulus testing for these materials is ±4.5 N. Therefore, a range of twice the minimum resolution of the load cell is used, i.e., ±9 N. This range provides acceptable tolerances for testing at low load levels.

- *Logic*. The minimum load allowed is 0 N.

For each time step in the load curve, the tolerance range from all of these components is computed. The maximum value of these three components is selected as the upper tolerance limit, while the minimum value is used for the lower limit at each time step. Over the entire range of loading, 5 points are allowed to be out of tolerance before the load cycle is considered failed. If pulse duration and shape are not improved within a reasonable number of iterations, problems such as friction in the servoram piston, inadequate servovalve size, problems with software controlling the load, etc., should be investigated.

Also, review the time history data for each load pulse. Ensure that one load cycle consists of 500 points. If the load cycle does not have 500 points, the system fails this check. The experiment should be repeated using a data acquisition rate of 500 points/s.

For this experiment, the user is looking for the following acceptance criteria:

- Generated haversine waveform is within tolerance.

- Load consists of 500 points per cycle.

Deformation Response Reasonableness

Plot the deformation values (readings from the deformation device) versus time for a representative cycle(s) at each load level. Superimpose an ideal deformation response over this typical deformation pulse. Compare the actual deformation pulse with the ideal deformation pulse. For resilient modulus testing, the approach is set forth in the following paragraphs.

Construct a theoretical ideal deformation pulse for each load sequence from the maximum deformation and the 0.1 s loading duration specified in the protocol. The peak theoretical deformation is matched in time with the peak recorded deformation of a given sequence. An acceptance tolerance band is then created around the theoretical deformation pulse and used to flag suspect data falling outside of the band. The development of the minimum and maximum values of the acceptance band are based on the following considerations:

- *Acceptable tolerance range*. A ±10 percent variation from the theoretical deformation is judged to be acceptable. The theoretical deformation is established by finding the maximum deformation and applying the checks set forth in the next paragraph to it using the equation for a haversine waveform. It should be noted that for a real specimen, the deformation response is specimen specific and may not follow a haversine waveform exactly.

- *Logic*. The minimum deformation allowed is 0.

For each step in the deformation curve, the tolerance range from these components is computed based on the maximum deformation point for the cycle. The maximum value of these checks is selected as the upper tolerance and the minimum value of these checks is selected as the lower limit for each time step. The actual deformation is then compared with the tolerances at each time step to determine conformance. Over the entire range of loading, 5 points are allowed to be out of tolerance before the deformation cycle is considered failed. If the system fails this check, then problems with system response and deformation response should be evaluated in a similar fashion as if the load pulse failed the check.

Perform this test for all deformation devices.

For this experiment, the user is looking for the following acceptance criteria:

- Generated deformation output is within tolerance.

- Load consists of 500 points per cycle.

Load versus Deformation Time Lag

Determine the maximum load point for a given cycle and extract the corresponding time stamp. Determine the maximum deformation for the same cycle and extract the corresponding time stamp. Subtract the maximum deformation point time stamp from the maximum load point time stamp. This value should be positive.

If the time delay is negative, it means that the maximum deformation is occurring prior to the maximum load, a practical impossibility.

Perform this analysis for each deformation device used for this experiment.

For this experiment, the user is looking for the following acceptance criterion:

- Maximum deformation is occurring after the maximum load.

Review of Data Computation Process

In this analysis, the raw data are manually reduced and the results compared to the summary data developed by the computer software system. For resilient modulus testing, the following values should be analyzed as is practical:

- Cyclic load.
- Maximum load.
- Contact (seating) load.
- Deformation response (for all deformation devices).
- Confining pressure (soils and aggregate testing).
- Temperature (asphalt testing).
- Deviator stress (soils and aggregate testing).
- Strain (soils and aggregate testing).
- Resilient modulus.

These values should be derived from the raw data using procedures stated in each protocol.

Special note should be paid to testing under LTPP Protocol P07. The data analysis routines in this protocol are very complicated. The data analysis routines used by LTPP have previously been verified by hand and are considered stable, thus no further evaluation should be conducted.

For this experiment, the user is looking for the following acceptance criterion:

- All manually calculated values should be within 5 percent of the automated calculated values.

Conformance to Protocol

After the summary data have been verified by hand, adherence to the protocol parameters should be analyzed. This analysis is undertaken to determine how close the laboratory is to the protocol test requirements.

The following items should be checked as appropriate for a particular protocol:

- Target deviator stress (soils and aggregate testing).
- Target confining pressure (soils and aggregate testing).
- Target temperature (asphalt testing).

- Target deformation response (asphalt testing).

For this experiment, the user is looking for the following acceptance criterion:

- All test parameters should be within 5 percent of the test requirements.

Coefficient of Variation of the Deformation Devices

The deformation devices should be stable within a given loading regime and test cycle. In this analysis, the coefficient of variation of the deformation devices is calculated at a given test sequence. To perform this analysis, select the deformation values for all collected cycles of data at a given test sequence. Determine the coefficient of variation of the values. Repeat for all test sequences and deformation devices.

For this experiment, the user is looking for the following acceptance criterion:

- Vertical deformation readings from each of the sequences should be such as to ensure that the deformation devices are recording values with averages that (for the collected cycles) have a coefficient of variation less than 2.5 percent.

Deformation Balance

This test is only conducted if more than one deformation device is mounted on the system. All deformation devices used for this comparison should be mounted in approximately the same location in the system, such as on top of the triaxial chamber or on the test specimen. In this analysis, the balance of the deformation devices is evaluated. If deformation devices are mounted in approximately the same location on the sample or in the system, it can be reasonably expected that the devices would experience similar deformation measurements.

For a given deformation cycle, extract the cyclic deformation value from the summary (calculated) data. The collected deformation readings will be checked to ensure that acceptable vertical deformation ratios are being measured. Acceptable vertical deformation ratios (R_v) are defined as $R_v = Y_{max}/Y_{min} \leq 1.30$, where Y_{max} equals the larger of the two vertical deformations and Y_{min} equals the smaller of the two vertical deformations. This analysis should be performed for each deformation device in order. If more than one deformation device is used, deformation transducer 1 should be used as the reference deformation value.

For this experiment, the user is looking for the following acceptance criterion:

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

Reasonableness of Final Results

The final results of the test procedure should be reviewed for reasonableness. This check can only be conducted by personnel familiar with the test procedure.

For asphalt testing, the user should review the resilient modulus values versus temperature. The resilient modulus values should be decreasing versus increasing temperature.

For soils and aggregate testing, a basic check can be made of the resilient modulus versus confining pressure results. Generally, resilient modulus values at lower confining pressures should be lower than those at higher confining pressures (for a given deviatoric stress).

In this experiment, the bottom line is that the results should look reasonable to the user. Any anomalies should be investigated.

For this experiment, the user is looking for the following acceptance criterion:

- All final test results should be reasonable as determined by the review team.

In addition, the overall proficiency of the operator should be evaluated. Does the operator confidently run the test machine? Does the operator monitor progress of the test as it progresses? Is the operator capable of saving and retrieving test results?

All of these items should be evaluated in the most objective manner possible. For resilient modulus testing, the acceptance criteria used in other areas of this report can be used for proficiency testing. For instance, the pressure for a soil/aggregate test must be within ±2.5 percent of target. Example acceptance criteria are given in a later section of this document.

Calculations

Many test procedures have been automated to the point that data analysis and result preparation are handled automatically by computer. It is necessary, at least in the beginning of a testing program, to verify that the computer algorithm used to generate data is functioning properly and is indeed calculating correct values. Therefore, a manual analysis of the data results should be undertaken prior to accepting the data-calculation procedure. This can be a very time-consuming effort but is highly recommended to ensure accurate data.

To perform this procedure, the raw data should be broken down by hand and all test results calculated independently of the test system software or calculation algorithm. All values should generally match within 5 percent of those calculated using the test system calculation algorithm.

Data Reporting

The reviewer should inspect the data-collection forms to ensure the completeness and accuracy of the results. All sample numbering and naming should be checked for completeness and all calculated values should be checked for accuracy.

Data Reasonableness

As a final check, the resultant data should be checked for reasonableness. This should include reviewing the data patterns to ensure that suitable test results are obtained.

Data Analysis

All raw data (time, load, deformation, etc.) and summary data (calculated data) should be extracted from the test system. All of these data are used for the data analysis portion of this procedure.

Material Preparation

All calculations should be verified by hand to ensure accuracy.

DISCUSSION

If, using the acceptance criteria, the system fails this test, repeat the procedure. If the system fails the second test, the system fails the check. If the system passes the second test, then a third test should be run to determine acceptance or failure. The apparatus should be disassembled and re-assembled between each test.

Appendix A contains examples of a checklist for the LTPP resilient modulus procedures (figures 20 and 21).

A laboratory performing resilient modulus testing should consider participating in an inter-laboratory testing program to verify the calibration of the equipment and the procedures with respect to other laboratories. Also, it may be desirable to manufacture or procure a standard specimen to test on a continuing basis to detect gross changes in system performance over time.

EXAMPLE

The following is an example of the evaluation of results from a LTPP protocol P46 type 1 sample.

The proficiency check requires acceptable performance of the following major activities:

- Material preparation.
- Test performance.
- Calculations.
- Data reporting.
- Data reasonableness.

Material Preparation

The evaluation team observed the compaction procedures. In general, the compaction procedures observed were performed in accordance with the protocol. It was noted that the laboratory uses a standard compaction worksheet and all values on this worksheet, including specimen identification information, were verified for completeness and accuracy.

Test Performance

The individual load pulses and deformation pulses were reviewed for conformance with applicable standards. An example of the loading conformance check is shown in figure 10.

Table 22 contains a summary of the results of this analysis for load and deformation.

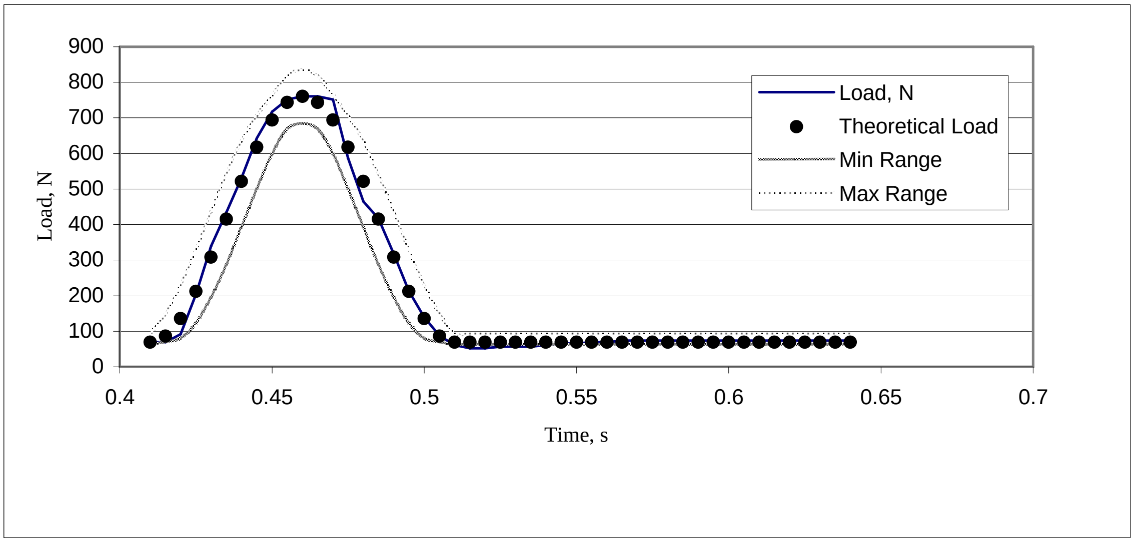

Figure 10. Graph. Example of load versus time check.

Table 22. Sample results of load pulse and deformation response analysis.

Sequence	Load Pulse	Deformation Pulse
1	Fail	Fail
2	Pass	Fail
3	Pass	Fail
4	Pass	Fail
5	Pass	Fail
6	Pass	Fail
7	Pass	Fail
8	Pass	Fail
9	Pass	Fail
10	Pass	Fail
11	Pass	Fail

Table 22. Sample results of load pulse and deformation response analysis—*Continued*

Sequence	Load Pulse	Deformation Pulse
12	Pass	Fail
13	Pass	Fail
14	Pass	Fail
15	Pass	Fail

In summary, the load pulses appear reasonable. It will be noticed that lower and upper acceptance curves are shown on the loading figures. These curves are based on the same rationale as presented previously in this document. For load pulses that fail the check, the load pulse was outside of the acceptance bands.

The LVDT plots were also reviewed for reasonableness. Deformations were plotted versus the acceptance criteria; an example is shown in figure 11.

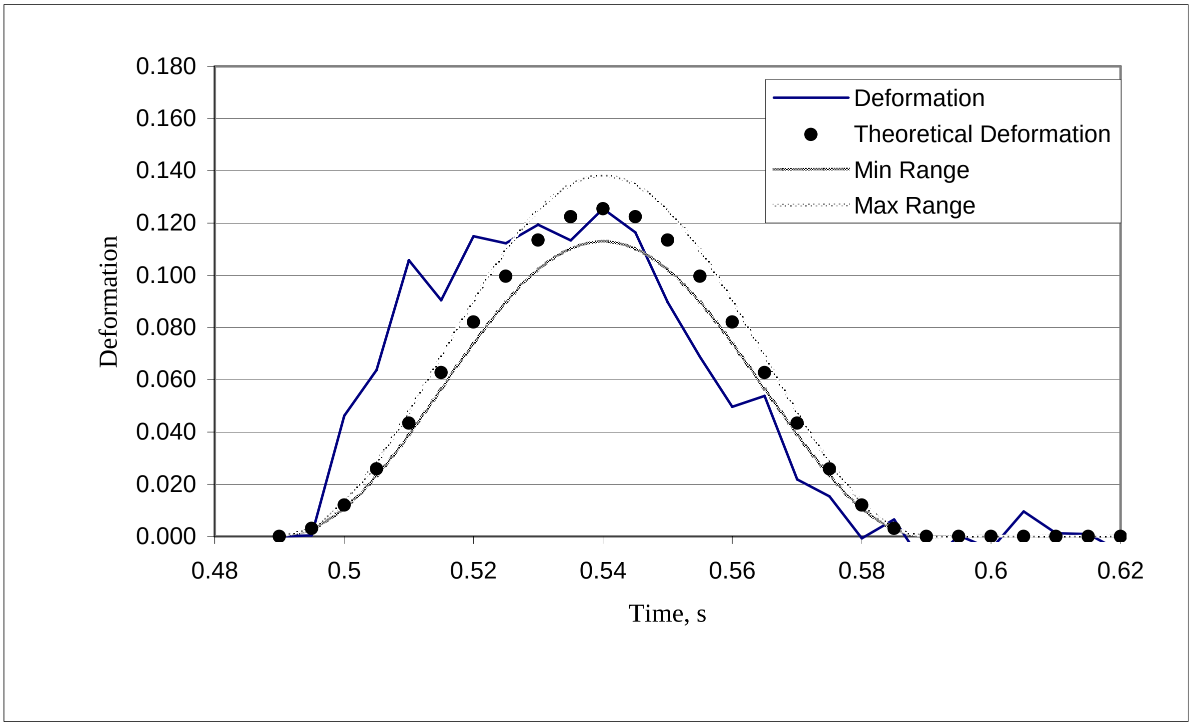

Figure 11. Graph. Example of deformation response analysis, type 1.

Most deformation curves were fairly flat at the maximum deformation point. This may be a case of the LVDT reaching its maximum stroke during operation or sticking during travel. All deformations fail the acceptance criteria rather badly; this phenomenon should be investigated more completely.

Next, a thorough evaluation of the data-computation process was undertaken. In this exercise, the raw data are manually reduced (per P46 specifications) to yield deformation and load values. These values are then used to calculate axial stresses, strains, and ultimately resilient modulus. All data for the resilient modulus test were obtained and independently analyzed. Table 23 contains the result of this comparison. In this table, all values are expressed as percent differences between calculated values and the independent review conducted by the evaluation team. As can be seen, all values showed very good correlation, indicating that the laboratory's analysis algorithm is calculating values per the procedure.

Table 23. Sample results of calculation verification.

Sequence	Cyclic Load	Confining Pressure	LVDT 1	LVDT 2	LVDT 3	Deviator Stress	Bulk Stress	Strain	Resilient Modulus
1	0.1	0.9	0.1	0.1	0.1	0.1	0.1	0.0	0.1
2	0.2	0.4	0.2	0.2	0.2	0.2	0.2	0.0	0.1
3	0.2	0.5	0.1	0.1	0.1	0.2	0.2	0.0	0.2
4	0.1	0.4	0.2	0.2	0.2	0.1	0.1	0.0	0.2
5	0.2	0.2	0.0	0.0	0.0	0.2	0.2	0.0	0.0
6	0.4	0.8	0.4	0.4	0.4	0.4	0.4	0.0	0.0
7	0.6	0.1	0.8	0.8	0.8	0.6	0.6	0.0	0.0
8	0.1	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1
9	0.2	0.6	0.3	0.3	0.3	0.2	0.2	0.1	0.1
10	0.6	1.1	0.0	0.0	0.0	0.6	0.6	0.1	0.1
11	0.5	1.0	0.5	0.5	0.5	0.5	0.5	0.1	0.1
12	0.1	0.1	0.2	0.2	0.2	0.1	0.1	0.2	0.2
13	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.2	0.2
14	0.3	0.5	0.1	0.1	0.1	0.3	0.3	0.2	0.2
15	0.0	0.4	0.1	0.1	0.1	0.0	0.0	0.2	0.2

Next, the deviator stress and confining pressure values obtained from the summary data file were compared to the test parameters to determine whether the test was performed in accordance with the procedure. Table 24 contains the results of this analysis.

As shown in this table, the maximum deviation from the target deviator stress is 2.8 percent. These percentages generally trend lower as the test progresses. This is considered an acceptable result. Likewise, the confining pressure values are very close to the target values identified in the procedure. These meet the acceptance criteria.

Table 24. Sample results of conformance checks.

Sequence	Target Deviator Stress, kPa	Actual Deviator Stress, kPa	Difference, %	Target Confining Pressure, kPa	Actual Confining Pressure, kPa	Difference, %
1	18.6	19.3	2.8	20.7	20.7	0.7
2	37.2	37.9	1.9	20.7	20.7	0.3
3	55.8	56.5	1.6	20.7	20.7	0.4
4	31.0	31.7	1.3	34.5	33.8	1.0
5	62.0	63.4	1.8	34.5	33.8	1.7
6	93.0	91.6	1.2	34.5	34.5	0.8
7	62.0	61.3	1.6	68.9	67.5	1.9
8	124.0	123.3	0.3	68.9	67.5	2.1
9	186.0	184.7	0.6	68.9	68.2	1.2
10	62.0	60.6	1.7	103.4	100.6	3.0
11	93.0	91.6	1.5	103.4	102.7	0.9
12	186.0	188.1	1.3	103.4	101.3	1.8
13	93.0	91.6	1.1	137.8	136.4	1.2
14	124.0	123.3	0.8	137.8	135.0	2.0
15	248.0	250.1	0.9	137.8	136.4	1.1

The coefficient of variation for the LVDTs was checked. Table 25 shows the results; all LVDTs were within the prescribed tolerances (coefficient of variation less than 2.5 percent for 14 of the 15 test cycles). This indicates that the LVDT measurements are very stable within a given test sequence.

Table 25. Sample results of LVDT coefficient of variance (CV) check.

Sequence	LVDT 1 CV	LVDT 2 CV	LVDT 3 CV
1	0.9	2.2	1.5
2	1.0	0.9	1.5
3	0.6	0.9	1.2
4	1.3	0.9	1.4
5	1.1	1.0	0.9
6	0.6	0.9	0.7

Table 25. Sample results of LVDT coefficient of variance (CV) check—*Continued*

Sequence	LVDT 1 CV	LVDT 2 CV	LVDT 3 CV
7	0.7	1.9	1.3
8	1.7	1.0	1.8
9	0.3	0.7	0.9
10	1.3	1.9	1.6
11	0.8	1.7	1.5
12	0.7	0.8	0.4
13	0.7	0.9	1.3
14	1.1	0.7	1.0
15	0.5	0.7	0.5

Also, the LVDT deformation ratios were calculated as shown in table 26. This value is determined by taking the maximum cyclic deformation between the three LVDTs divided by the minimum deformation among the three LVDTs. A value less than 1.30 is an indication that the LVDTs are mounted properly on the sample and are recording consistent data. As can be seen from this table, the balance of the LVDTs is very poor for this test. Some values are measuring more than two times the deformation of the others. This is not an acceptable result, and this phenomenon should be investigated more thoroughly.

Table 26. Sample results of LVDT ratio check.

Sequence	LVDT Ratio
1	1.28
2	1.47
3	2.18
4	1.37
5	1.72
6	2.27
7	1.33
8	1.59
9	1.81
10	1.46

Table 26. Sample results of LVDT ratio check—*Continued*

Sequence	LVDT Ratio
11	1.45
12	1.65
13	1.51
14	1.53
15	1.50

Finally, the resilient modulus results were reviewed. The results of the resilient modulus test are given in figure 12. The sample behaved in an expected manner and the overall resilient modulus results appear reasonable.

A completed checklist with the results from this procedure is shown in figure 13. The checklist in blank form is included in appendix A (figure 20).

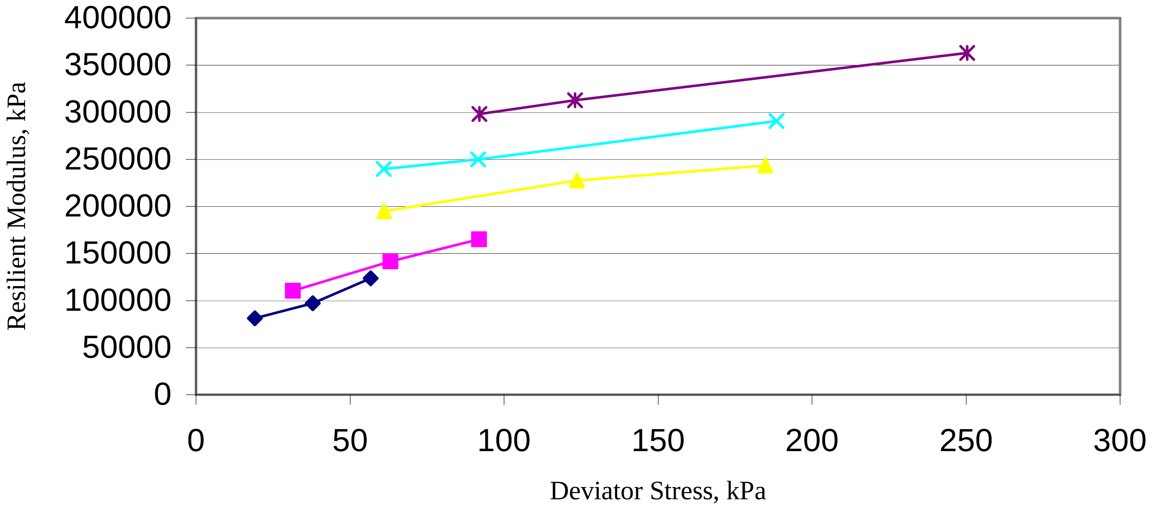

Figure 12. Graph. Example of P46 type 1 (base/subbase) results.

Equipment Availability

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

√ Latest version of procedure.
√ Computer with sufficient hardware/software for data analysis.
√ Pressure gauge.
√ Triaxial cell and pressure system.
√ Loading device.
√ Electronic load cell.
√ Spring-loaded LVDTs.
√ 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.
N/A 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.
N/A Moisture content within ±1 percent of specified.
N/A 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.
NO Triaxial chamber checked for levelness.
√ Initial pressure of 14 kPa applied to specimen in chamber.
√ Apply confining pressure of 103 kPa.
√ Load cell and LVDTs ready to begin testing.
√ Sample is not decreasing in height after preconditioning.
√ The type 1 (subgrade) test sequence has been performed.
N/A Remove specimen and determine moisture content.
√ Triaxial pressure maintained within tolerance throughout testing.
NO LVDT ratios are within acceptable tolerances.
√ Specimen was handled appropriately throughout the test procedure.

N/A: Not applicable in this instance; NO: Procedure not done or criterion not met.
Note: The checklist in blank form is included in appendix A (figure 20).

Figure 13. Form. Sample checklist for base/subbase proficiency procedure.

VI. SUMMARY

The procedures outlined here were developed to verify the operation of closed-loop, servohydraulic systems for specific application to the resilient modulus procedure. They have been written to be as general as possible to promote application in a variety of test applications. The user should implement these procedures with an open mind and not in a cookbook approach.

From use of the procedures, many potential sources of error in future testing programs have been identified and rectified. The following are among the problems that have been identified through implementation of the procedures in numerous laboratories:

Electronics

- Over-ranged load cells.
- Inadequate filters (amplitude attenuation).
- Unmatched filters (excessive time delay between channels).

Software

- Inadequate software control of load.
- Inadequate sampling rates.
- Raw data without units.
- Lack of gain control adjustment during testing.
- Improper raw data format: command values were saved rather than feedback values.

Mechanical

- System not fast enough to apply proper haversine loads.
- Oversized servovalve.
- Friction in servovalve piston.
- Friction in triaxial cell seals.
- Misalignment caused by improperly designed triaxial cell.
- Excessive deformation, up to 76 percent of deformation due to bending of triaxial cell base plate.

- Excessive deformation due to unrestrained fixture.
- Slippage of LVDT holders.
- Lack of control of pressure transducer.
- Air pressure regulator malfunction.

These examples are not meant to produce fear or anxiety in test operators. Rather, they are illustrative of the types of problems a user can face when implementing a resilient modulus testing program. Use of the verification procedure can alert users to problems with the system and with laboratory processes quickly and efficiently.

APPENDIX A. SAMPLE DATA COLLECTION FORMS

Sample forms used for recording the appropriate data during the verification testing are contained in this appendix. A checklist of items to be completed, arranged in an order designed to follow the proficiency procedure from start to finish, also is included.

Inspection Date: ______/_______/__________

Laboratory Name: ______________________________

Equipment Model: ______________________________

Channel Designation: ______________________________

Input Voltage Amplitude: (peak-to-peak, pp) _____________________

Data Collection Channels

Input Freq. (Hz)	**Input Voltage (pp)**	**Data Acquisition Recorded Voltage (pp)**	**Data Acquisition Derived Input-Output Delay (ms)**
2	— —.— —	— —.— —	
4	— —.— —	— —.— —	
6	— —.— —	— —.— —	
8	— —.— —	— —.— —	
10	— —.— —	— —.— —	
12	— —.— —	— —.— —	
14	— —.— —	— —.— —	
16	— —.— —	— —.— —	
18	— —.— —	— —.— —	
20	— —.— —	— —.— —	
50	— —.— —	— —.— —	— — — —

Gain Setting: ____________________________________

Filter Setting:____________________________________

Figure 14. Form. Sample form 1—data collection channel check.

Inspection Date: _______/_______/__________

Laboratory Name: ______________________________

Equipment Model: ______________________________

Load Cell Zero Reading

Load cell description	______________________________
Vendor	______________________________
Model number	______________________________
Serial number	______________________________
Capacity	______________ kN
Sensitivity	__ . __ __ __ mV/V
ax. Zero value (±1.5 percent of sensitivity)	±1.5 percent of full scale
	±__ . __ __ __ mV/V
Strain indicator error	±5 micro strain
Gauge factor on strain indicator	2
Balance range	0
Balance pot	500
Measured zero value (including strain indicator error)	+ or - __ __ __ micro strain + or - __ . __ __ __ ±0.0025 mV/V
Load cell zero values within specified tolerances?	Yes / No
Last calibration date	_____ /_____ / ________

Figure 15. Form. Sample form 2—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**
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—
—. — —	— — —	—.— — —	—.— — —	—.—

Figure 16. Form. Sample form 3—load cell check.

Inspection Date: _______/_______/__________

Laboratory Name: ______________________________

Equipment Model: ______________________________

Load versus Deformation

Nominal Target Load[*] (kN)	**Mean Applied Load (kN)**	**Mean LVDT Reading, mm**	**$R_v=Y_{max}/Y_{min}$ 1.1**	**Point within ±5%?**
_ _._ _	_ _._ _	_._ _ _ _ _	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

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

Figure 17. Form. Sample form 4—dynamic 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)	
	System	**Gauge**	**System**	**Gauge**	**System**	**Gauge**	**System**	**Gauge**	**System**	**Gauge**
0	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
1	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
2	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
3	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
4	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
5	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
6	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
7	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
8	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
9	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._
10	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._	_ _ _._

Figure 18. Form. Sample form 5—triaxial cell check.

Inspection Date: _______/_______/__________

Laboratory Name: ______________________________

Equipment Model: ______________________________

Environmental Chamber

Time, min.	Temperature Level 1 (°C)		Temperature Level 2 (°C)		Temperature Level 3 (°C)	
	System	Gauge	System	Gauge	System	Gauge
0.00	— . —	— . —	— — . —	— — . —	— — . —	— —.—
1	— . —	— . —	— — . —	— — . —	— — . —	— —.—
2	— . —	— . —	— — . —	— — . —	— — . —	— —.—
3	— . —	— . —	— — . —	— — . —	— — . —	— —.—
4	— . —	— . —	— — . —	— — . —	— — . —	— —.—
5	— . —	— . —	— — . —	— — . —	— — . —	— —.—
6	— . —	— . —	— — . —	— — . —	— — . —	— —.—
7	— . —	— . —	— — . —	— — . —	— — . —	— —.—
8	— . —	— . —	— — . —	— — . —	— — . —	— —.—
9	— . —	— . —	— — . —	— — . —	— — . —	— —.—
10	— . —	— . —	— — . —	— — . —	— — . —	— —.—

Figure 19. Form. Sample form 6—environmental chamber check.

Equipment Availability

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

____ Latest version of procedure.
____ Computer with sufficient hardware/software for data analysis.
____ Pressure gauge.
____ Triaxial cell and pressure system.
____ Loading device.
____ Electronic load cell.
____ Spring-loaded LVDTs.
____ 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 LVDTs 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 20. Form. Sample form 7—checklist for proficiency procedure

—*Continued on next page*

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 procedure in LTPP Protocol P46.
____ 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 LVDTs 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 20. Form. Sample form 7—checklist for proficiency procedure—*Continued*

Equipment Availability

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

____ Latest version of procedure.
____ Computer with sufficient hardware/software for data analysis.
____ Environmental chamber and temperature control system.
____ Loading device.
____ Diametral loading heads and specimen restraint system.
____ Gauge points.
____ Contact point template.
____ Gauge point mounting system.
____ Humidity cabinet.
____ Data reduction and analysis system.
____ LVDT calibration unit.
____ Electronic load cell.
____ Extensometers (4).
____ Signal excitation, conditioning, and recording equipment.
____ All other miscellaneous equipment needed for preparing samples.
____ Masonry saw capable of cutting smooth surfaced specimens.

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.

Proficiency Testing

Sample Preparation
____ Cores for testing have visible cracks or deformed in any manner.
____ Specimens for test of one pavement layer.
____ Specimens from one area of test specimen.
____ Top and bottom surfaces trued as necessary.
____ Test specimen greater than 25.4 mm but less than 53.3 mm in thickness.
____ Core examination and thickness performed.
____ Bulk specific gravity performed.
____ Bulk specific gravities similar for the three candidate test specimens.
____ Thickness measurement conducted by averaging four measurements located at quarter points around the sample perimeter and 13 to 25 mm in from the edge.
____ Diameter measured (1) along the axis parallel to the direction of traffic and (2) the axis perpendicular to the axis measured in (1).
____ Diameter ≥ 97.8 mm or ≤ 105.4 mm.
____ Diametral axis marked with loading head contact template.
____ Specimen sawn to provide smooth, parallel surfaces for mounting the measurement gauges.
____ Gauge points attached per protocol.

Figure 21. Form. Sample form 8—checklist for asphalt proficiency procedure

—Continued on next page

____ Samples' temperature and moisture conditioned properly before test.
____ Core samples in the cabinet/chamber for a minimum of 24 hours before testing at 5 °C and 25 °C.
____ Specimens held at 40 °C for a minimum of 3 hours, but not exceeding 6 hours, before testing.
____ Specimens stored in an environment where the temperature is maintained between 5 and 21 °C until they are to be conditioned for testing.
____ Deformation devices mounted on sample and zeroed/rebalanced before test.

Creep Compliance Testing

____ Load strip alignment mark on test specimen located in line of action of actuator shaft and loading strips (back and front).
____ Specimen to strip surface in a contact condition (no obvious projections or depressions).
____ Static load of fixed magnitude applied without impact to specimen.
____ Fixed load produce horizontal strain of 150 to 350 micro strain.
____ Constant static load within 2 percent of required loading during entire test procedure.
____ Reasonable deformation response.
____ Data collected at 10 Hz for first 10 s and 1 Hz for remaining 90 s.
____ Initial load level achieved at end of test.
____ Three temperatures achieved and within tolerance.

Resilient Modulus Testing

____ Deformation devices zeroed or rebalanced prior to start of test.
____ Correct haversine waveform produced.
____ Reasonable deformation response.
____ Horizontal strain in the 150 to 350 micro strain range.
____ Data collected uniformly at 500 Hz.
____ Five load cycles recorded.
____ All three temperatures achieved and within tolerance.

Strength Testing

____ All other testing complete and results checked prior to commencing test.
____ Test performed at the correct temperature and within tolerance.
____ Deformation devices zeroed or rebalanced prior to start of test.
____ Load applied to specimen correctly.
____ Data collected at 1 Hz.
____ Test stopped when load begins to decrease.

Calculations

____ Calculations performed completely and accurately.

Completion of Data Forms

____ Calculations performed completely and accurately.

Figure 21. Form. Sample form 8—checklist for asphalt proficiency procedure—*Continued*

APPENDIX B. DETERMINATION OF PHASE ANGLE

This appendix provides one method for calculating phase angles for the sinusoidal dynamic response checks performed as part of this procedure. Other methods may be used to perform this calculation; this procedure is included here 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.

THEORY

The sinusoidal frequency and phase angle response tests produce 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 these 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 are in the form of:

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

where

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

The equation shown above can be rearranged as follows:

$$y = m_1\sin(2\pi Ft) + m_2\cos(2\pi Ft) + b \tag{3}$$

where

A = square root of $(m_1^2 + m_2^2)$

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

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

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

$y = m_1x_1 + m_2x_2 + b$.

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.[1] In addition, it will return the R^2 value.[2] 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 DAS 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 start 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 “$m_2$cosine,” column F “$m_1$sine,” 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.”

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(s) between LVDT #1 and the load.

Perform the same sequence of calculations for all deformation channels.

---

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

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