SANDIA NATIONAL LABORATORIES
CIVILIAN RADIOACTIVE WASTE MANAGEMENT
TECHNICAL PROCEDURE (TP)

TP-267

Determination of the Nonlinear Dynamic Material Properties of Welded Tuff from Cyclic Loading Experiments

Revision 00

Effective Date: 09/23/2004

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REVISION HISTORY

Revision	**Description**
0	Initial issue

Scope and Objective

The objective of this Technical Procedure (TP) is to define the process for New England Research, Inc. (NER) to determine the stiffness and linear and non-linear attenuation coefficients through low frequency cyclic loading experiments at ambient pressure and temperature. This procedure is intended for implementation in a laboratory environment, in conjunction with work for the Yucca Mountain Site Characterization Project (YMP).

1.0 Prerequisites

Before performing work under this technical procedure, personnel must be trained by the author and/or the Principal Investigator (PI), and demonstrate their proficiency in performing the work in this procedure. The trainer has the responsibility for generating a record of the personnel proficiency training, as well as the responsibility that work is performed and documented in accordance with this procedure.

The personnel using this procedure are responsible for ensuring that a controlled copy of this procedure is available and used for performing the work in this procedure.

2.0 Description of Activity

This TP details procedures for laboratory mechanical experiments on rock specimens. The experiments will be performed on right-circular cylinders of tuff. The specimens should be as large as possible. The specimens will be tested in the dry state. The mechanical experiments will be run by applying a sinusoidal strain perturbation about a pre-load that produces 25%, 50% or 75% of the estimated failure strain of the specimen (the magnitudes of the strain will be determined based on prior baseline testing). The sinusoidal strain will be applied at two or three frequencies (e.g., 1 Hz, 10 Hz and 50 Hz), at each of the three stages (pre-loads) of the stress-strain curve.

For this experimental series, outputs from a variety of transducers (e.g., load and strain) will be monitored. The output voltage from each device is conditioned, amplified and converted to digital format, and recorded as a function of time. The outputs from the devices are recorded with a PC-based data acquisition system (DAS). All devices (with the exception of strain gages, which are calibrated after the specimen is set up using a shunt resistor in parallel with one leg of the Wheatstone bridge) will be calibrated, in accordance with AP 12.1Q, *Control of Measuring and Test Equipment*.

A description of the equipment and an overview of the test procedures will place the step-by-step procedures in the proper context. All of the cyclic loading tests and system checks will be carried out in servo-controlled hydraulic test systems with a minimum axial force capacity of 5.1×10^5 N. The servo-controller is a self-contained digital unit, which operates in either force or displacement feedback. The confining pressure will be ambient atmospheric pressure (one atmosphere). The samples will be tested in the room dry state. The axial and radial strains of the specimen will be measured with strain gages and/or LVDTs. The force on the test column is measured with a load cell. The position of the loading piston is observed with a displacement transducer.

3.0 Operations

3.1 System Checks

Prior to any series of cyclic loading tests, when test results are suspect, or at other times specified by the PI, an evaluation of the operation of the entire test procedure will be performed. The evaluation consists of performing a cyclic compression test at each specified frequency on a specimen material having known elastic properties and quality factor (Young's modulus, Poisson's ratio and Q). An acceptable check will result in a determination of the elastic properties to within ±5% of the published values. Otherwise, the overall procedure must be checked before tests on rock specimens can be performed, or continued. The proper operation of the test apparatus, measurement devices and data acquisition system are verified by a successful check. The check shall be documented on the Test Data Report (TDR) in Appendix A, noting that the test is a system check.

The material chosen for the system test will have a quality factor (Q) that is known to be very high (>500). Any attenuation observed is assumed to be that of the overall system and not the check specimen. The "System-Q" that is computed from tests of the check material will be used to correct the rock attenuation data for system effects.

3.1.1 System Check Procedure

1. A test assembly is constructed by placing the aluminum system-check specimen between a metal end piece on each end of the specimen. The stack will be placed on a load cell and centered on the base plug of the loading frame with an appropriate centralizer.

2. The LVDTs are placed in the appropriate set-up on the sample assembly. The axial gage(s) is (are) positioned in such a way to ensure that the line of the displacement measurement is parallel to the axis of the specimen. The radial displacement gage (as described in Holcomb and McNamee, 1984) is positioned in such a way to ensure that the line of the displacement measurement: (1) passes through, and (2) is perpendicular to the axis of the specimen. Depending on the condition of the sample, foil strain gauges may be used instead of LVDTs

3. Attach the strain measurement devices to their appropriate feed-through electrical connectors.

4. Make the final mechanical adjustments on the LVDTs, if necessary.

5. Check the position of the sample assembly to ensure that all loading column components are coaxial.

6. Advance the loading platen and apply a differential stress of approximately 0.5 MPa on the specimen. This seats the specimen and all the elements in the loading column. This procedure is accomplished by manually operating the servo-controller in load feedback.

7. Change the servo-controller feedback to displacement control. Retract the loading platen until there is no force on the loading column.

8. Once again, advance the loading platen and apply a predetermined differential stress to the specimen.

9. Adjust the setting on the displacement controller to provide a sinusoidal voltage with amplitude estimated to produce a maximum strain of 10^{-5}. The frequency of the sinusoid should be set to the defined levels (e.g., 1 Hz, 10 Hz and 50 Hz).

10. Initiate a sweep and acquire data. The amplified outputs from all transducers are monitored and recorded using a microprocessor based DAS. The conditioned output signals from the strain devices and the force cell are presented to an A/D converter and the voltage data are stored on the data acquisition computer.

11. Repeat data acquisition for subsequent defined frequencies.

12. Unload the specimen until the loading piston is out of contact with the specimen.

13. Terminate data acquisition.

14. Remove the specimen from the test apparatus.

3.1.2 Data Processing

Reduce the data. Commercial software with a built-in linear fitting function will be used. The voltages recorded by the DAS will be converted to engineering units by employing simple mathematical formulae that incorporate the scale factors determined for the individual measurement devices during calibration. The following elastic constants will be computed:

Young's modulus, E (GPa), where E= Δaxial stress/Δaxial strain and

Poisson's ratio, ν, where ν = Δradial strain/Δaxial strain.

The stress is computed by dividing the axial force by the initial cross-sectional area of the specimen. Stress will be reported in MPa. When using LVDTs, axial strain is obtained by dividing the axial displacement by the gage separation. The measured displacement is corrected for any endcap contribution, if the support rings for the axial LVDTs are attached to the endcaps. The average of the axial strains recorded by the two axial devices is used in the moduli calculations. When using LVDTs, radial strain is computed by dividing the change in specimen diameter observed by the radial displacement gage by the initial specimen diameter. Where strain gages are used, their outputs are multiplied by their respective scale factors, as determined by their response to the shunt resistor. All strains will be reported as strain, percent strain, millistrain or microstrain.

The elastic constants will be calculated by least-squares linear fit to the stress-strain ellipse generated by the sinusoidal load. The elastic constants are compared with those documented for the standard material. If either, or both of the values deviate from those expected by more than 5% the system check indicates unacceptable operation of the entire test system. No further rock properties testing will ensue until a resolution of the problem(s) is determined. If the results meet the 5% tolerance, the test system is deemed to be operating satisfactorily, and tests on rock specimens may continue.

A phase difference (time shift) will be determined between the recorded stress and the recorded strain sinusoids. Since the system-check specimen has very high Q (>500), the phase shift is assumed to be related to system attenuation and is used to make a system correction to the rock attenuation coefficients.

3.2 Low Frequency Dynamic Tests (Cyclic Loading)

Specimens of tuff will be cyclically loaded about strain points of approximately $2x10^{-3}$, $4x10^{-3}$ and $6x10^{-3}$. There will be two or three defined frequencies of cyclic loading (e.g., 1 Hz, 20 Hz and 50 Hz). The cyclic strain range will be 10^{-6} to 10^{-3}. The following sections include the step-by-step procedures for the mechanical experiments.

3.2.1 Experimental Procedures

1. The specimen designated for testing will be prepared per TP-51, entitled “Preparing Cylindrical Samples, Including Measurement of Dimensional and Shape Tolerances.” If drying and/or saturation are required, use SNL TP-65, entitled “Drying Geological Samples to Constant Weight” and/or SNL TP-64, entitled “Vacuum Saturation of Geologic Core to Constant Weight.” All initial conditions, work activities and a list of all measurement devices (with relevant information) will be documented on the TDR.

2. Visually inspect the rock core. Any major surface irregularities/imperfections should be noted on the TDR, along with a sketch and/or photograph of the specimen.

3. A sample assembly is constructed by placing the rock specimen between a metal end piece on each end of the specimen. The assembly will be placed on a load cell and centered on the base plug of the loading frame with an appropriate centralizer.

4. Where LVDTs are to be used, place the gages in the appropriate set-up on the sample assembly. The axial gage(s) is (are) positioned in such a way to ensure that the line of the displacement measurement is parallel to the axis of the specimen. The radial displacement gage is positioned in such a way to ensure that the line of the displacement measurement: (1) passes through, and (2) is perpendicular to the axis of the specimen.

5. Attach the strain measurement devices to their appropriate feed-through electrical connectors.

6. Make the final mechanical adjustments on the LVDTs.

7. Position the sample assembly to ensure that all loading column components are coaxial.

8. Advance the loading platen and apply a differential stress of approximately 0.5 MPa on the specimen. This seats the specimen and all the elements in the loading column. This procedure is accomplished by manually operating the servo-controller in load feedback.

9. Change the servo-controller feedback to displacement control

10. Initiate data acquisition. The amplified outputs from all transducers are monitored and recorded using a microprocessor based DAS. The conditioned output signals from the strain devices, pressure transducers, thermocouples and the force cell are presented to an A/D converter, and the voltage data are stored on the data acquisition computer.

11. Load the specimen manually to a strain of $2.0x10^{-3}$.

12. Apply a sinusoidal strain perturbation of approximately 10^{-6} at the lowest defined frequency (e.g., 1 Hz).

13. Apply a sinusoidal strain perturbation of approximately 10^{-6} at the second lowest defined frequency (e.g., 20 Hz).

14. Apply a sinusoidal strain perturbation of approximately 10^{-6} at the third lowest frequency, if necessary (i.e., if a third frequency is defined) (e.g., 50 Hz).

15. Repeat steps 12, 13 and 14 for a strain perturbation of approximately 10^{-5}

16. Repeat steps 12, 13 and 14 for a strain perturbation of approximately 10^{-4}.

17. Repeat steps 12, 13 and 14 for a strain perturbation of approximately $3x10^{-4}$

18. Repeat steps 12, 13 and 14 for a strain perturbation of approximately 10^{-3}.

19. Load the specimen manually to a strain of $4.0x10^{-3}$.

20. Repeat steps 12 through 18.

21. Load the specimen manually to a strain of $6.0x10^{-3}$. .

22. Repeat steps 12 through 18.

23. If the specimen has not failed, load at a strain rate of 10^{-5}/sec to failure.

24. Terminate the data acquisition.

25. Unload the specimen until the loading piston is out of contact with the specimen.

26. Remove the specimen from the test apparatus and examine the manner in which the specimen failed. Record the observations on the TDR.

3.2.2 Data Processing

Reduce the data. Commercial software with a built-in linear fitting function can be used. The voltages recorded by the DAS will be converted to engineering units by employing simple mathematical formulae that incorporate the scale factors determined for the individual measurement devices during calibration. The following elastic constants will be computed:

Young's modulus, E (GPa), where E= Δaxial stress/Δaxial strain and

Poisson's ratio, ν, where ν = Δradial strain/Δaxial strain.

The stress is computed by dividing the axial force by the initial cross-sectional area of the specimen. Stress will be reported in MPa. When using LVDTs, axial strain is obtained by dividing the axial displacement by the gage separation. The measured displacement is corrected for any endcap contribution, if the support rings for the axial LVDTs are attached to the endcaps. The average axial strain recorded by the two axial devices is used in the moduli calculations. Radial strain is computed by dividing the change in specimen diameter observed by the radial displacement gage by the initial specimen diameter. Where strain gages are used, their outputs are multiplied by their respective scale factors, as determined by their response to the shunt resistor. All strains will be reported as strain, percent strain, millistrain, or microstrain.

The elastic constants will be calculated by least-squares linear fit to the stress-strain ellipse generated by the sinusoidal load. A phase difference (time shift) will be determined between the recorded stress and strain sinusoids.

The phase shift will be used to compute the quality factor, Q, according to the formula:

$$Q^{-1} = \tan \phi,$$

where ϕ is the phase shift between stress and strain (Toksoz and Johnson, 1981).

3.2.3 Electronic Media and Hard Copy Document Handling

Data in digital format, and hard copy documents are handled so as to maintain their integrity, and protect information from damage, or destruction. All digital and hardcopy documentation of the testing will be retained at NER for a minimum of three years following the end of the testing sequence.

Data collected during the testing is stored directly on to the hard disk of the data acquisition computer in the laboratory. At least once each day, the data files are accessed, over the NER internal network, by the operator using the non-laboratory computer on which data processing will occur. The original, unmodified content of the accessed raw file is also maintained on the data processing computer. The raw data will be manipulated in order to convert the voltage information to engineering units from which to determine the mechanical properties. System checks serve to verify proper input, transfer and manipulation of the data, so as to insure completeness and accuracy of the information, including changes thereto. The file generated by the data processing software program will include the unmodified raw data and the processed data, and it will also be retained on the hard disk of the operator's computer.

All computers are password protected, and behind a firewall. Access to the computers is limited to the employees qualified for YMP activities. Backups of non-laboratory computers are automatically performed nightly, with a redundant technique. All backups contain the actual date and time stamps of the original files, so no time stamp information is lost. The date and time that the backup was performed is also stored. Integrity verification is done by using checksums on source and backup files.

Multiple labeled, and redundant copies of all backups are kept offsite on removable hard disks in order to maintain i. One copy, on disk, is rotated into onsite use on a weekly basis, while rotating another copy offsite. Additional integrity checks are performed when an offsite copy is rotated into redundant onsite service. In addition, the operator will backup all files on the data processing computer, weekly, by copying them to a compact disk that will be stored offsite along with the hard copy documents.

Hard copy documentation of the work will be maintained by ensuring that there is a copy of completed originals available offsite at all times. The operator will photocopy any completed documents. The copies will be stored offsite until the documents have been formally submitted to the YMP. All completed documents and copies will be stored in an environment suitable for their maintenance.

4.0 <u>Safety</u>

There should be no safety hazards other than the normal hazards of the equipment. Operations will be in accordance with safety requirements of the facility where the work is being performed and those of the employer of person(s) performing the work.

5.0 <u>Nonconformance, Deviations, and Corrective Actions</u>

Any nonconformance or deviations must be reported to the PI as soon as possible. Deviations, deficiencies and corrective actions must be determined and documented in accordance with AP-16.1Q, *Condition Reporting and Resolution.*

6.0 QA Records

QA records, and any corrections or changes thereto, generated as a result of implementing this procedure will be prepared and submitted as inclusionary QA records (QA:QA) by the PI in accordance with AP-17.1Q, *Records Management*. These records include:

Proficiency training records (Section 2.0)

Test Data Reports (TDR) (Section 4.0)

Calibration records (if applicable)

7.0 References

Holcomb, D. J. and M. J. McNamee, 1984. Displacement *Gage for the Rock Mechanics Laboratory*. SAND 84-0651. Albuquerque, New Mexico: Sandia National Laboratories.

Tokzos, N. and Johnson, D. H., Seismic Wave Attenuation, Chapter 1 - Definitions and Terminology, Geophysics Reprint Series, 2, 1981.

TP-51, *Preparing Cylindrical Samples, Including Measurement of Dimensional and Shape Tolerances*

TP-64, *Vacuum Saturation of Geologic Core to Constant Weight*

TP-65, *Drying Geological Samples to Constant Weight*

AP-12.1Q, *Control of Measuring and Test Equipment*

AP-16.1Q, *Condition Reporting and Resolution*

AP-17.1Q, *Records Management*

8.0 Appendices

Appendix A Test Data Report

TEST DATA REPORT (TDR)

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Test Plan Number / Rev.:________________________________Specimen ID:__________________________

Moisture Condition:_______________Length: ____________Diameter:____________Weight:_____________

Dry Bulk Density:_________Saturated Bulk Density: _________Grain Density:_________Porosity: _________

Required Test Conditions (e.g., differential stress, pressures, temperatures, frequencies):_________________

____

Test Apparatus Used:_________________________________Latest System Check Date:_________________

Measurement Devices (Some categories not relevant to all devices) / Label unused channels “Inactive”:

Raw DAS Channel (Column)	Device/Model/Serial#	Latest Calibration Date	Gain Setting	Gage Factor	“Zero” Voltage	Shunt Voltage Difference	Scale Factor: Units/Volt	Notes

DAS raw voltage data file: ____

Processed data file:____

Operator(s): Name:________________________Sign/Date:____________________________________

Name:________________________Sign/Date: ____________________________________

Name:________________________Sign/Date: ____________________________________

Name:________________________Sign/Date: ____________________________________

Organization / Location of Testing:____

TEST DATA REPORT (TDR)

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Continuation Page

Specimen ID: ____________________________

Operator(s): Name:____________________Sign/Date:______________________________

Name:____________________Sign/Date: ______________________________

Name:____________________Sign/Date: ______________________________

Name:____________________Sign/Date: ______________________________