ATTACHMENT 6

ENTO002-PI-05, Revision 1
(189 pages)

Geologic, Geotechnical, and Geophysical Field Exploration and Laboratory Testing

Project Instructions

for the

Entergy Nuclear Potomac Early Site Permitting Project

Geologic, Geotechnical, and Geophysical
Field Exploration and Sampling

Project Instruction No: ENTO002-PI-05

Revision No: 1

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Revision Summary Page

Revision No.	Date	Summary of Changes and List of Changed Pages
0	7/17/02	Initial issue.
1	7/29/02	Revised to delete step 6.2.h, and revise para. 6.1.2.1.d. Added this Revision Summary page, and changed page count in procedure body (pages 2 – 17). Corrected typos in Definitions/Acronyms.

1.0 PURPOSE

1.1. Project Scope

This instruction provides guidelines for the following geologic, geotechnical, and geophysical site characterization activities which are required to be performed under a QA Program:

- Exploratory Borings
- Borehole and Surface Geophysical Surveys
- Cone Penetrometer Soundings (CPT)
- Geotechnical Sample Collection

This Project Instruction synthesizes the relevant and important methodology and QA procedures to ensure that field and laboratory studies are performed to a high standard in accordance with regulations and nuclear industry standards, are appropriately reviewed by qualified technical personnel, and are well documented.

The collected data from these activities will be used to evaluate general geologic conditions and site stratigraphy, potential geologic and earthquake hazards, site ground motion response, and an initial assessment of foundation conditions and properties. Collected data will be presented in a data report that will include borehole and geophysical logs, engineering geologic cross sections, and data tables. Separate follow-on reports describing the analysis of site ground motion response and foundation conditions will be prepared upon completion of this data report.

The proposed work will be performed using Draft Regulatory Guide DG-1101, February 2001, Site Investigations for Foundations of Nuclear Power Plants (Proposed Revision 2 of Regulatory Guide 1.132) as a guide.

1.2. Responsibilities

William Lettis & Associates, Inc. (WLA) will be responsible for managing and directing the field activities. Work by WLA will be performed under the ENERCON Services, Inc. (ENERCON) QA Program and will follow applicable 10 CFR 50 QA provisions.

Various specialty subcontractors will be used for the following: exploratory drilling and sampling, geophysical surveying, and laboratory testing. GEOVision (Corona, California) will be the geophysical surveying contractor. Dynamic soil testing will be performed at the University of Texas, Austin (UTEXAS). Other subcontractors will be qualified and selected by the WLA Project Manager, and the Enercon Project Manager and/or QA Manager.

The WLA Project Manager will provide overall direction for the work, including work performed by subcontractors, and will act as liaison to the project owner, Entergy Nuclear Potomac (Entergy). He will supervise a staff of senior and staff geologists. The senior geologist will be responsible for day-to-day performance of the technical work and will be either a Principal or Senior Geologist with WLA. Staff geologists will be either Project or Staff Geologists at WLA.

2.0 APPLICABILITY

This instruction is applicable to all WLA staff performing geologic, geotechnical, and geophysical field exploration and surveys, and collection and transportation of geotechnical laboratory test samples for the Entergy Nuclear Potomac Early Site Permitting Project.

3.0 DEFINITIONS AND ACRONYMS

The definitions of commonly used acronyms are presented below:

- NRC – Nuclear Regulatory Commission
- ASTM – American Society for Testing and Materials
- ESP – Early Site Permit Application
- OSHA – Occupational Safety and Health Agency
- EPRI – Electric Power Research Institute
- LLNL – Lawrence Livermore National Laboratories
- DOE - Department of Energy

4.0 DAILY REPORTS

Reports shall be prepared by the WLA geologist and/or WLA Project Manager each day field work is performed to document daily activities in a dedicated, fixed-page, numbered notebook. All daily reports shall be signed and dated.

The following information shall be included in the notebook entries:

- Date
- Personnel on site, first name listed should be the geologist making the log book entry.
- Work performed, e.g. drilling, surveying, etc.
- If drilling or cone penetrometer (CPT) work occurred, the boring/CPT number and total depth drilled, or sounded, should be included
- Resources used, e.g. geophysical casing, cement, etc. (for information purposes only)
- Any problems or unusual circumstances

5.0 SAFETY

Field work shall comply with applicable OSHA requirements and with GGNS industrial safety and any other GGNS requirements for the work being done.

6.0 METHODOLOGY

6.1. Exploratory Borings

Three exploratory borings will be made in the general vicinity of the proposed facility to characterize subsurface geologic conditions, perform in-situ testing, perform borehole geophysical surveys, and obtain laboratory samples. One of the boreholes will be drilled to a total depth of about 250 to 300 feet. The other two boreholes will be drilled to total depths of between about 140 to 180 feet. The finish boreholes shall be between 4 to 8 inches in diameter, and will be used to characterize subsurface materials and conditions, collect geotechnical test samples, and borehole geophysical surveys. All borehole locations shall be clearly marked in the field prior to drilling, and checked for underground utilities.

6.1.1. Equipment

a. Boreholes will be drilled with truck, track, or skid mounted drill rigs using mud rotary and rock coring equipment. In addition to a drill rig, a water truck will be used to provide fluids for drilling and borehole backfilling.

b. Drill equipment should be steam cleaned prior to mobilizing to the site, and will be inspected by the WLA field geologist in conjunction with the drill crew prior to drilling to ensure materials and equipment are clean, in good condition, and of appropriate dimensions and quality. A checklist will be developed by the WLA geologist and provided to the drilling subcontractor to document that a pre-work check is conducted. The drilling subcontractor shall fill out the checklist prior to beginning work, and the WLA geologist will review the checklist and make a copy for the WLA file. Gauges to record drilling rotation and downfeed pressure, which are used for general information by the geologist, shall be in good working order.

c. Samplers and core barrels shall be in good condition without visible defects.

d. Bedrock will be sampled with a standard five-foot long, double- or triple-tube core barrel. Diameter dimensions for approved, standard core barrels to be used in this study are given below.

Standard Sizes of Core Barrels

Standard Barrels	**O.D. (in.)**	**I.D. (in.)**
HWD	3-3/4	2-7/8
HQ Wireline	3-25/32	2-1/2

From Diamond Core Drill Manufacturers Association standards

e. The core barrel dimensions and condition of bits and steel will be checked prior to drilling and recorded in the daily report notebook.

f. Overburden soils and weathered rock may be sampled by either hammer drive sampling, rotational pitcher sampling, and/or hydraulic push sampling. The following equipment specified in paragraphs 6.1.1.1 and 6.1.1.2 is to be used for these techniques.

6.1.1.1. Hammer Sampling

Hammer sampling equipment shall meet ASTM specification D1586-84 "Standard test method for penetration test and split-barrel sampling of soils", and include:

- Delivery system (one of the following): (1) Cat-head hammer; (2) Automatic-trip hammer; (3) Downhole hammer
- 3.0-inch O.D., 2.5-inch I.D., 18-inch to 24-inch interior length, split-spoon sampler with 1 or 6-inch long brass ring liners
- 2.5-inch O.D., 2.0-inch I.D., 18-inch to 24-inch interior length, split-spoon sampler with 1 or 6-inch long brass ring liners
- SPT Sampler: 2.0-inch O.D., 1.375-inch I.D., 18-inch to 24-inch interior length, split-spoon sampler. Brass liners shall not be used in SPT samplers.

Dimensions are standard for this type of sampler. All drive sampler shoes should be in good condition, i.e. not contain visible deformations, dings, or excessively worn edges.

6.1.1.2. Undisturbed Thin-Wall Push Samplers

Equipment for thin-walled sampling shall meet ASTM 1587-94 "Standard practice for thin-walled geotechnical sampling of soils", and shall include:

- Fixed-piston sampler head with check valve
- Rotary Pitcher core barrels
- Thin-walled, metal "Shelby" sample tubes
- Sample tube plastic end caps

Thin-walled Shelby tubes shall be 24-to 36-inches long, 3.0 in. I.D., and with a wall thickness of 0.065-inches. The tubes shall be of standard manufacture, and provided with corrosion-protection coating on the inside of the tube, such as a lacquer coating.

6.1.1.3. Geologist Field Equipment

Equipment for the field geologist logging the boring and locating boreholes includes:

- Soil and rock boring logs
- Camera and film
- Retractable steel measuring tape
- Engineering scale
- Knife and/or spatula
- Geologic hammer

- Hand lens
- Notebook
- Munsell Color Charts
- Sample bags and marking pens
- Duct tape (to seal the caps on push samples)
- Protractor
- Stop watch (standard commercial manufacture, calibration not required)
- Roll of heavy-duty plastic wrap / shrink wrap to preserve core
- Core boxes with PVC splits and dividers of the appropriate size (HQ, etc.)
- Stakes or paint to mark boring locations
- Pocket penetrometer and pocket shear torvane for obtaining general information on soil strength properties for classification purposes (calibration not required)
- Wax and stove for melting the wax to seal undisturbed samples
- Tarp for shade and rain protection

6.1.2. Procedures

6.1.2.1. Mud Rotary Drilling

a. Mud rotary drilling methods and equipment will be used for portions of holes in unconsolidated material overlying bedrock. Mud rotary drilling should be conducted in accordance with ASTM D5783-95 "Standard guide for use of direct rotary drilling with water-based drilling fluid for geoenvironmental exploration and the installation of subsurface water-quality monitoring devices". The finished hole size shall be between 4 and 8 inches.

b. Drill string advance shall be carefully controlled to minimize disturbance to formation soils and bedrock.

c. Hammer sampling and thin walled push will be driven at varying depth intervals in the boreholes. Samples should be obtained at a minimum of 5-foot intervals within the upper 50-feet of hole, and at a minimum of 10-foot intervals below a depth of 50-feet. Samplers shall be driven or pushed into the bottom of the drilled hole under the direction of the site geologist. Prior to sampling, the hole bottom shall be flushed to remove drill cuttings.

d. The depth of each sample interval should be established by measurements of the downhole drilling rod length to within 3-inches, and measured from a fixed reference point (such as the top of drill casing) with a measuring tape. These measurements will be recorded by the geologist on the borehole log (Section 6.1.4). The measurement shall be made after the sampler is lightly seated into the bottom of the hole with either two light seating taps from the hammer (driven samples), or slight hydraulic pressure on the drill string (undisturbed push samples). These measurements should be periodically checked by the geologist.

e. Upon retrieval, samples should be inspected, logged, and photographed (selected samples) by the geologist, and transferred into suitable containers for transportation.

Sample handling shall be performed in accordance with ASTM D4220-95 "Standard practices for preserving and transporting soil samples".

f. Mud rotary drilling will be used in conjunction with HQ wireline core equipment of similar size for hole advance into bedrock materials. Casing may be required to maintain an open hole through overburden soils, and to enhance drill water circulation. The decision to use casing will be made in the field, but the drilling subcontractor shall be prepared to case through the full thickness of overburden soils.

The table below lists drill rods and casing sizes approved for the Entergy study.

Standard Sizes of Drill Rods and Casing

Size	**O.D. (in.)**	**I.D.(in.)**
Drill Rods		
NW	2-5/8	2-1/4
HW	3-1/2	3-1/16
Casing		
HW	4-1/2	4

From Diamond Core Drill Manufacturers Association standards

6.1.2.2. Diamond Wireline Rock Coring

a. Rotary diamond coring shall be used to advance borings through bedrock, and to obtain continuous rock core samples. Rock coring will be conducted according to ASTM D2113-83 "Standard practice for diamond core drilling for site investigation". Coring shall be accomplished by advancing an outer steel casing with a rock carbide or diamond bit, and an inner sample core barrel that is locked into the drill string annulus.

b. Core barrels shall be 5 feet long, and recovered after advancing the drill string a sufficient distance to fill the barrel (core run).

c. The core barrel shall be retrieved through the drill string while leaving the outer casing in place, and opened carefully at the surface while noting its orientation and direction to retrieve the core sample.

d. Core samples shall be inspected by the geologist, transferred into split PVC trays, logged, and placed in labeled core boxes for transportation and storage. Photographs shall be taken of the filled core box by the WLA geologist. Core sample handling should be in general accordance with ASTM D5079-90 "Standard practices for preserving and transporting rock core samples".

6.1.2.3. Borehole Completion

a. Depth to groundwater will not be measured in the boreholes because water and drilling mud/polymer will be injected into the hole during drilling operations, masking the natural groundwater table.

b. Borehole geophysical surveys will be performed upon completion of drilling. The drilling water and mud/bentonite should be maintained within 2 feet of the top of the borehole, if possible, until the geophysical survey is initiated. Circulation should be minimized after completion of drilling to reduce destabilization of the borehole wall.

c. Upon completion of the borehole geophysical survey, the hole shall be completely backfilled to the ground surface with a bentonite-grout mix installed by the tremmie method, and according to local and state requirements for protection of groundwater.

d. Steel rebar stakes shall be placed in the backfill grout at the approximate center of the borehole, and shall project at least 3-inches above the ground surface. The rebar shall be provided with a safety plastic cap. Each borehole rebar stake shall be surveyed with electronic survey equipment to an accuracy of 1-inch, and tied in to NAD 84 and plant coordinate grids by a surveyor.

6.1.3. Sampling Techniques

6.1.3.1. Soil Sampling

a. Soils may be sampled either by hammer or push sampler, in accordance with ASTM Standards D1586-84, "Standard test method for penetration test and split-barrel sampling of soils" or D1587-94 "Standard practice for thin-walled geotechnical sampling of soils".

b. When hammer sampling, the following information shall be recorded: (1) delivery system; (2) sampler size; (3) whether inner brass rings are used; (4) blow counts, recorded every six inches for a total of 18 inches; and (5) length of recovered sample.

c. Sample driving process shall be performed carefully and in a repeatable manner, and according to ASTM D1586-84. Driven samplers shall be driven 18-inches, unless refusal is met at lesser penetration depth. Driven samplers shall not be driven more than 18-inches. The length of sample drive shall be carefully measured with a measuring stake or stick, and marked to within ½-inch on the drill rod from a fixed reference point.

d. When push sampling, the following information shall be recorded: (1) sampler type, and drive method; (2) maximum down feed pressure read from the gauges on the drill rig; (3) information regarding difficulty of sample pushing; and (4) length of recovered sample.

e. Pocket penetrometer and/or pocket torvane measurements shall be measured in the ends of selected samples and recorded on the boring logs. This information is used for general informational purposes and will be recorded on the boring log as described in Section 6.1.4.

f. Push samples shall not be advanced more than 20-inches for a 24-inch long tube, or 32-inches for a 36-inch long tube.

g. Samples shall be obtained in soils at intervals not to exceed 5-feet for the upper 50-feet of borehole, and at intervals not to exceed 10-feet below a depth of 50-feet.

6.1.3.2. Rock Sampling

a. Rock core samples shall be sampled with rotary coring equipment, and recovered in double- or triple-tube core barrels. Care should be exercised during drilling to enhance recovery of rock core.

b. During coring, the geologist should record the time required for each core run, drill rig gauge readings for rotation and downfeed pressure, and describe drill water and rock cutting recovery and conditions. This information is used for general informational purposes and will be recorded on the boring log as described in Section 6.1.4.

c. Recovered rock core shall be laid in wood core boxes that are provided with longitudinal spacers and laid out in sequence as a book would read from upper left to lower right. Spacer blocks shall be marked and inserted into the core column within the separators to denote the beginning of each core run.

d. The inside and outside cover and both sides of the core box shall be clearly labeled with the job name, job number, borehole number, date, core box number and total number of boxes (i.e. 1 of 5), and the depth interval contained within (i.e. 20' to 35'). The starting and ending depth of each core run shall be labeled on the core box or on spacers at either end of the recovered core.

e. Once a core box is full, or the hole is terminated, the core shall be photographed in the field, and then each run shall be wrapped in plastic wrap and taped to help preserve moisture and keep samples intact.

6.1.4. Borehole Logging

All exploratory borings will be logged on Boring Log Sheets (Attachment 1) that include descriptions of drilling procedures, sampling, geologic materials, and general subsurface information. Boring logs will be reviewed by a senior WLA geologist. The following data, as applicable, is to be included on these sheets for all borings:

1. Project name and job number
2. Date started and completed
3. Description of drill rig
4. Boring number
5. Type & diameter of boring
6. Elevation @ top of hole (estimated from existing topographic maps) and total depth
7. Boring location (estimated by GPS coordinates and/or measurements from fixed reference features with a measuring tape and Brunton compass)
8. Sampling method: including all samplers used (3", 2.5", and/or SPT split spoon samplers; Shelby tubes, etc.)
9. Sample driving hammer type and drop (ASTM standards for SPT sampling require a 140 lb. hammer with a 30 inch drop)
10. Rock Quality Designation (RQD) for rock
11. Name of geologist logging the hole
12. Hammer sample blows per 6-inch drive

13. Description of soil and bedrock unit, including bedrock discontinuities (see discussion in Section 6.1.4.1 below)
14. Specific notes, as applicable, regarding drilling fluid circulation, casing dimensions, type of grout backfill, etc.

6.1.4.1. Soil and Rock Unit Descriptions/Nomenclature

a. Descriptive terms and geologic classification of overburden and bedrock material shall be based on the following sources:

    i. Rock descriptions including discontinuity description:
        1. Brown, E.T., Rock characterization, testing, and monitoring, ISRM suggested methods: Pergamon Press, Oxford.
        2. Hoek, E., 1996, Very poor quality rock masses, draft paper.

    ii. Soil and overburden description:
        1. ASTM D2487-00 standard classification of soils for engineering purposes, D2488-00 standard practice for description and identification of soils,
        2. Munsell soil color charts, 1994

b. Field data sheets that summarize the soil and rock classification protocols are included in Attachment 3. These data sheets will be used by the WLA field geologist for all borehole logging. In addition to classification and logging of bedrock lithology, rock discontinuities should be described and logged, and Rock Quality Designation (RQD) shall be measured and recorded for each core run according to ASTM D6032-96 "Standard test method for determining rock quality designation (RQD) of rock core".

6.1.5. Collection and Transportation of Samples

a. Preserving rock and soil samples for lab testing or future analysis is extremely important, and ASTM standards D4220-95 "Standard practices for preserving and transporting soil samples" and D5079-90 "Standard practices for preserving and transporting rock core samples" will be followed.
b. All samples should be clearly labeled with the job name, job number, borehole number, date collected, and name of geologist collecting the sample.
c. Whenever possible, samples should be sealed and placed in the shade immediately after collection.
d. Drive soil samples obtained in the SPT and split-spoon liner samplers, and intended for index classification tests, shall be handled as ASTM D4220-95 "Group B" type samples. Drive soil samples obtained in split-spoon liner samplers that are selected for triaxial strength testing shall be handled as "Group C" samples. Undisturbed thin-wall samples shall be handled as "Group D" samples.

e. The WLA field geologist and senior geologist will review samples to develop the laboratory testing program. Test samples will be selected that are representative of each discrete soil and rock unit, and will be accurately described in the field by the WLA geologist according to Section 6.1.4.1.

f. After selection, samples will be prepared for transportation to the laboratories and documented according to the attached Chain-of-Custody (COC) form (Attachment 3). All parties involved in sample transportation shall fill in the COC form to completely document the transportation process.

g. Rock cores shall be placed in sturdy wood core boxes and cradled within PVC pipe split in half and sized to hold the core tightly in the box and prevent core rolling and disruption during transportation.

h. Selected sample intervals of rock for laboratory testing shall be cut from the core, carefully lifted to minimize disturbance, and placed in a transport core box within the PVC pipe split. Note cards shall be placed in the core box locations of extracted rock core samples that document the depth interval of extracted core, date of extraction, name of extractor, anticipated laboratory tests, and name of laboratory used for testing.

i. Drive soil samples shall be placed in plastic sample bags (SPT samples), or capped brass liners that are then placed in sample bags.

j. Brass liner samples selected for triaxial testing shall be carefully removed from the sampler, and kept in the original vertical position. These samples shall be inspected and provided with tight-fitting, plastic endcaps that are taped onto the brass tube. These samples shall be carefully handled and transported in padded boxes to the testing laboratory.

k. Undisturbed soil samples in thin-wall Shelby or Pitcher tubes shall be carefully extracted from the borehole and sampling devices, and kept in the original vertical position during logging, sample handling, and transportation to the laboratory. Undisturbed samples shall be held vertically in a padded container that protects the sample from vibrations or disturbance for transport.

l. Thin-wall sample tubes for undisturbed samples shall be sealed with a minimum thickness of ½-inch of non-shrinking wax (e.g., Petrowax) on both the top and bottom of the sample.

m. Drive sample bags, and undisturbed sample tubes, shall be clearly marked with the following information in indelible ink:

   - Job Name
   - Date of Sampling
   - Borehole Number
   - Depth Interval and Sample Length
   - Field Sample Number
   - Initials of Geologist

6.1.6. Sample Storage

a. Rock core and soil samples should be stored on site in a weather-protected shed or warehouse following completion of the work.

b. Portions of rock core and soil samples that are left-over after testing should be repacked in labeled plastic bags, or metal sample tubes, and returned to the site for storage in labeled containers. Upon receipt at the site, these samples should be stored along with the rock soil samples.

c. Chain-of-custody forms documenting transport of the samples from the field to the testing laboratories shall be maintained in the WLA project file. Chain-of-custody forms shall also be filled out by the testing laboratories and sent along with returned samples.

6.2. Cone Penetrometer Sounding (CPT)

a. Approximately four cone penetrometer (CPT) soundings will be made at the site within, or adjacent to, the proposed facility footprint to obtain continuous logs of texture and mechanical properties of unconsolidated soils.

b. At least one CPT sounding shall be made adjacent to a mud rotary boring, after it has been backfilled, to provide site calibration.

c. CPT soundings shall not be made closer than 25 borehole diameters from any unbackfilled or uncased borings. CPT testing should be performed under the observation of the WLA geologist.

d. CPT testing shall be performed using standard commercial electronic friction cone, piezocone, and seismic cone equipment and procedures, and according to ASTM D5778-95 "Standard test method for performing electronic friction cone and piezocone testing of soils".

e. The CPT subcontractor shall produce records of previous calibration testing and equipment calibration traceable to the National Institute of Standards and Technology (NIST).

f. Data processing should be performed using commercial software that has been calibrated no more than 6 months prior to the field work.

g. CPT downhole equipment shall be water washed or steam cleaned prior to mobilizing to the site, and should be inspected by the WLA field geologist in conjunction with the CPT crew to ensure materials and equipment are clean, in visibly good condition, and of appropriate dimensions and quality.

h. Notes regarding equipment response and penetration shall be recorded by the WLA geologist during each sounding. This shall include the following observations: (1) company and personnel overseeing and performing CPT field work; (2) visible condition of equipment prior to each sounding; (3) pre-sounding equipment calibration; (4) general ease of penetration and/or indications of difficult penetration or refusal; and, (5) possible deflections of push rods or unusual noise or vibration.

i. Field test results shall be plotted on draft graphical plots and reviewed by the WLA geologist prior to demobilizing from each sounding location.

j. Repeat tests shall be performed 1.5 meters from the original sounding location at the direction of the WLA geologist.

k. Field CPT logs shall be reviewed by the WLA Project Manager.

l. Upon completion of CPT soundings, and review and approval of collected data by the WLA geologist, each sounding hole is to be completely backfilled to the ground surface with bentonite-grout mix.

6.3. Geophysical Surveys

a. Geophysical surveys will include P-S suspension velocity logging in boreholes, and possibly also surface refraction velocity surveys. P-S surveys will be performed in each of the three borings.

Refraction surveys, if used, will be performed in the general footprint area of the proposed facility. Descriptions of the P-S and refraction survey methods are included in Attachment 4.

b. The geophysical team shall keep daily records of each survey that are signed and dated. Preliminary and final data sheets and logs shall be reviewed by the WLA Project Manager.

6.3.1. P-S Suspension Logging

a. P-S suspension velocity surveys will be performed in the exploratory boreholes to obtain vertical compressional and shear wave velocity profiles of site bedrock and overburden materials. P-S borehole logging will be performed using the OYO P-S suspension logging method in uncased boreholes prepared by the mud rotary and diamond coring techniques.

b. P-S surveys should be performed according to the methodology described in Nigbor and Imai, 1994 "The suspension P-S velocity logging method" included in Attachment 4.

c. Field verification of test results will be performed by comparing downhole receiver-to-receiver velocities against source-to-receiver velocities.

d. Survey results should be reviewed by a second geophysicist from GEOVision subcontractor's company, and the review should be documented in a letter sent to the WLA Project Manager.

6.3.2. Surface Refraction Surveys

a. Surface refraction velocity surveys may be performed to obtain shallow compressional wave velocity data in the upper unconsolidated soil materials. The surveys are to be performed at locations determined in the field by the WLA geologist.

b. Surface refraction surveys shall be performed using the equipment and methodology described in the GEOVision "Procedure for seismic refraction method" in Attachment 4.

c. Survey endpoint locations should be staked in the field. Geophone and shotpoint locations should be determined in the field using measuring tapes and compasses.

d. Velocity interpretations should be made by two geophysicists working and evaluating data together to a positional accuracy about 5 feet by the geophysical team using existing S.F. maps.

6.4. Laboratory Testing

a. Laboratory Testing will be performed on samples collected from exploratory boreholes to determine geotechnical, mechanical, and dynamic properties of soil and rock materials. The following tests are planned:

- Unit weight/moisture content – ASTM D2216-91 and D2166-91
- Mechanical sieve grain-size analyses – ASTM D422-63 and D1140-97
- Atterberg Indices - ASTM D4318-98
- Unconfined compression rock – 2938-95
- Unconfined compression soil – D2166-91

- Torsional Shear/Resonant Column – UTEXAS procedure PBRCTS-1D4015-92, and attached procedures (Attachment 5)
- Consolidated un-drained triaxial compression – D4767-88 .

b. Testing shall be performed according to the testing schedules denoted on the Chain-of-Custody form, or according to a modified testing schedule to be discussed and approved with the WLA Project Manager.

c. Upon arrival at the laboratory, samples shall be carefully unpacked to minimize disturbance, inventoried against the Chain-of-Custody form, and inspected. The condition of the samples upon receipt at the laboratory shall be documented by laboratory personnel on the Chain-of-Custody form or a letter. The signed Chain-of-Custody form and sample condition letter shall be returned to the WLA Project Manager for review prior to initiation of testing, and will be placed in the WLA file.

d. Tests requiring undisturbed samples shall not be performed on samples obtained from sample tubes with recovery lengths of less than 90% unless inspection of the samples prior to testing indicates no visible evidence of sample disturbance. Tested samples should have no visible distortions, planes of failure, pitting, discoloration, or other signs of disturbance that can be attributed to sampling operations or handling unless examination by a WLA geologist determines that the sample is still valid. Test results obtained from such samples shall not be used for subsequent analyses unless sample properties such as density are determined to be consistent with those of samples in similar soils obtained from tubes with full recovery and that do not show signs of disturbance.

e. Sample extraction and trimming shall be performed with care to prevent disturbance and changes in water content.

f. Prior to testing, samples shall be stored in a separate storage room from the testing room at a controlled relative humidity maintained at or near 100%.

7.0 PHOTOGRAPHS

A setting and locational photograph shall be taken of the drill and CPT rigs at each borehole/sounding location, and of the geophysical equipment setup at each borehole and refraction survey line location. Additionally, photographs shall be taken in the field of each filled rock core box prior to preparation of the core boxes for transportation, and of select samples of overburden soils. Each photograph of core or samples should have corebox notations or index cards that document the date of photograph and sample location and depth (borehole number and depth interval). A unique number shall be assigned to each roll of film, and shall be accompanied by a photo log filled out in the field and kept in the file. A copy of the photo log is provided on Attachment 6.

8.0 WLA PROJECT FILE

The following records shall be maintained in the WLA project file until directed by the ENERCON Project Manager that they may be disposed of or shall be transferred to ENERCON:

- WLA daily reports
- Subcontracts between WLA and subcontractors

- WLA field notebooks, and data sheets
- Data reports prepared by subcontractors
- Instrument calibration records
- Photograph logs, photos, and associated negatives
- Boring logs
- Laboratory sample Chain-of-Custody forms
- WLA field exploration data report

9.0 LOST DATA

In cases where exploratory boring logs, photo logs, samples, or photographs are lost or damaged, the WLA Project Manager shall determine if interpretations can be made from existing data or if data needs to be recollected. These actions shall be documented in a memorandum to the file indicating the type and number of data lost or damaged.

10.0 TECHNICAL REVIEW

Technical review shall be provided by the WLA Technical Reviewer assigned to the project. The review shall be performed on a periodic basis or as requested by the WLA Project Manager. The Technical Reviewer shall document their findings and recommendations in a letter report.

11.0 DELIVERABLES

The deliverables from the field characterization work shall consist of collected data presented in a data report that includes borehole and geophysical logs, engineering geologic cross sections, and laboratory data. The format of the data report may follow that suggested in the ENTERGY procedure ES-P-003-00, "Engineering Reports." The data report shall be independently reviewed, and the review documented, in accordance with the review requirements specified in ENERCON CSP 3.01 for calculations. Technical peer review of activities shall be provided by the WLA Technical Reviewer assigned to the project. The peer review shall be performed on a periodic basis or as requested by the Project Manager.

12.0 REFERENCES

American Society for Testing and Materials (ASTM) References:

D1586-84	Standard test method for penetration test and split-barrel sampling of soils
D1587-94	Standard practice for thin-walled tube geotechnical sampling of soils
D2113-83	Standard practice for diamond core drilling for site investigation
D2487-00	Standard classification of soils for engineering purposes (Unified Soil Classification System)
D2488-00	Standard practice for description and identification of soils (visual-manual procedure)
D4220-95	Standard practice for preserving and transporting soil samples
D5079-90	Standard practice for preserving and transporting rock core samples

D5778-95	Standard test method for performing electronic friction core and piezocone testing of soils
D1140-97	Standard test method for amount of material in soils fines than the No. 200 sieve
D422	Standard test method for particle-size analysis of soils
D4767-88	Standard test method for consolidated-undrained triaxial compression test on cohesive soils
D2166-91	Standard test method for unconfined compressive strength of cohesive soil
D2216-91	Standard test method for unconfined compressive strength of cohesive soil
D4318-98	Standard test methods for liquid limit, plastic limit, and plasticity index of soils
D2938-95	Standard test methods for unconfirmed compressive strength of intact rock core specimens
D5783-95	Standard guide for use of direct rotary drilling with water-based drilling fluid for geoenvironmental exploration and the installation of subsurface water-quality monitoring devices
D6032-96	Standard test method for determining rock quality designation (RQD) of rock core
D4318	Standard test method for liquid limit, plastic limit, and plasticity index of soils
D4767-88	Standard test method for consolidated undrained triaxial compression test for cohesive soils

<u>Other References:</u>

Brown, E.T., Rock characterization, testing, and monitoring, ISRM suggested methods: Pergamon Press, Oxford.

Hoek, E., 1996, Very poor quality rock masses, draft paper.

Munsell soil color charts, 1994, Marbeth Division of Kollmarsen Instruments Corporation, New Windsor, New York.

University of Texas, Austin, 1993, PBRCTS-1, Technical procedures for resonant column and torsional shear (RCTS) testing of soil and rock samples

13.0 ATTACHMENTS

13.1 Boring Log Forms

13.2 WLA Soil and Rock Field Classification Sheets

13.3 Geotechnical Sample – Chain of Custody Form

13.4 Geophysical Survey Procedures

13.5 University of Texas – Dynamic Soil Testing Procedure

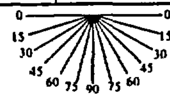
13.6 Photo Log

13.1. Boring Log Forms (6 pages)

LOG of ROCK BORING________

Page __1__ of ____

Project	Job Number	Boring Location	Total Depth
Type & Diameter of Boring	Elevation and Datum	Ground Water Depth	Depth to Bedrock
Drilling Contractor and Rig	Length of Core Barrel and Bit	No. of Core Boxes	Date Started
Casing Size and Depth	Borehole Inclination	Logged By	Date Completed



WLA

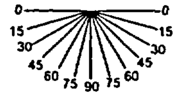
Depth (feet)	Log	Drill Rate (min/ft)	Run No.	Recovery/Cut	% Recovery	RQD	Weathering	Fracture Spacing	Strength	Lithologic Description	Discontinuities	Description of Discontinuities	Remarks
0													
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													
13													
14													
15													

Weathering: Fr-Fresh, SW-Slight, MW-Moderate, HW-Highly, CW-Completely, and RS-Residual soil. Fracture Spacing: VW -Very Wide (>3'), Wi-Wide (1'-3'), Mo-Moderate (0.3'-1'), Cl-Close (0.1'-0.3'), and VC-Very Close (<0.1'). Strength: R6-Extremely Strong, R5-Very Strong, R4-Strong, R3-Medium Strong, R2-Weak, R1-Very Weak, and R0-Extremely Weak. Lithologic Description: Rock type, color, texture, grain size, etc. Discontinuities: Be-Bedding, Fa-Fault, Fo-Foliation, Jo-Joint, Me-Mechanical break, Sh-Shear, and Ve-Vein. Joint descriptions: Dip, Surface shape (Pl-Planar, St-Stepped, or Wa-Wavy), Roughness (Sm-Smooth, Sl-Slightly Rough, Ro-Rough, and VR-Very Rough). Aperture (Fi-Filled, He-Healed, Op-Open and Ti-Tight), type of infilling, slickensides, etc.

ROCK BORING LOG

Page ____ of ____

Project	Job Number	Date	Boring No.



WLA

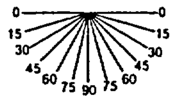
Depth (feet)	Log	Drill Rate (min/ft)	Run No.	Recovery/Cut	% Recovery	RQD	Weathering	Fracture Spacing	Strength	Lithologic Description	Discontinuities	Description of Discontinuities	Remarks
5													
6													
7													
8													
9													
0													
1													
2													
3													
4													
5													
6													
7													
8													
9													
0													

Weathering: Fr-Fresh, SW-Slight, MW-Moderate, HW-Highly, CW-Completely, and RS-Residual soil. Fracture Spacing: VW -Very Wide (>3'), Wi-Wide (1'-3'), Mo-Moderate (0.3'-1'), Cl-Close (0.1'-0.3'), and VC-Very Close (<0.1'). Strength: R6-Extremely Strong, R5-Very Strong, R4-Strong, R3-Medium Strong, R2-Weak, R1-Very Weak, and R0-Extremely Weak. Lithologic Description: Rock type, color, texture, grain size, etc. Discontinuities: Be-Bedding, Fa-Fault, Fo-Foliation, Jo-Joint, Mc-Mechanical break, Sh-Shear, and Ve-Vein. Joint descriptions: Dip, Surface shape (Pl-Planar, St-Stepped, or Wa-Wavy), Roughness (Sm-Smooth, Sl-Slightly Rough, Ro-Rough, and VR-Very Rough), Aperture (Fi-Filled, He-Healed, Op-Open and Ti-Tight), type and amount of infilling, slickensides, etc.

ROCK BORING LOG

Page ____ of ____

Project	Job Number	Date	Boring No.



WLA

Depth (feet)	Log	Drill Rate (min/ft)	Run No.	Recovery/Cut	% Recovery	RQD	Weathering	Fracture Spacing	Strength	Lithologic Description	Discontinuities	Description of Discontinuities	Remarks
0													
1													
2													
3													
4													
5													
6													
7													
8													
9													
0													
1													
2													
3													
4													
5													

Weathering: Fr-Fresh, SW-Slight, MW-Moderate, HW-Highly, CW-Completely, and RS-Residual soil. Fracture Spacing: VW -Very Wide (>3'), Wi-Wide (1'-3'), Mo-Moderate (0.3'-1'), Cl-Close (0.1'-0.3'), and VC-Very Close (<0.1'). Strength: R6-Extremely Strong, R5-Very Strong, R4-Strong, R3-Medium Strong, R2-Weak, R1-Very Weak, and R0-Extremely Weak. Lithologic Description: Rock type, color, texture, grain size, etc. Discontinuities: Be-Bedding, Fa-Fault, Fo-Foliation, Jo-Joint, Mc-Mechanical break, Sh-Shear, and Ve-Vein. Joint descriptions: Dip, Surface shape (Pl-Planar, St-Stepped, or Wa-Wavy), Roughness (Sm-Smooth, Sl-Slightly Rough, Ro-Rough, and VR-Very Rough), Aperture (Fi-Filled, He-Healed, Op-Open and Ti-Tight), type and amount of infilling, slickensides, etc.

WLA

BORING LOG

Page 1 of ___

Project	Job No.	Boring No.	Boring Location
Type & Diameter of Boring		Elevation @ Top of Hole / Total Depth	
Sampling Method		Sample Driving Hammer and Drop	
Drilling Contractor and Rig		Date Started	Date Completed
		Depth to groundwater	Logged By
		Notes:	

SPT N (60) 0 10 20 30 40 50 60	Uncorrected Blows per 6-inch drive	Depth (feet)	Soil Type (USCS)	Sampler Type	Recovery (inches)	Pocket Pen. (TSF)	Shear Torvane (TSF)	Description	Remarks
		0							
		1							
		2							
		3							
		4							
		5							
		6							
		7							
		8							
		9							
		10							
		11							
		12							
		13							
		14							
		15							

3.0-inch O.D. split spoon sampler

2.5-inch O.D. split spoon sampler

Standard Penetration Test (SPT) sampler

WLA

BORING LOG

Page 2 of ___

Project	Job No.	Boring No.

SPT N1(60) 0 10 20 30 40 50 60	Uncorrected Blows per 6-inch drive	Depth (feet)	Soil Type (USCS)	Sampler Type	Recovery (inches)	Pocket Pen. (TSF)	Shear Torvane (TSF)	Description	Remarks
		15							
		16							
		17							
		18							
		19							
		20							
		21							
		22							
		23							
		24							
		25							
		26							
		27							
		28							
		29							
		30							
		31							
		32							

3.0-inch O.D. split spoon sampler 2.5-inch I.D. split spoon sampler Standard Penetration Test (SPT) sampler

WLA

BORING LOG

Page ____ of ____

Project	Job No.	Boring No.

SPT $N_1(60)$ 0 10 20 30 40 50 60	Uncorrected Blows per 6-inch drive	Depth (feet)	Soil Type (USCS)	Sampler Type	Recovery (inches)	Pocket Pen. (TSF)	Shear Torvane (TSF)	Description	Remarks

3.0-inch O.D. split spoon sampler

2.5-inch I.D. split spoon sampler

Standard Penetration Test (SPT) sampler

13.2. WLA Soil and Rock Field Classification Sheets (7 pages)

WLA SOIL DESCRIPTION REFERENCE SHEET 1

SOIL TYPE (USCS symbol); color; moisture condition; consistency or density; component percentages; other characteristics; additional comments (Geologic Interpretation).

SOIL TYPE: See back side of page regarding USCS soil types. List main component first in CAPITAL letters, followed by secondary components in order of decreasing abundance, separated by a comma or "with".

COLOR: Use Munsell colors when possible or use following table by default (color terms below can be prefaced with"light" or "dark").

Generalized Color Terms				
	gray	red	yellowish brown	olive
	greenish gray	reddish brown	reddish yellow	white
	black	brown	olive brown	yellow

Based on Munsell color charts, 1994

MOISTURE CONDITION:

Dry	Absence of moisture, dusty, dry to the touch
Damp	Slight moisture content, difficult to mold fines into ball.
Moist	Moisture evident but no visible water, fines can be molded into ball
Wet	Visible free water, soil is usually below water table

modified from ASTM 2488-93

CONSISTENCY (fine grained)

SPT blow counts	Pocket Pen. (ksf)	CONSISTENCY	Field Test
<2	<1/4	Very soft	Extruded between fingers when squeezed
2 - 4	1/4 - 1/2	Soft	Molded by light finger pressure
4 - 8	1/2 - 1	Medium stiff	Molded by strong finger pressure
8 - 15	1 - 2	Stiff	Readily indented by thumb but penetrated with great effort
15 - 30	2 - 4	Very stiff	Readily indented by thumbnail
>30	>4	Hard	Indented with difficulty with thumb nail

DENSITY(coarse grained)

SPT blow counts	DENSITY
0 to 4	Very loose
4 - 10	Loose
10 - 30	Medium dense
30 - 50	Dense
>50	Very dense

Consistency: NAVFAC Design Manual 7.01, 1986; Density: EPRI EL-6800 Manual on Estimating Soil Properties for Foundation Design, 1990.

COMPONENT PERCENTAGE: Estimate the relative percentage of coarse and fine grain material to the nearest 5%, if possible. Refer to the charts on Sheet 2 for estimating percentages in hand samples. This can also be done using the Jar Method as described in ASTM 2488: Mix the soil sample and water in a small jar with a lid (ex. a baby jar); shake thoroughly; allow to settle; coarse grain particles will settle first, sand will fall out of suspension in 20 to 30 seconds, silts will take over 30 seconds, and clays may or may not settle during the duration of test.

OTHER CHARACTERISTICS:

FINE-GRAIN COMPONENT (tests briefly described on Sheet 2 and fully explained in ASTM 2488-93):

Dry Strength		Dilatancy		Toughness		Plasticity	
None	Crumbles w/mere pressure	None	No visible change	Low	Slight pressure, thread soft&weak	Nonplastic	Thread cannot be rolled at any water content
Low	Crumbles w/some pressure	Slow	Water appears slowly on surface& disappears slowly upon squeezing	Medium	Medium pressure, thread medium stiff	Low	Thread can barely be rolled, ball cannot be formed after rolled
Medium	breaks w/considerable pressure			High	Considerable pressure, thread very high stiffness	Medium	Thread easily rolled, cannot be rerolled
High	Breaks between thumb & hard surface	Rapid	Water appears quickly on surface & disappears quickly			High	Considerable time needed to roll thread, can be rerolled several times, ball can be formed without crumbling when drier than PL.
V. high	Cannot be broken						

SOIL SYMBOL	DRY STRENGTH	DILATENCY	TOUGHNESS
ML	None to low	Slow to rapid	Low or thread cannot be formed
CL	Medium to high	None to slow	Medium
MH	Low to medium	None to slow	Low to medium
CH	High to very high	None	High

From ASTM 2488

Soil structure: Note any soil structure, blocky, prismatic, etc.

COARSE-GRAIN COMPONENT:

Lithology: eg. quartz sand, chert gravels, gravels of varied lithologies including granite, diorite, and phyllite.
Grading: Well graded or poorly graded
Grain angularity (coarse sand or larger): rounded, subrounded, subangular, angular. Refer to Sheet 2 figure.
Maximum grain size (gravels or larger)

ADDITIONAL COMMENTS: presence of roots; reaction with HCl: none, weak, strong; odor; clay films; etc.
(GEOLOGIC INTERPRETATION): Alluvium, colluvium, weathered rock, landslide deposit, soil horizons, etc.

WLA SOIL DESCRIPTION REFERENCE SHEET 1

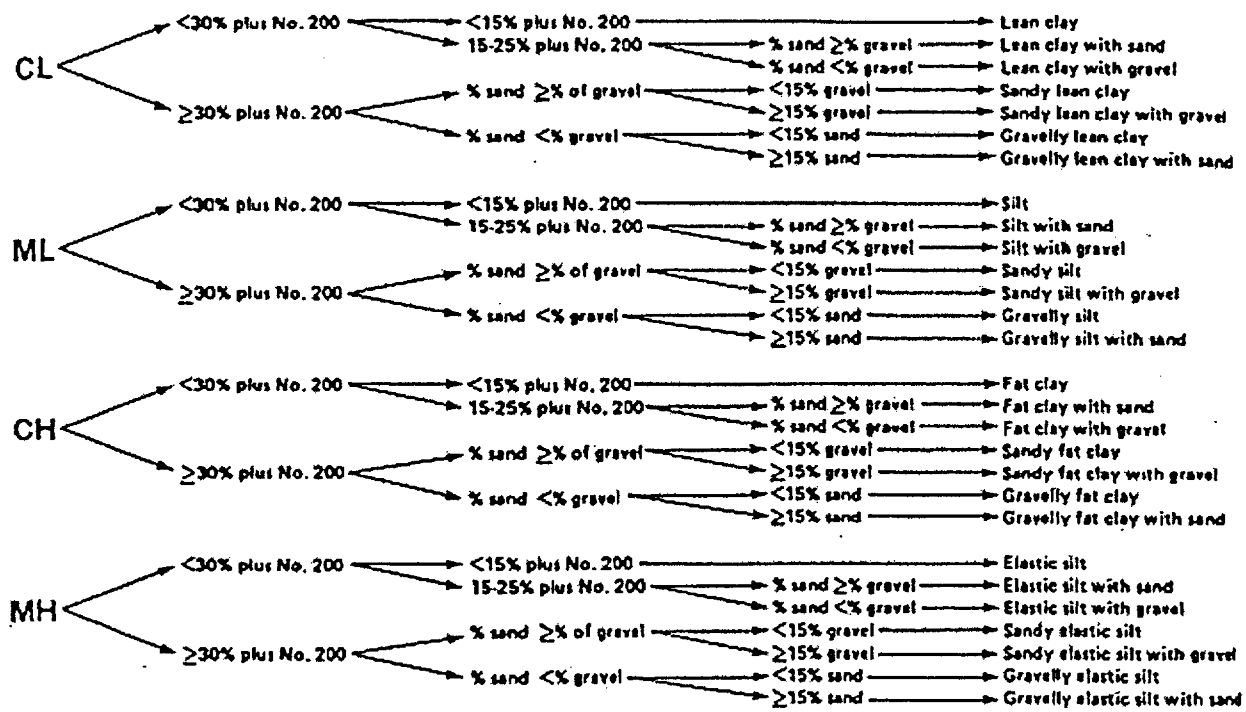
WLA MODIFIED PROCEDURES:

(1) Primary component should be listed first in CAPITAL letters, followed by secondary components in order of decreasing abundance separated by a comma or "with".

(2) The terms fat, lean, and elastic can be dropped from field classification and added to final logs based on basis of laboratory test results.

FINE-GRAIN SAMPLES

GROUP SYMBOL GROUP NAME



NOTE—Percentages are based on estimating amounts of fines, sand, and gravel to the nearest 5 %.

COARSE-GRAIN SAMPLES

GROUP SYMBOL GROUP NAME

When hammer sampling, the following data should be recorded:
Delivery system: Cat-head hammer
Automatic trip hammer
Downhole hammer
Weight/drop: ASTM Standard is 140 lb w/30" drop
Sampler size:
SPT Sampler: 2.0-in. O.D., 1.375-in. I.D. split-spoon sampler, may need brass liners
2.5-inch O.D., 2.0-inch I.D. split-spoon sampler with 1 or 6-inch long brass ring liners
3.0-in. O.D., 2.5-in. I.D. split-spoon sampler with 1 or 6-inch long brass ring liners

Blow counts: Should be recorded at six inch intervals for a total of 18 inches.

Push Samples:
When push sampling, the following data should be recorded:
Sampler type: Shelby tubes, pitcher tubes, others
Downfeed pressure: This is read off of gauges on the drill rig. It should be checked throughout sampling, and a range of values should be given if appropriate. Drillers should be asked about reliability of gauges.

WLA SOIL DESCRIPTION REFERENCE SHEET 1

WLA Soil Classification based on ASTM 2488-93 Standards with minor modifications:
Primary component should be listed first in CAPITAL letters, followed by secondary components in order of decreasing abundance separated by a comma or "with".

FINE GRAINED SOIL TYPES

Soil Type	Percent composition	USCS Group Symbol ***
All CLAY's	Clay + Silt ≥ 50%, clay% > silt%	CL(lean) or CH (fat)
All SILT's	Clay + Silt ≥ 50%, silt% > clay%	ML(lean) or MH (fat)
CLAY or SILT	< 15% sand + gravel	clay (CL or CH), silt (ML or MH)
CLAY or SILT with sand,	15-29% sand + gravel, sand ≥ gravel	clay (CL or CH), silt (ML or MH)
CLAY or SILT with gravel	15-29% sand + gravel, gravel > sand	clay (CL or CH), silt (ML or MH)
CLAY or SILT, sandy	≥ 30% sand + gravel, sand ≥ gravel, <15% gravel	clay (CL or CH), silt (ML or MH)
CLAY or SILT, sandy with gravel	≥ 30% sand + gravel, sand ≥ gravel, ≥15% gravel	clay (CL or CH), silt (ML or MH)
CLAY or SILT, gravelly	≥ 30% sand + gravel, gravel > sand, <15% sand	clay (CL or CH), silt (ML or MH)
CLAY or SILT, gravelly with sand	≥ 30% sand + gravel, gravel > sand, ≥15% sand	clay (CL or CH), silt (ML or MH)
CLAY, silty	Clay+Silt ≥ 50%, clay%≈silt%(±5%)	CL - ML
CLAY, silty with sand	15-29% sand + gravel, sand ≥ gravel	CL - ML
CLAY, silty with gravel	15-29% sand + gravel, gravel > sand	CL - ML
CLAY, silty, sandy	≥ 30% sand + gravel,	CL - ML
CLAY, silty, sandy with gravel	≥ 30% sand + gravel, sand ≥ gravel, ≥15% gravel	CL - ML
CLAY, silty, gravelly	≥ 30% sand + gravel, gravel > sand, <15% sand	CL - ML
CLAY, silty, gravelly with sand	≥ 30% sand + gravel, gravel > sand, ≥15% sand	CL - ML

FINE GRAINED SOIL TYPES

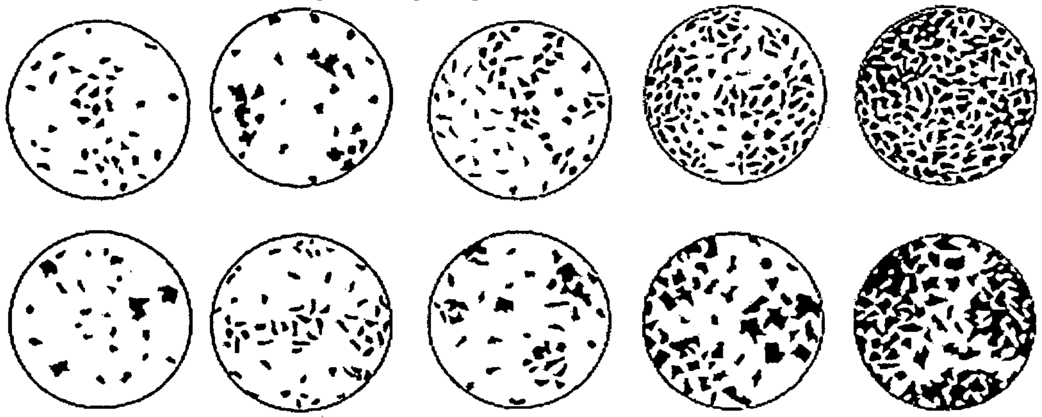
Soil Type	Percent composition	USCS Group Symbol ***
All SAND's	Sand + Gravel ≥ 50%, sand% ≥ gavel%	SP (poorly graded)or SW (well graded)
All GRAVEL's	Sand + Gravel ≥ 50%, ravel% > sand%	GP (poorly graded)or GW (well graded)
SAND	<5% fines, <15% gravel	SW or SP
SAND with gravel	<5% fines, >15% gravel	SW or SP
SAND with silt	5-12% silt, <15% gravel	SW-SM or SP-SM
SAND with silt and gravel	5-12% silt, >15% gravel	SW-SM or SP-SM
SAND with clay	5-12% clay, <15% gravel	SW-SC or SP-SC
SAND with clay and gravel	5-12% clay, >15% gravel	SW-SC or SP-SC
SAND with silty clay	5-12% silty clay, <15% gravel	SW-SC or SP-SC
SAND with silty clay & gravel	5-12% silt y clay, >15% gravel	SW-SC or SP-SC
SAND, silty	>12% silt, <15% gravel	SM
SAND, silty with gravel	>12% silt, ≥15% gravel	SM
SAND, clayey	>12% clay, <15% gravel	SC
SAND, clayey with gravel	>12% clay, >15% gravel	SC
SAND, silty, clayey	>12% silty clay, <15% gravel	SC-SM
SAND, silty, clayey with gravel	>12% silty clay, ≥15% gravel	SC-SM
GRAVEL	<5% fines, <15% sand	GW or GP
GRAVELwith sand	<5% fines, ≥15% sand	GW or GP
GRAVELwith silt	5-12% silt, <15% sand	GW-GM or GP-GM
GRAVELwith silt and sand	5-12% silt, ≥15% sand	GW-GM or GP-GM
GRAVELwith clay	5-12% clay, <15% sand	GW-GC or GP-GC
GRAVELwith clay and sand	5-12% clay, ≥15% sand	GW-GC or GP-GC
GRAVELwith silty clay	5-12% silty clay, <15% sand	GW-GC or GP-GC
GRAVELwith silty clay & sand	5-12% silt y clay, ≥15% sand	GW-GC or GP-GC

GRAVEL, silty	>12% silt, <15% sand	GM
GRAVEL, silty with sand	>12% silt, ≥15% sand	GM
GRAVEL, clayey	>12% clay, <15% sand	GC
SAND, clayey with sand	>12% clay, ≥15% sand	GC
GRAVEL, silty, clayey	>12% silty clay, <15% sand	GC-GM
GRAVEL, silty, clayey with sand	>12% silty clay, ≥15% gravel	GC-GM

* The term rocky may be used for gravel-sized, angular-to-subangular rock clasts that do not appear to be fluvial in nature, but rather colluvial or related to in-situ rock weathering.
** Organic soils (OL& OH) are not included, See ASTM2488-93

WLA SOIL DESCRIPTION REFERENCE SHEET 2

PERCENT COMPOSITION: Estimating coarse grain percentage of hand samples.



7% 10% 15% 30% 50%

From AGI Data Sheets for Geology in the Field, Laboratory, and Office, 1982.

OTHER CHARACTERISTICS:

Fine Grain Component Tests

Dry strength: None, low, medium, high, or very high. Test: Work material into putty-like consistency, adding water if necessary; mold into either ball or square (1/2 in. ø); allow to dry; crush between fingers; note strength..

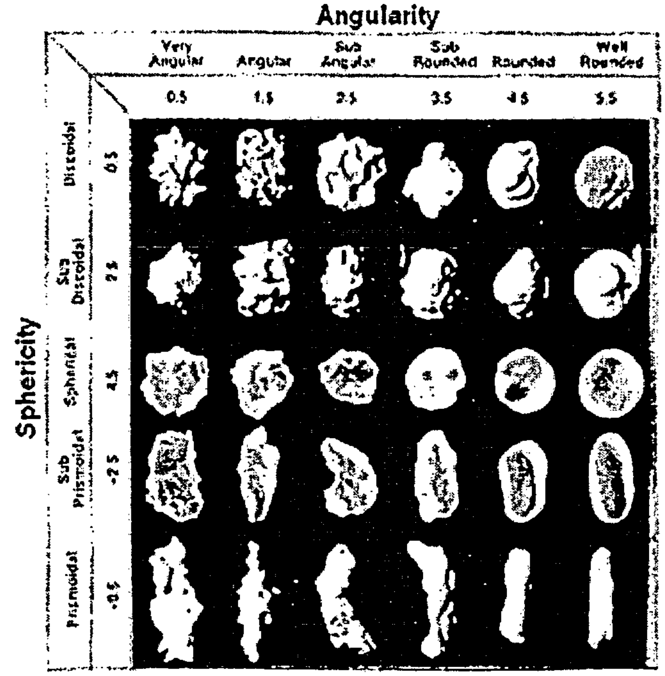
Dilatancy: None, slow, or rapid. Test: Work material into putty-like consistency, adding water if necessary; mold into either ball or square (1/2 in. ø); smooth ball into hand; shake vigorously; note reaction of water appearing on the surface of the soil; squeeze the sample; note reaction.

Toughness: Low, medium, or high. Test: Following dilatancy test; roll sample into 1/8 in. ø thread; fold thread & reroll until thread begins crumbling at 1/8 in. ø (this is near the plastic limit); note pressure required near PL.

Plasticity: Nonplastic, low, medium, or high. Test: Use same method as toughness test if sample is inorganic.

Coarse Grain Component

Grain angularity and sphericity (coarse sand or larger): rounded, subrounded, subangular, angular. Refer to figure below.



SOIL SAMPLING TECHNIQUES

Hammer Samples:

WILLIAM LETTIS & ASSOCIATES, INC.

ROCK CHARACTERIZATION REFERENCE GUIDE

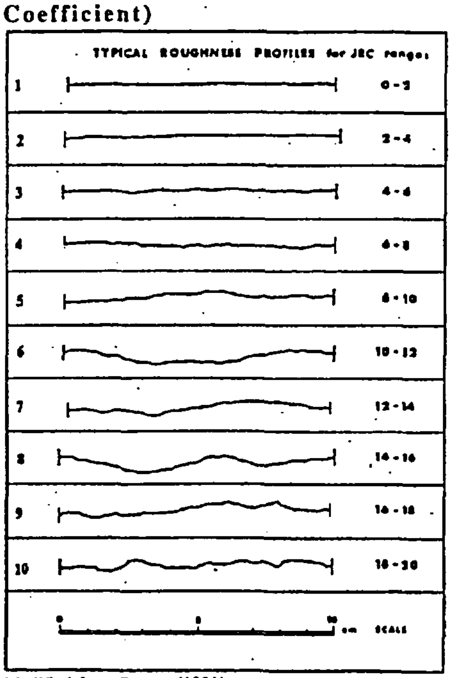
ROCK STRENGTH CLASSIFICATION SCALE

Term	Hardness Designator/ Grade	Field Identification	Approximate range of uniaxial compressive strength
Extremely Weak	R0	Can be indented with difficulty by thumbnail. May be friable or moldable with finger pressure.	<150 psi
Very Weak	R1	Crumbles under firm blows with point of geologic hammer. Can be pealed by a pocket knife.	150-725 psi
Weak	R2	Can be peeled or scraped by a pocket knife with difficulty. Cannot be scratched by fingernail. Shallow indention made by firm blow of geologic hammer.	725-3,625 psi
Medium Strong	R3	Cannot be scraped or picked with a pocket knife. Specimen can be fractured with a single firm blow of a hammer/geologic pick.	3,625-7,250 psi
Strong	R4	More than one blow of geologic hammer required to fracture specimen.	7,250-14,500 psi
Very Strong	R5	Specimen requires many hard blows of hammer to fracture or chip. Hammer rebounds after impact.	14,500-36,250 psi
Extremely Strong	R6	Specimen can only be chipped by hammer.	>36,250 psi

Modified from Brown (1981), Hoek (1996).

ROCK DISCONTINUITY ROUGHNESS

JRC (Joint Roughness Coefficient)



Modified from Brown (1981)

ROCK WEATHERING CLASSIFICATION SCALE

Designation	Symbol	Field Identification	Grade
Fresh	F	No visible sign of rock material weathering: perhaps slight discoloration on major discontinuity surfaces. Rings under hammer impact	I
Slightly Weathered	SW	Rock mass is generally fresh with slight discoloration in rock fabric. Discontinuities are stained and may contai clay. Decomposition extends upto 1" into rock.	II
Moderately Weathered	MW	Less than 50% of rock is decomposed. Significant portion of rock shows discoloration and weathering effects. Crystals are dull and/or altered. Discontinuities are stained and may contain secondary minerals. Strength is significantly less than fresh rock.	III
Highly Weathered	HW	Rock mass is more than 50% decomposed. Rock can be broken by hand or scraped with knife or pick. All discontinuities exhibit secondary mineralization. Surface of core is friable and/or pitted due to washing out of highly altered minerals by drill water.	IV
Completely Weathered	CW	Rock mass is completely decomposed but rock fabric and structure may still be evident (saprolite). Specimen is easily crumbled or penetrated with pocket knife or geologic pick.	V
Residual Soil	RS	All rock material is decomposed to soil. Rock fabric and structure completely destroyed. There is a large change in volume, but soil has not been significantly transported.	VI

Modified from Brown (1981)

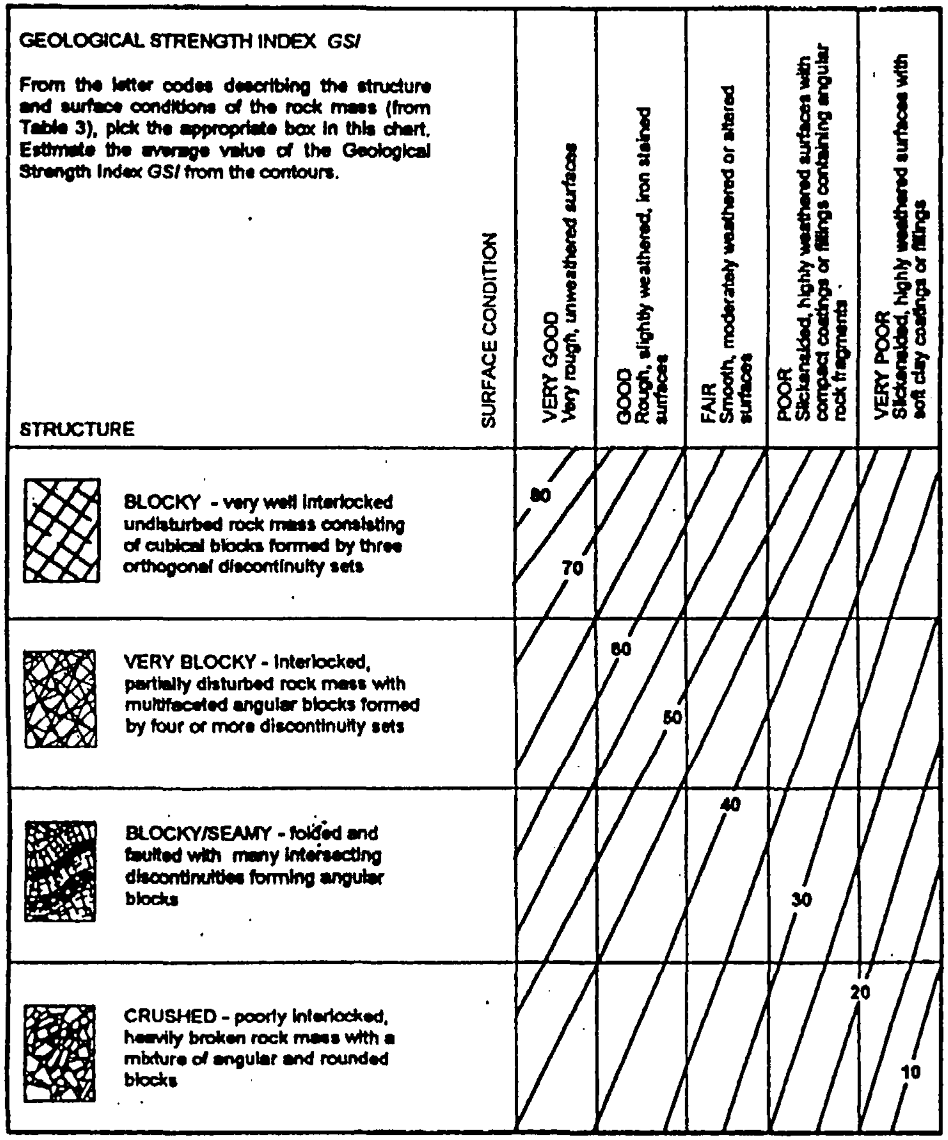
JOINT AND BEDDING SPACING TERMS

Spacing	Joint Spacing Term	Spacing	Bedding/Foliation Spacing Term
Less than 0.1 ft	Very close	Less than 1.5 in.	Very thin (laminated)
0.1 - 0.3 ft.	Close	1.5 in. - 4 in.	Thin
0.3 - 1.0 ft.	Moderately close	4 in. - 1 ft.	Medium
1.0 - 3.0 ft.	Wide	1 ft. - 3 ft.	Thick
3.0 - 10 ft.	Very wide	More than 3 ft.	Very thick
More than 10 ft.	Extremely wide		

Modified from Brown (1981) and Caltrans, 1996

ROCK MASS CHARACTERIZATION

Geologic Strength Index



from Hoek, 1996

Hoek-Brown Constant (m_i)

Rock type	Class	Group	Texture: Coarse	Texture: Medium	Texture: Fine	Texture: Very fine
SEDIMENTARY	Clastic		Conglomerate (22)	Sandstone 19	Siltstone 9	Claystone 4
				← Greywacke (18) →		
	Non-Clastic	Organic		← Chalk 7 →		
				← Coal (8-21) →		
		Carbonate	Breccia (20)	Sparitic Limestone (10)	Micritic Limestone 8	
		Chemical		Gypstone 16	Anhydrite 13	
METAMORPHIC	Non Foliated		Marble 9	Hornfels (19)	Quartzite 24	
	Slightly foliated		Migmatite (30)	Amphibolite 25 - 31	Mylonites (6)	
	Foliated*		Gneiss 33	Schists 4 - 8	Phyllites (10)	Slate 9
IGNEOUS	Light		Granite 33		Rhyolite (16)	Obsidian (19)
			Granodiorite (30)		Dacite (17)	
			Diorite (28)		Andesite 19	
	Dark		Gabbro 27	Dolerite (19)	Basalt (17)	
			Norite 22			
	Extrusive pyroclastic type		Agglomerate (20)	Breccia (18)	Tuff (15)	

from Hoek, 1996

13.3. Geotechnical Sample – Chain of Custody Form (1 page)

Chain of Custody Form – Grand Gulf NPP
(Controlled Document)

Project: ______________________ Date: ______________ Sheet ____ of ____

Shipped by: ______________________ Attention of: ______________________

Shipped to: ______________________ Hazardous materials suspected? yes/no

Borehole No.	Depth	Material	Field ID No.	Date Sampled	Sample Type	Sampled By	Analysis/Test Required (see index)	Lab ID (optional)

Sampler Signature: ______________________ Date: ______________

Relinquished by: (print)	Destination	Date	Received by: (print)	Organization	Date	Comments

Shipment Prepared By: (print/signature) ______________________ Date: ________ Shipment Method: ______________________

Received for Lab By: (print/signature) ______________________ Date: ________ Comments: ______________________

Receiving Laboratory: Please return original form after signing for receipt of samples; keep copy for your records. Retain all portions of unused samples in labeled containers.

Index of Sample Analyses:

(1) Unit Weight/Moisture Content	(4) Uniaxial compressive strength	(7) Consolidation series
(2) Sieve with minus 200 wash	(5) Triaxial compression (Cu w/pore press.)	(8) Dynamic shear torsion
(3) Atterberg Index	(6) Young's modulus	(9) Resonant column

13.4. Geophysical Survey Procedures (46 pages)

SUSPENSION P-S VELOCITY LOGGING METHOD

GEOVision
geophysical services
a division of Blackhawk Geometrics

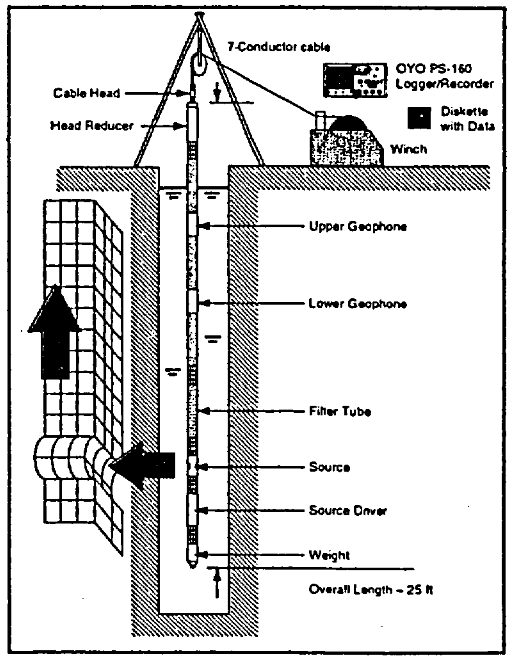
Overview

Suspension P-S velocity logging is a relatively new method of measuring seismic wave velocity profiles. Developed in the mid-1970s to answer the need for a technique that could measure seismic shear-wave velocities in deep, uncased boreholes, it was originally used by researchers at the OYO Corporation of Japan. The method gained acceptance in Japan in the mid-1980s and was used with other velocity measurement methods to characterize earthquake site response. Since the early 1990s it has gained acceptance in the U.S., especially among earthquake engineering researchers. GEO*Vision* personnel have logged over 300 boreholes using this technique since 1991.

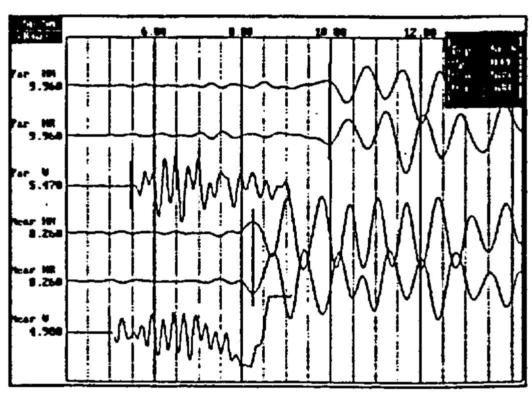
Procedure

The OYO P-S Logging System uses a 7-meter probe, containing a source and two receivers spaced 1 meter apart, suspended by a cable. The armored 4- or 7-conductor cable serves both to support the probe and to convey data to and from a recording/control device on the surface. The probe is lowered into the borehole to a specified depth (a rotary encoder on the winch measures probe depth), where the source generates a pressure wave in the borehole fluid. The pressure wave is converted to seismic waves (P and S) at the borehole wall. Along the wall at each receiver location, the P and S waves are converted back to pressure waves in the fluid and received by the geophones, which send the data to the recorder on the surface.

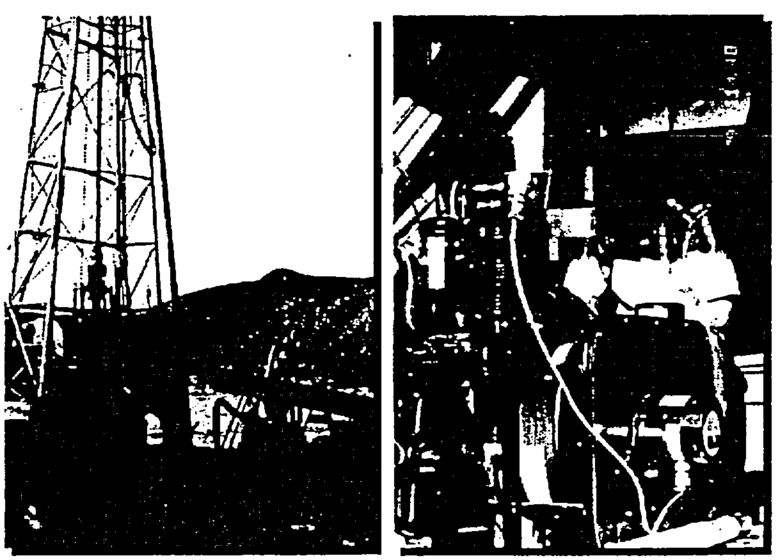
The elapsed time between arrivals of the waves at the receivers is used to determine the average velocity of a 1-meter-high column of soil around the borehole. Source to receiver analysis is also performed for quality assurance.



Oyo PS Suspension Logger Setup



Waveform Data for a Single Measurement

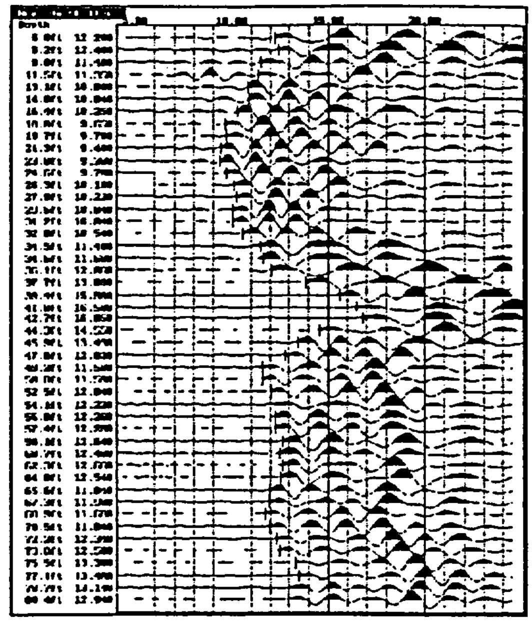


Oyo PS Suspension Logging System

Applications

Typical applications of suspension P- and S-wave velocity logging include:

- Dam safety investigations
- Seismic site response studies for bridge abutments, dams, buildings, etc.
- Foundation studies
- Measurement of soil/rock properties (i.e. shear modulus, bulk modulus, compressibility, and Poisson's ratio)
- Characterization of strong motion sites
- Velocity control for seismic reflection surveys

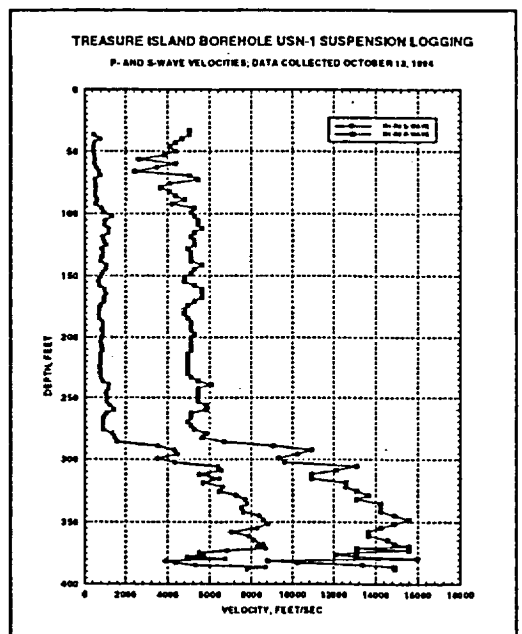


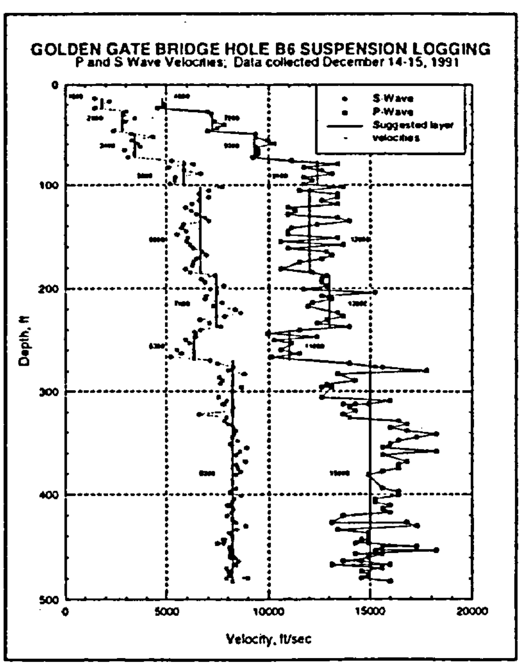
Depth Sequential Waveform Arrivals

Key Benefits

Suspension P- and S-wave velocity profiling using the OYO Suspension Logger has become the method of choice for obtaining high resolution borehole velocity measurements. The reasons are many:

- Only method that obtains both P- and S-wave velocity data reliably in a single hole at depths greater than 200 ft.
- Can be used in either uncased or cased (PVC) boreholes, although results are always better in uncased holes.
- Can be used in boreholes drilled from barges.
- Offers very high resolution (typically 1 meter) for resolving thin layers that can have a dramatic effect on surface response.
- Requires only 1 hole, as opposed to crosshole methods that require at least 2.
- Has been used to depths of 2,000 ft.





- Specifically adapted to soils, whereas tools developed for oil exploration are optimized for rock.
- Permits measurement of soil and rock properties such as shear modulus, bulk modulus, compressibility, and Poisson's ratio.
- Not hindered by fast layers and lack of depth penetration like surface methods such as downhole.

USE OF IN SITU TESTS IN GEOTECHNICAL ENGINEERING

Proceedings of In Situ '86, a Specialty Conference sponsored by the Geotechnical Engineering Division of the American Society of Civil Engineers

Co-sponsored by the Civil Engineering Department and the Continuing Education Department of Virginia Tech

Virginia Tech
Blacksburg, Virginia
June 23-25, 1986

Edited by Samuel P. Clemence

Geotechnical Special Publication No. 6

Published by the
American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398

In Situ P and S Wave Velocity Measurement

Satoru Ohya*

ABSTRACT

A review of the in situ techniques to measure P and S wave velocities by seismic wave propagation is presented. A relatively new technique, the suspension PS logging method, is described in detail. Field results of P and S wave velocity measurements utilizing the downhole method, cross hole method, and suspension PS logging method are compared and discussed. The PS suspension logging method is a promising technique and provides accurate velocity information in layered soils.

INTRODUCTION

All earthquakes provide a great opportunity to acquire information applicable to further development of earthquake engineering and earthquake hazard mitigation. Detailed observation of damage caused by earthquakes has given impetus to earthquake engineering research. This is especially true in the case of the Niigata earthquake of 16 June 1964.

The Niigata earthquake caused extensive damage to various engineering structures. Modern structures in Niigata were seismically designed and had adequate strength to resist strong shaking. However, because they were not designed taking into account liquefaction potential, a number of buildings and other structures overturned when the ground liquefied.

After the Niigata earthquake, the many investigations that were carried out revealed useful correlations between SPT blow counts and occurence or nonoccurence of liquefaction. Seed and Idriss (1967, 1971) first proposed the well-known practical method to assess liquefaction potential in which the dynamic shear strength of sand is compared with the earthquake-induced shear stress. Later, Seed (1979) proposed a more simplified procedure using SPT N-values for estimating in situ dynamic strength of sands and liquefaction potential. With reference to the proposals made by Seed and his colleagues, Iwasaki, Tatsuoka, and others proposed another practical, simplified procedure in which the ratio of dynamic shear strength to earthquake-induced shear stress is introduced as a key factor for the assessment of liquefaction potential. This method is now widely used to evaluate a liquefaction potential in Japan.

Earthquake engineering requires an interdisciplinary approach including seismology, geology, geophysics, and soil dynamics. This is especially important for predicting earthquake induced stresses in soil. For realistic response analyses, it is indispensable to know values of S and P wave velocities from the ground surface through the base layer.

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The writer and his colleagues have developed many techniques to obtain values of in situ S wave velocities. In this paper, primary emphasis will be given to procedures for in situ S wave measurement and especially to some recent developments.

IN SITU S WAVE VELOCITY MEASUREMENT

General Considerations

The dynamic response of a site depends strongly on the dynamic properties of the soil/rock. Research into the dynamic characteristics of soil have been carried out using laboratory soil testing techniques and in situ tests, including geophysical methods.

These tests reveal dynamic moduli and damping factors under various conditions. Research continues into the degree to which these parameters are affected by rate of strain, because soil/rock is not elastic or linear.

Seismic methods are being used to measure the propagation velocities of P and S waves. Especially, the measurement techniques for S wave velocity have shown tremendous improvement within the past 10 years. In Japan, the downhole technique has been widely adopted and a great deal of data has been accumulated. This technique has become indispensable for determining values of dynamic moduli and Poisson's ratio of soils at relatively small strain levels. In field geophysical explorations, it is very difficult to apply dynamic stresses that induce various strain levels, but velocity measurements of P and S waves with small strain levels is quite easy. On the other hand, in laboratory testing it is difficult to measure P and S wave velocities of soil under actual stress conditions, but it is easier to carry out a dynamic test with various levels of strain under controlled stress conditions.

Geophysical methods have the advantage that they test a large volume of soil in the ground. Laboratory tests employ relatively small soil samples. Combining in situ measurement techniques and laboratory techniques, it is able to determine non-linear properties of soil over a range of strains from 10^{-6} to 10^{-2}.

In Situ PS Wave Velocities Measuring Methods

General.--The four dynamic parameters of soil/rock that must be known in order to analyze deformation and stress resulting from dynamic loads are Young's modulus (E), shear modulus (G), Poisson's ratio (ν), and damping factor (h).

Research has shown that these four parameters are greatly influenced by the conditions under which they are measured. Thus a range of values for these parameters is frequently obtained. The factor that exerts the greatest influence by far is the magnitude of the strain at which they are measured. Dynamic modulus values also vary as a function of frequency and loading conditions.

Various techniques can be used to measure P and S wave velocities in situ. The most frequently used techniques are

1) The surface refraction method,
2) The downhole method,
3) The seismic cone method,
4) The crosshole method, and
5) The suspension PS logging method.

As illustrated in Figure 1, values of dynamic modulus and Poisson's ratio of soil can be calculated from the P and S wave velocities using the following equations from elastic theory:

$$\nu = \{1 - 2(Vs/Vp)^2\}/\{2 - 2(Vs/Vp)^2\}$$
$$G = Vs\rho$$
$$E = 2Vs^2\rho(2 + \nu)(1 + \nu)/\nu$$

where: ν = Poisson's ratio
G = shear modulus
E = Young's modulus
ρ = mass density

Surface Refraction Method.--The surface refraction method has a serious limitation due to the fact that low velocity layers cannot be detected when they are overlain by high velocity layers. However, it is possible to investigate the general geological structure of a site using this method, especially the position of a firm base layer.

Downhole Method.--The downhole method involves the generation of seismic waves rich in shear energy using an impulse source at the ground surface adjacent to the borehole. The travel time of the downward-propagating shear wave is measured using multi-axis geophones clamped in the borehole at various depths. The travel times are plotted using depth, and the slope of the plot is the wave velocity. Records of downhole measurements are shown in Figure 2. Using another type of surface vibration source, usually a hammer blow or a falling weight, P wave records and velocities are obtained by the same method. The most common energy source for S wave generation consists of striking a plank with a wooden hammer. By reversing the direction of the impact and by taking two records at each depth, the S wave arrival is easily identified.

Since S and P wave velocities are calculated from the slope of a depth/travel time curve, the velocities are obtained not for each incremental interval but for a velocity layer that has a certain thickness including many measuring points as an averaged value.

The features of downhole method include:
1) low cost (it requires only one borehole and utilizes a simple energy source at ground surface),
2) measurement along a line (the borehole),
3) ease in reversing the polarity,
4) generating S waves that travel perpendicular to the layer intersurfaces, thus minimizing reflected and refracted Vp and Vs components,
5) determination of average S wave velocities,
6) applicability in a limited space,
7) applicability in noisy areas with stacking or signal enhancement

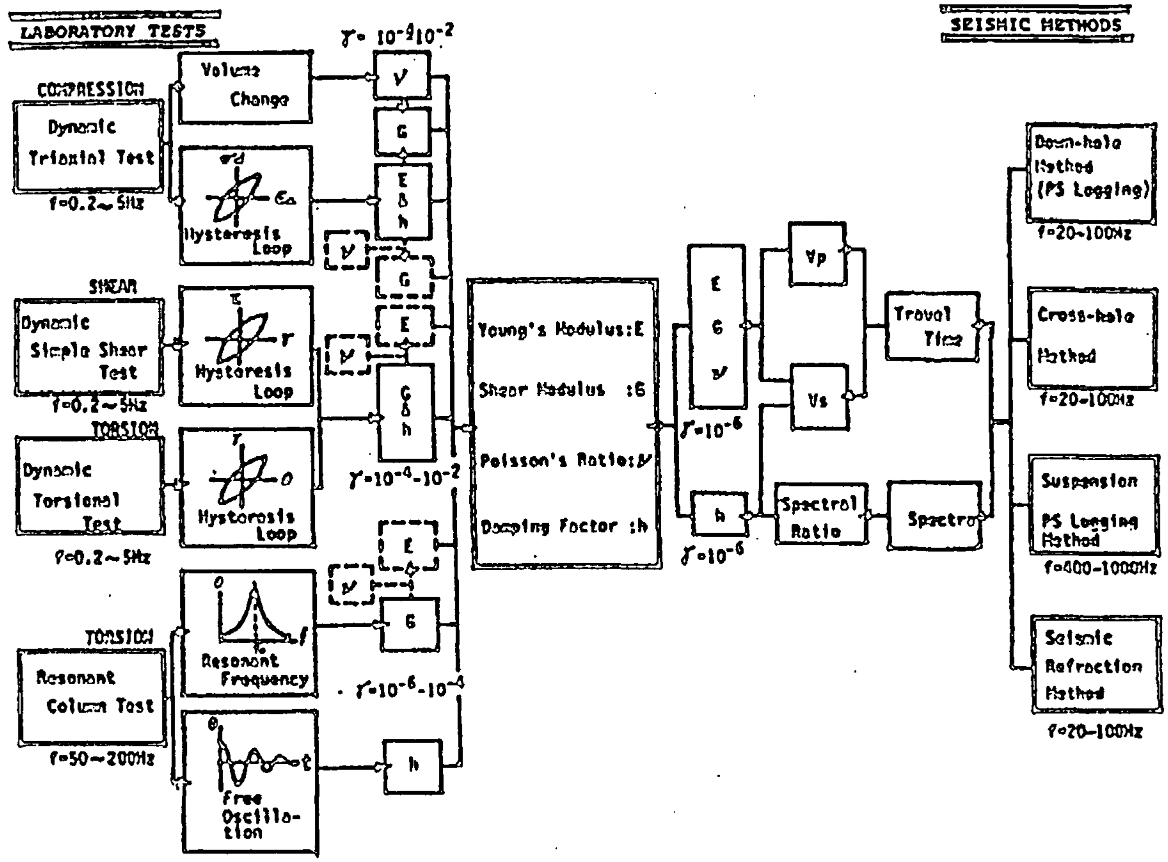


Figure 1. The comprehensive procedures and conditions of laboratory tests and seismic methods to obtain dynamic properties of soil.

techniques, or FFT/IFFT data processing techniques, and
8) well established and accepted techniques for use in earthquake engineering studies and widely used in Japan.

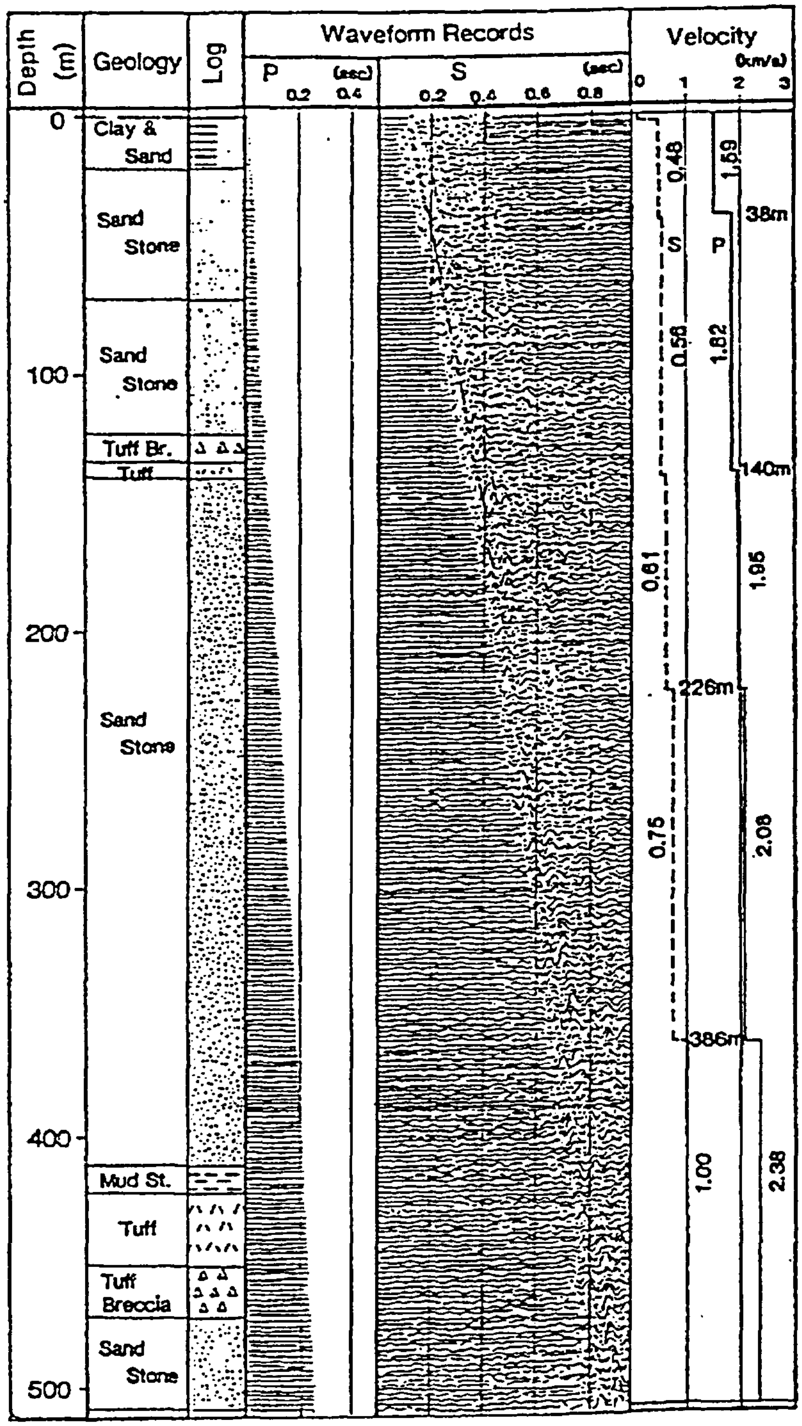


Figure 2. An example of records obtained by the downhole method.

Seismic Cone.--A new device called the seismic cone has been developed (Campanella and Robertson, 1984). This technique is a variation of the downhole method. A set of geophones is incorporated into the electric cone penetrometer. The method of advancing the cone penetrometer provides continuous, firm mechanical contact between the geophone carrier and surrounding soil. This allows excellent signal response. Generally the seismic cone method is very similar to the downhole method. One shortcoming of the method is due to the fact that the CPT has limited penetration capability, and it is sometimes not possible to investigate the entire depth from the ground surface through the seismic base layer. However, when the method is used in combination with the conventional CPT results, it can provide very useful near-surface information.

Crosshole Method.--The crosshole method generally requires one borehole for the seismic source and two or three holes for measuring the arrival times of the propagating waves.

Once the distances between the boreholes and the arrival times of the P and S waves have been determined, values of P and S wave velocities at the elevation can be calculated. Usually the interspacing between holes is two to four meters. At these close spacings wave bending, reflection, and refraction are minimized. With small spacing it is necessary to survey the drift of the boreholes to assure accurate distance measurements and velocity calculations. Because control of drift is difficult, the applicable depth of this method is usually limited to 30 to 50 meters.

The features of this method include:

1) high cost: at least three boreholes are needed and, accurate surveys of the drift of drillholes with depth are also required,
2) it does not provide values along a known path,
3) more space is required than for the downhole method,
4) the polarity can be reversed with an appropriate device,
5) after preparations are completed, the test itself is simple to perform,
6) the test is generally unaffected by casing (if plastic casing is used), and
7) there is a potential in layered soils that the waves may be refracted by high velocity layers close to the measuring elevation.

The disadvantages of this method are that more than three boreholes are needed, and the stand-by time for the drill rig increases the cost of the field work. Also, there are three essential problems:

1) in layered soils the wave may refract and the travel time will then correspond to the fastest path through the higher velocity layers,
2) difficulties in borehole drift control, and
3) the method does not provide an average along a known path.

Suspension PS Logging Method.

Principles of the system: The PS logging system consists of a single unit. Figure 3 shows the sonde used in this sytem. Basically, the system consists of an indirect type electromagnetic vibration source, two floating pick-ups spaced one meter apart, and a recorder with a wave memory function. Two geophones are built into each pickup--one horizontal and one vertical. A pre-amp to convey stable signals to the ground

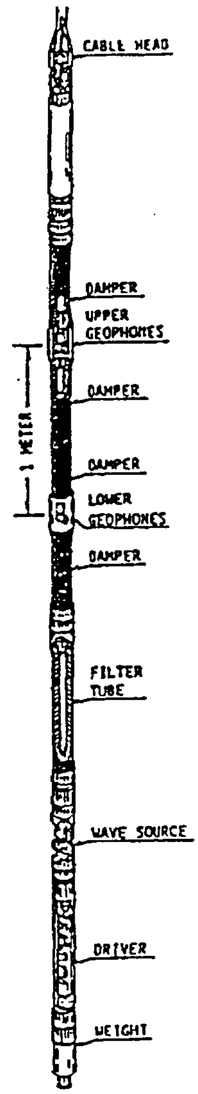


Figure 3. Schematic view of the sonde of suspension PS logging system.

surface and a vibration source drive system are built into the sonde.

The vibration source is an electromagnetic solenoid hammer which generates a force perpendicular to the borehole wall. The wave field can be treated approximately as that of a point source in an infinite homogeneous medium since the wave length is sufficiently longer than the borehole diameter. The source generates a pressure distribution of doublet in the borehole fluid. At excitation a force is applied to a rigid body (the sonde) suspended in the borehole fluid. Pressure changes (plus and minus) are produced at the front and rear of the sonde. Consequently, the borehole wall is excited indirectly through the water motion.

The receiver is neutrally buoyant; that is, the geophone unit with the specially designed case has an average specific gravity equal to that of the borehole fluid. When the borehole wall is horizontally displaced following wave motion, the borehole fluid and geophones suspended in the borehole fluid are moved with the borehole wall in the immediate vicinity. The horizontal displacement of the borehole wall, the borehole fluid and the suspended geophone receiver are the same because the geophone receiver unit is suspended freely in the borehole fluid using flexible rubber tubes. These rubber tubes attenuate wave propagation along the tool as well as filtering wave propagation along the tubes. Figure 3 shows a set of filter tubes.

Theoretically, the system can be applied at any depth, but the presently developed model has the following limitations:

1) applicable depth up to 500 m,
2) measurable velocity range up to 2.0 km/s in S-wave velocity,
3) drill hole must be fluid-filled, and
4) use of plastic casing will not cause any problems, but steel casing will produce difficulties.

Operational procedure of the suspension PS logging method: The sonde is lowered into the borehole to the desired depth. A signal is sent in the normal direction and is received by the two horizontal geophones. Another signal is then sent in the reverse direction and is received by the same horizontal geophones. The third signal is sent in the normal direction and received by the vertical geophones. The data from the above three measurements are transferred from the wave memory to the printer and permanently recorded. Interval velocity may be calculated on the basis of the difference of arrival time between geophone #1 and #2 for both the S and the P waves.

About one minute is required for each measurement, including moving the sonde.

Characteristic features: The suspension PS logging method is a technique for measuring P and S wave velocities more accurately and deeper using a single borehole. The characteristic features of this method include:

1) rather low cost: it requires only one hole,
2) quick measurement,
3) great depth applicability,
4) ease in reversing the polarity,
5) generating SH wave which travels perpendicular to layer interface keeping refracted Vp and Vs component to a minimum,
6) determination of accurate velocity for each 1 meter interval,
7) applicability in limited space,
8) workable in noisy areas by means of stacking or signal enhancement techniques and FFT/IFFT data processing techniques,
9) drift of borehole does not cause severe problems,
10) test hole must be filled with drilling fluid, and
11) plastic casing can be used.

Comparison of Methods for Measuring PS Wave Velocities

For convenience of description, the following notations are used: downhole (DH), crosshole (CH), and suspension logging (SL). A comparison of the three methods is shown in Table 1.

Table 1. *Main Features of the Three In Situ S Wave Velocity Measuring Methods*

METHOD	PRACTICE	S-WAVE SOURCE	WAVE FREQUENCY (Hz)	ABILITY TO REVERSE THE POLARITY	REQUIRED BOREHOLES	SURVEY OF DRIFT OF THE BOREHOLES	MEASURABLE DEPTH	APPLICABILITY IN OFFSHORE	COST
SUSPENSION	Logging	Built-in solenoid hammer	400-1000	yes	only 1 hole	not necessary	500 m	easy to apply	low
DOWN-HOLE	Well Shooting	Plank hammering	20- 100	yes	only 1 hole	not necessary	100 m	source problem	low
CROSS-HOLE	Inter-holes shooting	Explosive or mechanical, in a hole	20- 100	yes	at least 3 holes	very necessary	100 m	workability problem	high

<u>The Suspension PS Logging Method Compared to the Downhole Method</u>.— Conventional downhole and suspension methods have been carried out using the same boreholes at several sites. Since these two methods can use the same borehole, all conditions can be considered as common in these comparison tests. Figure 4 and Figure 5 show S wave and P wave velocity logs obtained in such tests.

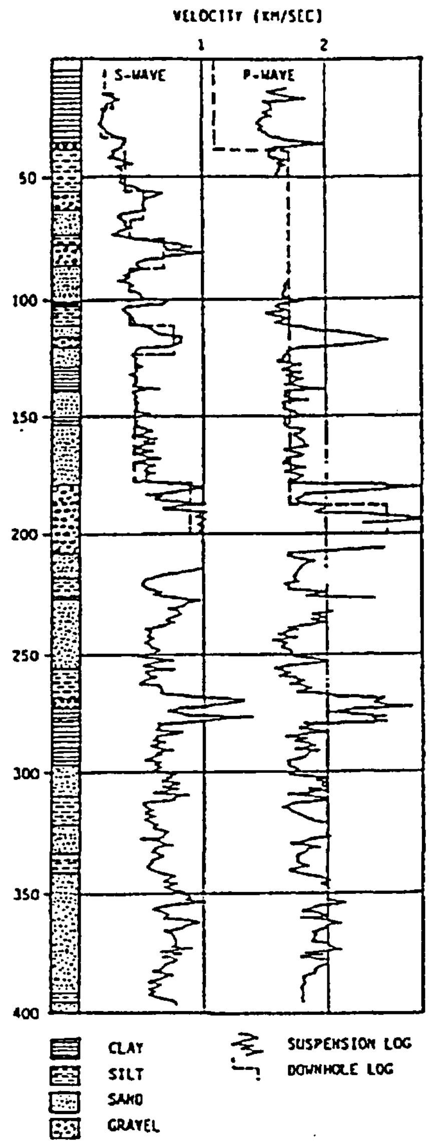
Figure 4 is an example of subsoil conditions consisting of layered sediments of the Pleistocene Age. Figure 5 is an example of subsoil conditions consisting of rather uniform mudstone and tuff of the younger Tertiary Age. P and S wave velocities were measured at each 1 meter depth intervals in the case of the SL method and each 2 meter depth intervals for the DH method. The average value for each 10 meter interval was calculated and values of the ratio V(SL)/V(DH) were obtained. The ratio is plotted in Figure 6 for S wave velocity and Figure 7 for P wave velocity.

It may be seen that the velocities obtained using these two methods are in good agreement. A total of 1450 meters comparison was carried out so that 144 samples of the ratio V(SL)/V(DH) were collected. The average ratio of the 144 samples was found to be 1.028 indicating that the S wave velocity measured by the suspension system averaged 2.8% higher than the velocity obtained by the downhole method.

For the P wave measurements, even better agreement was found. The average ratio Vp(SL)/Vp(DH) for 137 samples was 1.014 indicating that the P wave velocity measured by the suspension method is 1.4% higher than the velocity obtained by the downhole method.

<u>The Suspension PS Logging Method Compared to the Crosshole Method</u>.— Twenty-one values of S wave velocity measured by the SL and CH methods were compared as shown in Figure 8. The ratio Vs(SL)/Vs(CH) plotted in Figure 8 averaged 0.982.

In this comparison different boreholes are necessarily involved be-



gure 4. Comparison of P and S wave velocity log measured by the suspension method and the downhole method for a site of layered soil conditions, (site A).

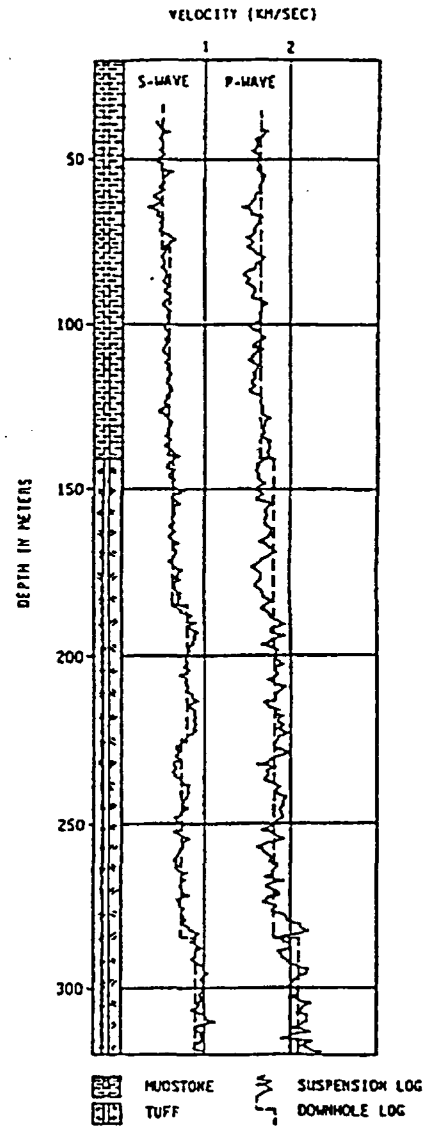


Figure 5. Comparison of P and S wave velocity log measured by the suspension method and the downhole method for a site of rather uniform soil conditions, (site B).

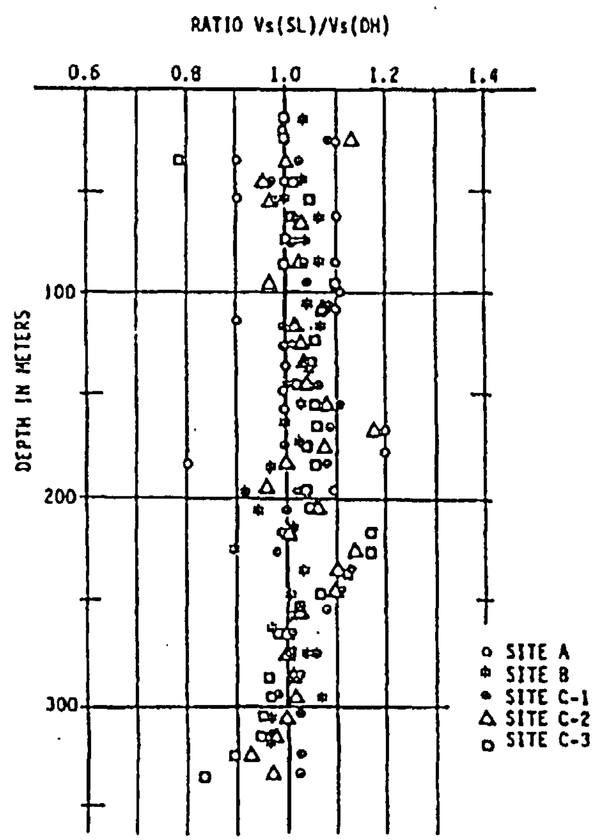


Figure 6. Comparison of S wave velocity measuring results from the suspension method and the down-hole method.

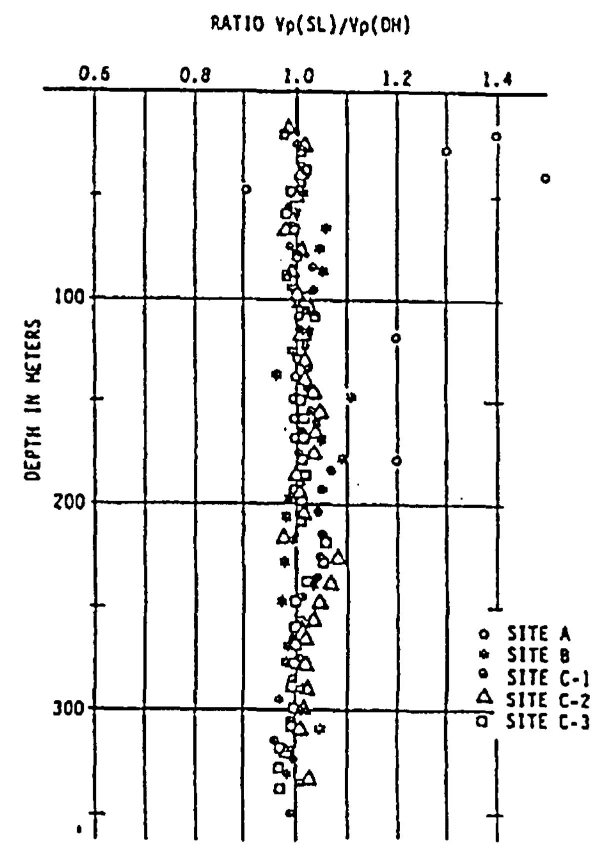


Figure 7. Comparison of P wave velocity measuring results from the suspension method and the down-hole method.

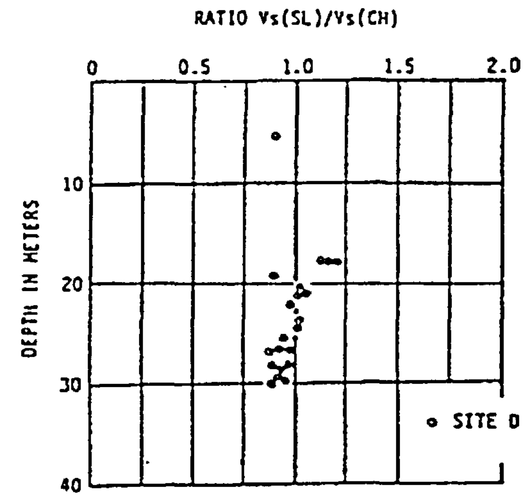


Figure 8. Comparison of the S wave velocity measuring results from the suspension and the crosshole methods.

cause the suspension technique needs only one borehole, whereas the crosshole method needs another two holes even if the same borehole used for the suspension method is also used as one of the holes for the crosshole method. Even though the holes were drilled closely, the use of different boreholes can produce different velocities. Taking into consideration such conditions, it may be concluded that fairly good agreement was obtained.

The Crosshole Method Compared with the Downhole Method.--Figure 9 shows a distribution of the ratio Vs(DH)/Vs(CH) with depth. Thirty-six comparisons were made for three sites in Japan and Indonesia by the writer, and additional data for U.S. sites, as reported by Wilson et al., is also shown in Figure 9.

The average value of the ratio Vs(DH)/Vs(CH) for the thirty-six comparisons made by the writer is 1.133. The average values of the ratio Vp(DH)/Vp(CH) is 1.06. Since the subsoil conditions at the sites at which these data were obtained were not uniform, there may be many factors responsible for the differences. Accordingly, it is not particularly meaningful to discuss the differences. However, this data is sufficient to confirm that these methods do not produce significant differences in the S and P wave velocities.

Discussion

Results of the Comparison Tests.--Velocity differences: Generally speaking, the results of the comparison tests show fairly good agreement in the velocity values. If the subsoil consists of layers with different velocities, the downhole method cannot detect the velocity of each layer. Also, the crosshole method has the potential that the wave may refract and travel a faster path through higher velocity layers. Then

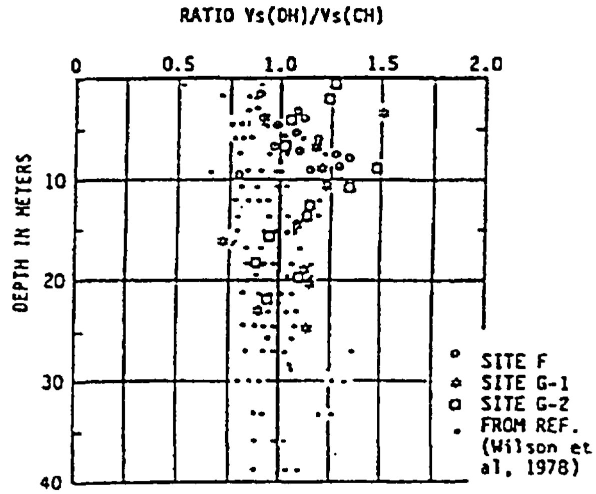


Figure 9. Comparison of the S wave velocity measuring results from the crosshole and downhole methods.

it may be concluded that the most effective and accurate method for measuring P and S velocities in layered soils is the suspension PS logging system. It is well demonstrated in Figure 4 that every gravel layer is clearly detected by the (SL) method. Accordingly, the suspension system may be used to measure not only S and P wave velocities but also to investigate a lithological facies distribution of the ground. Especially, the S wave velocity is closely related to soil strength. The writer believes that it may be possible to use the suspension PS logging system to estimate soil strength properties.

Further Consideration of a Limitation of the Crosshole Method in Layered Soils.--Many studies have been directed toward improving crosshole testing procedures, primarily by developing more repeatable energy sources and better techniques for identifying shear wave arrival times. Also, the influence of the effects of the interspacing between boreholes has been studied in detail.

On the basis of these studies, it has been concluded that 1) such repeatable energy sources such as striking up as well as down an embedded pipe or sampler at the borehole bottom, torsional loads in opposite direction at the bottom of the borehole, electromagnetic vibrators, and so forth, provide better data than using explosives or other nonrepeatable sources, and 2) the spacing of the boreholes should be eight to twenty feet to minimize wave refraction and reflection problems.

However, if the ground consists of thin alternating layers with different velocities, there is still a question of whether or not the recommended spacing of boreholes is sufficient to avoid an influence of wave refraction.

In Figure 10 it is assumed that there is a higher velocity layer,

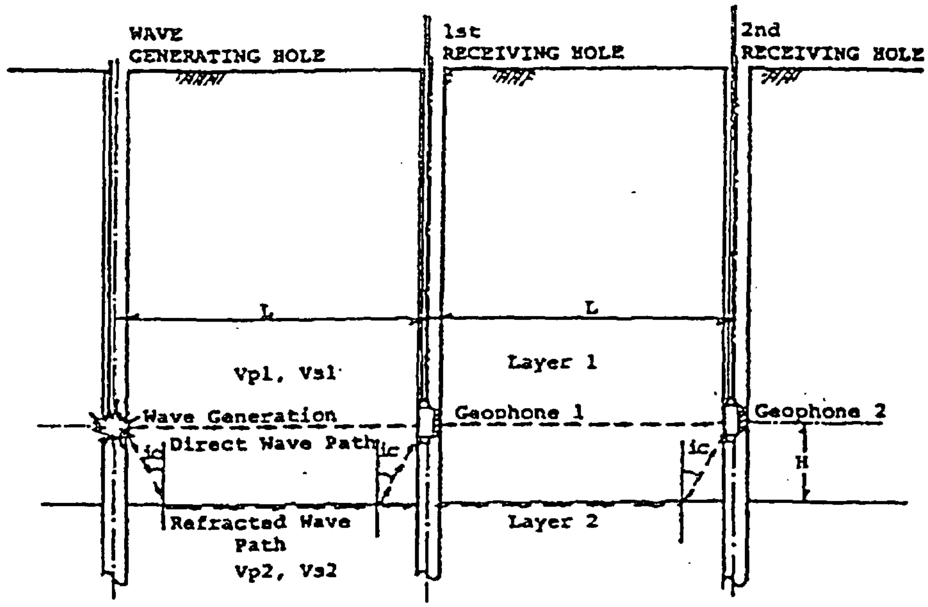


Figure 10. Example of crosshole interpretation.

layer 2, just beneath the velocity measuring layer, layer 1. If the thickness of layer 1 from the measuring elevation to the boundary between layer 1 and layer 2, (H), is considerably smaller than the interspacing of boreholes, (L), the refracted wave passing through layer 2 may arrive faster than the direct wave passing through layer 1. The velocity ratio V(Layer 1)/V(Layer 2) is a key factor in determining the possibility of such refraction.

In the model shown in Figure 10 the refraction angle, ic, is defined as:

$$ic = \sin^{-}(V_1/V_2)$$

The arrival times of direct waves at geophone 1 and geophone 2, t_1 and t_2, can be obtained by the following equations:

$$t_1 = L/V_1$$
$$t_2 = 2L/V_1$$

The arrival times of the refracted waves at geophone 1 and geophone 2, t_1' and t_2', can be obtained by the following equations:

$$t_1' = 2H/(\cos^{-} ic\ V_1) + (L - 2H \tan^{-} ic)/V_2$$
$$t_2' = 2H/(\cos^{-} ic\ V_1) + (2L - 2H \tan^{-} ic)/V_2$$

There are three possibilities with respect to the relative magnitude of t_1, t_2, t_3, and t_4:

Case 1: $t_1 < t_1'$ and $t_2 < t_2'$;

Case 2: $t_1 < t_1'$ and $t_2 > t_2'$;

Case 3: $t_1 > t_1'$ and $t_2 > t_2'$.

In Case 1 the velocity obtained using the arrival times at geophone 1 and geophone 2 will result in normal velocity of the layer 1, V_1. In Case 3 the velocity will produce the velocity of the layer 2, V_2. This is the case of complete refraction. And in Case 2 the velocity obtained using the differential arrival time at geophone 1 and geophone 2 will produce some intermediate value between V_1 and V_2. This is the case of partial refraction.

Taking a range of values of H from 0.5 to 5 meters, a range of values of L from 1 to 5 meters, and velocity ratio values, V_1/V_2, ranging from 0.2 to 0.8, arrival times, t_1, t_2, t_1', t_2', and apparent velocity values based on the first arrival times for the two geophones have been calculated.

Figure 11 is one example of the results calculated. It shows the relationship between the thickness (H) and the apparent velocity, with the interspacing of boreholes as a parameter. In this case, 300 m/s velocity value for layer 1 and 1000 m/s velocity value for layer 2 were assummed so that the velocity ratio was 0.3.

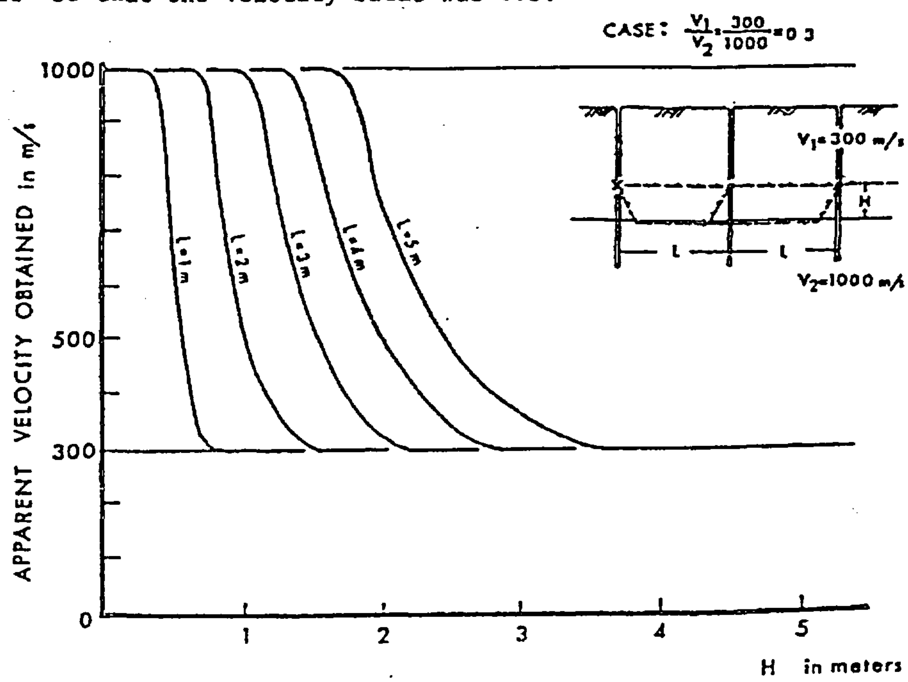


Figure 11. An example of calculated results between the thickness and the apparent velocity values with the interspacing of boreholes as parameter.

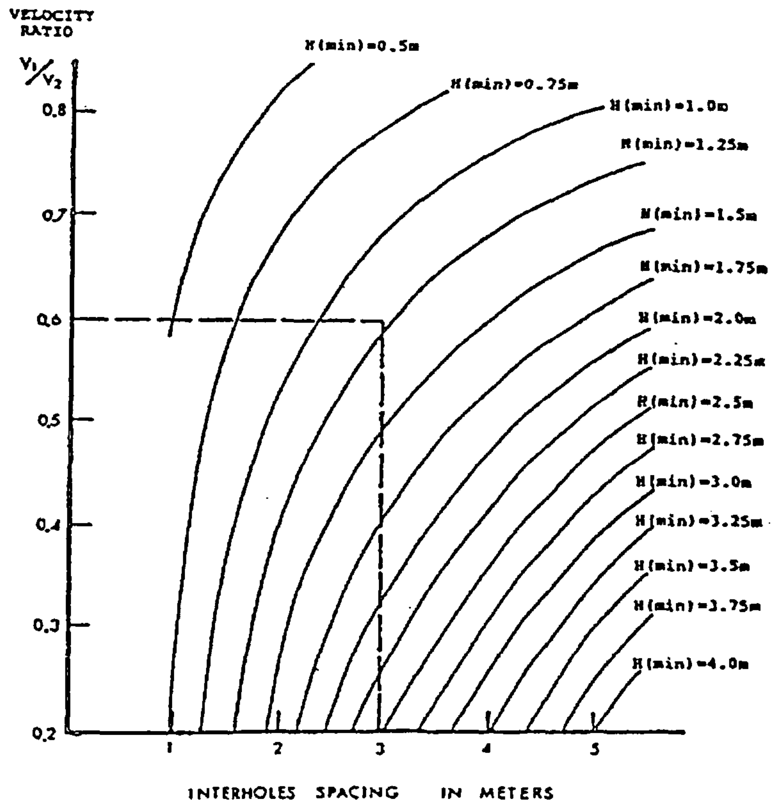


Figure 12. A diagram of interrelationship between the spacing of boreholes, velocity ratio, and minimum thickness of low velocity layers allowing measurement without interference by wave refraction.

Based on similar results for a variety of cases, the relationships own in Figure 12 were developed. In the calculations the spacing be-een the energy hole and the first wave receiving hole was assumed to the same as the spacing between the waves receiving holes.

For the case in which the velocity ratio is 0.6 and the interspacing tween boreholes is three meters, the corresponding minimum thickness layer 1 can be seen to be approximately 1.25 meters from this diagram.

Further, if the soil consists of alternating low and high velocity yers with a velocity ratio of 0.6, the minimum detectable thickness of e low velocity layer would be 2.5 meters. In other words, in a case volving thin alternating layers with higher and lower velocities in tio 0.6, the crosshole method can not detect the velocity of the low locity layer correctly unless the thickness of the low velocity layer more than 2.5 meters.

Conclusions

Based on comparisons of the various methods of in situ S and P wave velocities, the writer has drawn the following conclusions:

1) If the subsoil conditions are uniform, the downhole method, the crosshole method, and the suspension PS logging method will produce the same values of P and S wave velocity.
2) If the subsoil conditions are not uniform and consist of alternating high velocity layers and low velocity layers, the three different methods will produce different results as follows:
   a) the downhole method will produce an average value of velocity for the layers,
   b) the crosshole method may produce false velocity readings,
   c) the suspension PS logging method will produce more accurate velocity information, reflecting the changes in velocity from layer to layer.
3) Since the suspension PS logging method is able to detect S wave velocities with high resolution, a potential use of this system may be for estimation of soil strength.
4) Deformation or failure of the ground may be influenced very much by the properties of a weak layer. In this sense to obtain velocity information for a weak layer accurately is very important even if the weak layer is thin. The suspension PS logging technique is a very promising technique for such applications.

ACKNOWLEDGEMENTS

Data, illustrations, and experience cited herein were taken from a variety of research projects undertaken by OYO Corporation over a period of two decades.

The writer wishes to acknowledge the encouragement of Dr. K. Suyama and the help of my colleagues, Mr. T. Imai, Mr. Ogura, and others of OYO Corporation.

REFERENCES

1. Campanella, R.G., P.K. Robertson. "A Seismic Cone Penetrometer to Measure Engineering Properties of Soil," Annual Meeting of the Society of Exploration Geophysicists, Atlanta, 1984.
2. Imai, T. "P and S-Wave Velocities of the Ground in Japan," Proc. of the IXth International Conf. on Soil Mechanics and Foundation Engineering, Tokyo, 1977.
3. Imai, T., T. Kanemori, and K. Tonouchi. "Determination of Dynamic Deformation Characteristics of Soils by Seismic Methods and Laboratory Tests," Presentation at the 49th Annual Meeting of the SEG, New Orleans, 1979.
4. Kitsunezaki, C. "Shear Wave Logging by Suspension Type Geophone, I," Butsuri-tanko, 28, 13-21, (in Japanese), 1975.
5. Kitsunezaki, C. "A New Method for Shear-Wave Logging," Geophysics, Vol. 45, No. 10, pp. 1489-1506, 1980.
5. McClelland Engineers, "OYO PS Logging System Shear Wave Velocity Measurements Comparison with Crosshole and Resonant Column Data," Proprietary Report, August 1981.
7. Ogura, K. "Development of a Suspension Type S-Wave Log System," OYO

3. Ogura, K., S. Nakanishi, and K. Morita. "Development of the Suspension S-Wave Logging System," Presentation at the 50th Annual Meeting of the SEG, Houston, 1980.

9. Ohya, S. "Current State of Field Measurement in Japan--On the New Developments in Geophysical and Geotechnical Instruments," Proc. of the International Symposium on Field Measurements in Geomechanics, pp. 128-137, Zurich, 1983.

0. Regueiro, J., and J.E. White. "Evaluation of OYO Suspension Shear Logging Tool," Report of the CSM Integrated Geophysical Project, 1981.

1. Seed, H.B. "Soil Liquefaction and Cyclic Mobility Evaluation for Level Ground during Earthquake," Journal of the Geotechnical Engineering Division, ASCE, Vol. 105, No. GT2, 1979.

2. Seed, H.B., and I.M. Idriss. "Analysis of Soil Liquefaction: Niigata Earthquake," Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 93, No. SM3, 1967.

3. Uchiyama, S. "Borehole Seismic Velocity Measurements," Butsuri-tanko, Vol. 36, No. 5, 1983.

4. Wilson, S.D., F.R. Brown, and S.D. Schwarz. "In Situ Determination of Dynamic Soil Properties," Dynamic Geotechnical Testing, ASTM STP No. 654, pp. 295-317, 1978.

SEISMIC REFRACTION AND REFLECTION METHODS

GEO*Vision*
geophysical services
a division of Blackhawk GeoServices

GEO*Vision* geophysicists conduct high-resolution seismic refraction and seismic reflection surveys in support of a variety of engineering, environmental, and hydrogeologic investigations.

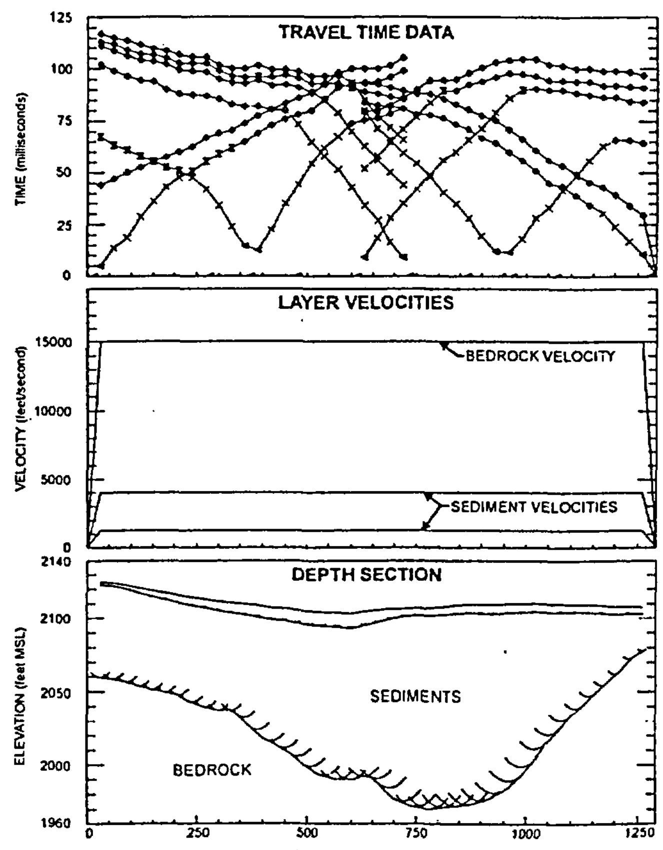
When conducting seismic surveys, acoustic energy is input to the subsurface by an energy source such as a sledgehammer impacting a metallic plate, weight drop, vibratory source, or explosive charge. The acoustic waves propagate into the subsurface at a velocity dependent upon the elastic properties of the material through which they travel. When the waves reach an interface where the density or velocity changes significantly, a portion of the energy is reflected back to the surface, and the remainder is transmitted into the lower layer. Where the velocity of the lower layer is higher than that of the upper layer, a portion of the energy is also critically refracted along the interface. Critically refracted waves travel along the interface at the velocity of the lower layer and continually refract energy back to surface. Receivers (geophones), laid out in linear array on the surface, record the incoming refracted and reflected waves. The seismic refraction method involves analysis of the travel times of the first energy to arrive at the geophones. These first arrivals are from either the direct wave (at geophones close to the source), or critically refracted waves (at geophones further from the source). The seismic reflection method involves the analysis of reflected waves, which occur later in the seismic record.

Seismic Refraction Survey in the Borrego Valley

GEO*Vision* typically uses the Oyo DAS-1 or Geometrics R24/60 seismograph for refraction and reflection investigations. Seismic energy sources used on past projects have included a sledgehammer, Betsy Seisgun™, EG&G Geometrics Dynasource (a vacuum-assisted weight drop), Bison Elastic Wave Generator (accelerated weight drop), IVI Minivib, and explosives.

GEO*Vision* geophysicists use the seismic refraction method to:

- **Map bedrock topography**
- **Map faults in bedrock**
- **Estimate depth to groundwater**
- **Estimate bedrock rippability**
- **Evaluate rock properties**

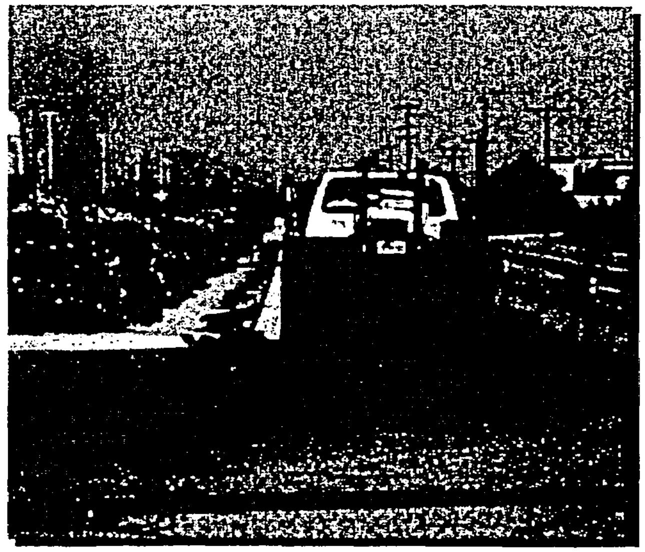


Seismic Refraction Survey to Map Bedrock Topography

GEO*Vision* geophysicists typically use the generalized reciprocal method (GRM) to analyze high-resolution seismic refraction data. Several computer programs are used in processing seismic refraction data including the program FIRSTPIX™ by Interpex, Ltd., which allows manual or automatic picking of first breaks, the program VIEWSEIS™ by Viewlog Systems, Ltd., which implements the GRM, and the program SeisOpt by Optim LLC for data modeling.

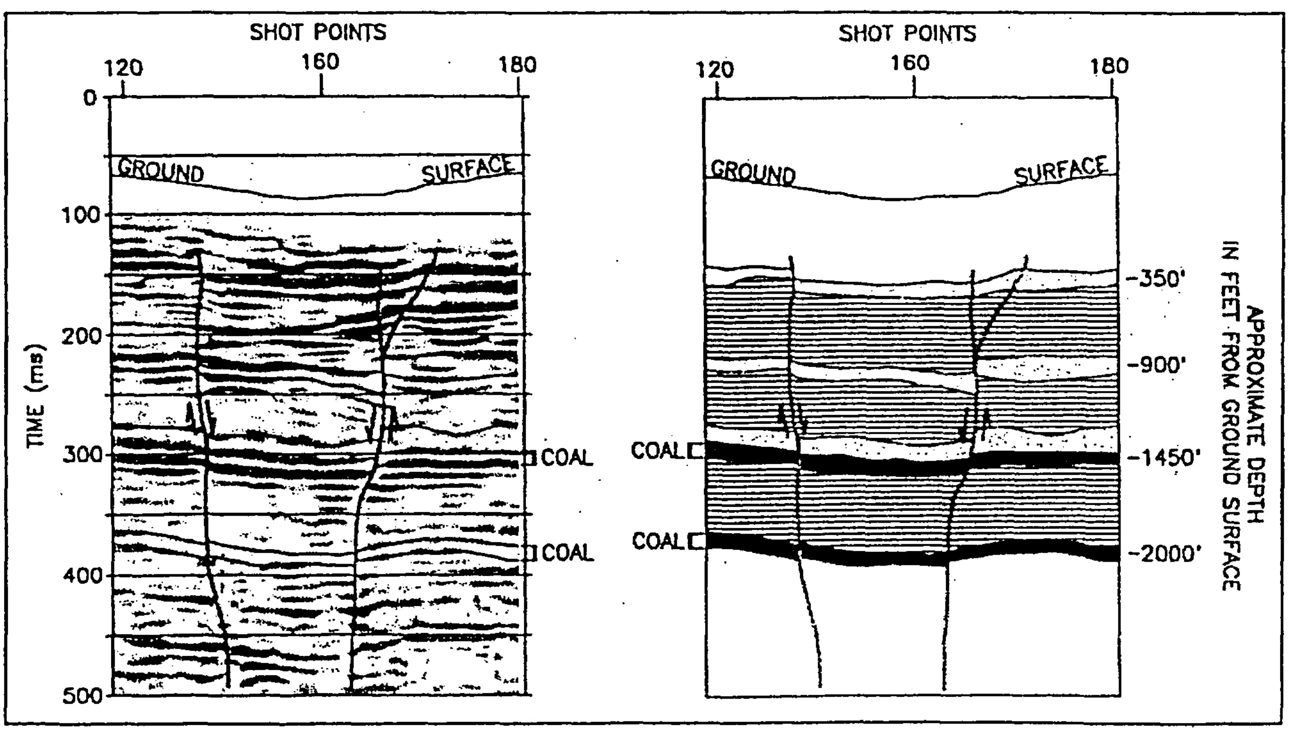
GEO*Vision* geophysicists use the seismic reflection method to:

- **Map subsurface stratigraphy**
- **Map lateral continuity of geologic layers**
- **Map buried paleo-channels**
- **Map faults in sedimentary layers**
- **Map basement topography**



IVI Minivib Seismic Reflection Source

GEO*Vision* geophysicists often use the program SPW by Parallel Geosciences to process seismic reflection data and the program 2Dpak by Seismic Micro-Technology Inc. for seismic interpretation. Processing steps generally applied to reflection data include format conversion, trace editing, pre-processing (description of field geometry), spectral whitening or deconvolution, velocity analysis, surface consistent statics, velocity analysis, normal moveout corrections, prestack filtering, prestack gains, residual statics, and migration.



Seismic Reflection Survey to Map Coal Seams

PROCEDURE FOR

SEISMIC REFRACTION METHOD

Reviewed 3/10/1998

Background

This procedure describes a method for measuring shear and compressional wave velocities in soil and rock. The Seismic Refraction Method is applied by generating compressional waves (*P*) (and sometimes shear (S_H)) on the land surface and measuring the travel time of the corresponding waves from the source to one or more geophones. These measurements are used to interpret subsurface conditions and materials. This travel time, along with distance between source and geophone(s), can also be interpreted to yield depth to refracting layer(s). The calculated seismic velocities can often be used to characterize some of the properties of natural and man-made subsurface materials.

This is a general procedure and does not address all the details and components of a seismic refraction survey. Please refer to the references provided for additional information.

Objective

The specific objective varies depending on the project. It can be simply to reconnoiter subsurface conditions, or to provide detailed subsurface information. For example, rippability studies require very few geophones and a very simple analysis. On the other hand, detailed studies require very careful design of geophone spacing, source energy and location, accurate measurement of geophone elevations, and so on. In general, the basic outcome is a measurement of seismic wave velocities. Detailed studies will also provide a profile of the depth to refractors.

Equipment

1. Seismic energy source. Four types of sources used by GEOVision include:

   1.1. Sledge hammers of various weights

   1.2. Mechanical or accelerated weight drop or impact devices, such as the Bison EWG-1 or Geometrics Dynasource

1.3. Projectile (gun) sources, such as the Betsy Seisgun, Betsy downhole percussion firing rod

1.4. Explosives

2. Multichannel seismograph, such as Geometrics Strataview R24, OYO DAS-1, or equivalent. GEOVision uses 24 to 48 channel systems for detailed refraction surveys. Seismographs must provide for digital recording, and for signal enhancement (energy) stacking. Single - 12 channel systems are acceptable for simple surveys such as rippability studies.

3. 4 - 14 Hertz geophones (vertical for P-wave refraction studies, horizontal for S-wave studies), connected to the seismograph by cable. Geophone and take-out (electrical connection) spacing is determined by the depth of exploration and the resolution required

4. Trigger cable or radio link, to provide a timing signal to the seismograph at the time of source impact

5. Batteries to operate refraction system

Figure 1 is a sketch of the field layout for a typical refraction survey.

Environmental Conditions

Seismic refraction data are affected by ground vibrations from a variety of sources. These include ambient sources such wind, water movement (such as waves breaking on a nearby beach), natural seismic activity, and rainfall on the geophones. They also include cultural sources such as vehicular traffic, construction equipment, nearby motors, aircraft, or blasting. Frozen ground can contribute a high-velocity near-surface path that will obscure the contribution of deeper layers.

Such sources should be minimized as much as possible. Where possible, refraction data should not be collected during high winds or rain, or while vehicles are passing.

Calibration

Calibration of the multichannel seismograph is required. Calibration is limited to the timing accuracy of the recorder. GEOVision's Seismograph Calibration Procedure or equivalent should be used. Calibration must be performed on an annual basis.

Measurement Procedure

The specific procedure varies according to the objective for the survey, the design of the survey, and the method used to define the planar refractors. These are described in more detail in other references (1 - 6).

The most important considerations are:

1. Location of seismic refraction lines
2. Length and orientation of lines
3. Geophone spacing
4. Location of shots (sources)
5. Approach or interpretation method. These can include:
   5.1. Intercept-time or crossover method
   5.2. Delay-time methods and variations thereof
   5.3. Reciprocal methods, including:
      5.3.1. Common Reciprocal Method
      5.3.2. Generalized Reciprocal Method
   5.4. Ray-tracing methods
   5.5. Tomographic methods

Of these approaches, the method most often used by GEOVision for detailed refraction surveys is the Generalized Reciprocal Method. This method is acknowledged superior to many other methods for modeling irregular dipping refractors and lateral velocity changes.

The general field procedures are as follows:

1. Check for adequate space to lay out a straight line in accordance with the survey design
2. Locate and position first geophone according to design and such that the location can be repeated or identified independently (the line should be referenced to absolute fiducials at several locations).

3. Accurately mark geophone locations. Locations must be surveyed to within a few percent of the geophone interval, including elevation
4. Lay out geophone cable
5. Place geophones at marked locations. Geophones must be vertical and well coupled to the ground using the spike provided. Where rock is exposed the spike may be replaced with a tripod base.
6. Test geophones and cables for shorts or open circuits.
7. Set up source(s) at design locations. Shot locations must also be surveyed to within a few percent of the geophone interval.
8. Place trigger cable
9. Test seismic source and trigger cable
10. Input survey geometry into seismograph
11. Test noise level and set gains and filters
12. Proceed with refraction measurements

Required Field Records

1) Field log for each refraction measurement describing:
   a) Location of each geophone
   b) Date and time of test
   c) Tester or data recorder
   d) Description of source (location, amplitude, number of stacks)
   e) Any gain or filtering by channel during recording
   f) Any deviations from test plan and action taken as a result
   g) File name as recorded on disk
   h) QA Review

   Much of the above information will be automatically recorded in the seismograph header at the time of recording (gains, filtering, and survey geometry) and need not be recorded on the paper log.

2) Diskettes or tapes with backup copies of data on hard disk, labeled with line and measurement designation, record ID numbers, date, and tester name.

Analysis and Interpretation

Following completion of field work, the recorded digital records are processed by computer and interactively analyzed by an experienced geophysicist to produce plots and tables of P and S_H wave velocity versus depth.

Again, the specific procedure varies according to the objective for the survey, the design of the survey, and the method used to define the planar refractors.

In general, GEOVision refraction data is processed using the Generalized Reciprocal Method (GRM), one of the most advanced modeling methods currently available for seismic refraction data. Processing steps consist of loading field records into a computer, picking the travel times of first arrivals, entering shot and spread geometry, phantoming data from all shots on a line to obtain one set of forward and reverse travel time curves for each refractor, and applying the GRM to obtain a depth section (model showing different geologic units and their velocities).

Preliminary interpretations are carefully verified using available geologic and drilling data. If at all possible, GEOVision recommends performing OYO P-S Suspension Logging or Downhole velocity survey in at least one borehole for a high-resolution constraint of the model. If such data is not available, the report will so mention.

Report

The final report will include the objective and scope of the survey, discussion of the geologic setting, any limitations of the survey, and any assumptions made. The field approach will be described including a description of equipment, procedures, and data acquisition parameters. The location of the seismic refraction line will be described along with a site map and the shot-point/geophone layout. Any corrections made to the field data will be discussed, including justification. The results of field measurements will be described including samples of raw data, and time-distance plots.

The methodology for picking first arrivals, and for interpreting the results will be described along with any software program used. The interpreted results based on these methods will be presented along with any qualifications and alternate interpretations. These will include depth sections and seismic velocities.

Appropriate references for any supporting data will be provided.

The report will be signed by the California Registered Geophysicist responsible for the refraction survey and data interpretation, and QA Reviewed in accordance with GEOVision QA Procedures.

Registered Geophysicist ____________ Date 7-17-00

QA Review ____________ Date 7-17-00

References:

1. ASTM Standard D 5777-95 "Standard Guide for Using the Seismic Refraction Method for Subsurface Investigation"

2. Redpath, Bruce B. "Seismic Refraction Exploration for Engineering Site Investigations", Explosive Excavation Research Laboratory, Livermore, CA, distributed by NTIS, US Dept. of Commerce, Springfield, VA

3. "Geophysical Exploration for Engineering and Environmental Investigations", Technical Engineering and Design Guides as adapted from the US Army Corps of Engineers, No.23, published by ASCE Press, Reston, VA

4. Dobrin, M.B. 1960 *Introduction to Geophysical Prospecting.* 2nd Edition. McGraw-Hill Book Co. Inc, New York

5. Telford, W.M., et al, 1976 *Applied Geophysics* Cambridge University Press

6. Milsom, J. 1989 *Field Geophysics* Open University Press, Milton Keynes

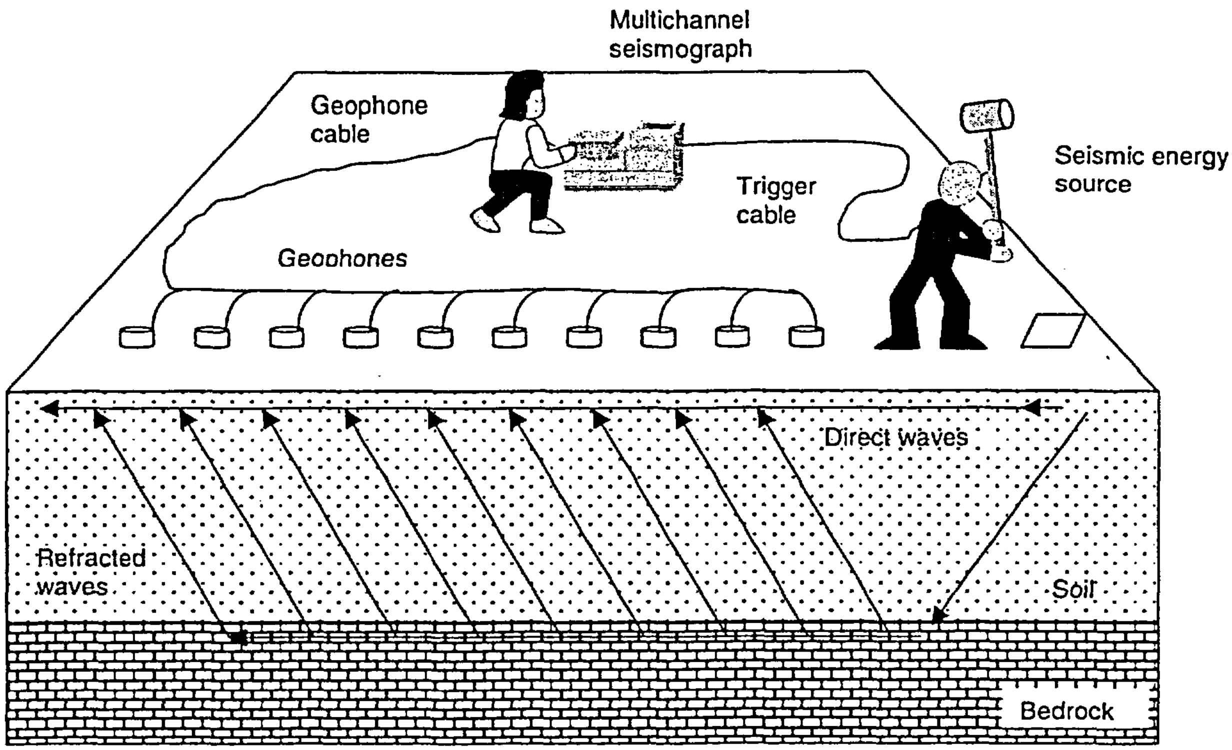


Figure 1 FIELD LAYOUT OF A MULTICHANNEL SEISMOGRAPH SHOWING WAVE PATHS

9/27/00 jgd

SPECIFICATIONS FOR DRILLING AND CASING BOREHOLES FOR P-S SUSPENSION LOGGING

1. Drilling must be done with minimal sidewall disturbance. We strongly recommend the rotary mud or rotary wash method. This method does little damage to the borehole wall, and the drilling fluid coats and seals the borehole wall reducing fluid loss and wall collapse. Drilling borehole diameter should not exceed the outer diameter of the casing by more than 100mm.
2. If the borehole must be cased, the casing must be PVC and properly installed and grouted. Any voids in the grout will cause problems with the data. Likewise, large grout bulbs used to fill cavities will also cause problems.
3. Casing must be about 100mm (4 inches) diameter, Schedule 40 PVC. This thickness and strength is necessary to minimize collapse due to the pressure of the grout. It is usually best to grout the casing while the casing is full of water to help minimize the differential pressure on the outside of the casing. The casing should be inserted with spacers or centralizers to keep the casing centered in the borehole.
4. The best way to grout the casing is through a small PVC pipe inserting through the casing and connected to a one-way ball-check valve in the bottom cap of the casing. Make sure the pump is capable of pumping grout all the way down to the bottom through the small pipe and up to the top of the borehole. Grout is then pumped down through the small pipe and fills up the annulus around the casing from the bottom to the top. Once the grout has filled the annulus around the casing up to the top, pumping is stopped, and the pipe disconnected from the valve and removed. The casing can be rinsed and flushed with water.

   Alternatively, a small PVC pipe (1-1/2 inch, or 35mm), called a tremie tube, can be fed down the side of the casing between the casing and the borehole wall. Once the tremie tube reaches the bottom of the borehole, grout can be pumped through the tremie tube and grout filled from the bottom of the borehole.

   Alternatively, the borehole can be partially filled with grout, and the capped casing forced down into the grout filled borehole until it reaches the bottom. Ideally the grout volume is calculated so that when the casing is fully inserted the grout is at the top of the borehole. In this method it helps to have the casing full of water.

   All of these methods attempt to fill the annular space with grout all the way, top to bottom, with no voids, displacing the mud and debris with minimal sidewall disturbance.
5. The grout mixture should be formulated to approximate closely the density of the surrounding in-situ material after solidification.
   For rock, use conventional portland cement that will harden to a density about 2.2Mg/m^3 (140lb/cubic ft).

   For soils, sands, or gravels, use a mixture with:
   - 450g (1lb) bentonite
   - 450g (1lb) portland cement
   - 2800g (6.25lb) of water.
6. Keep the casing anchored and centered in the borehole until the grout is set. If shrinkage occurs, additional grout should be inserted from the top until the annular space is filled flush with the ground surface.
7. The grout must be set before testing. This means the grouting must take place at least 48 hours before testing.
8. Borehole fluid is required for the logging. The PVC must be filled with water prior to logging. If there is a leak, then water must be available to refill the borehole prior to and/or during logging. Major leaks cannot be allowed because the seismic noise accompanying such rapid water loss will obscure data and prevent data acquisition.

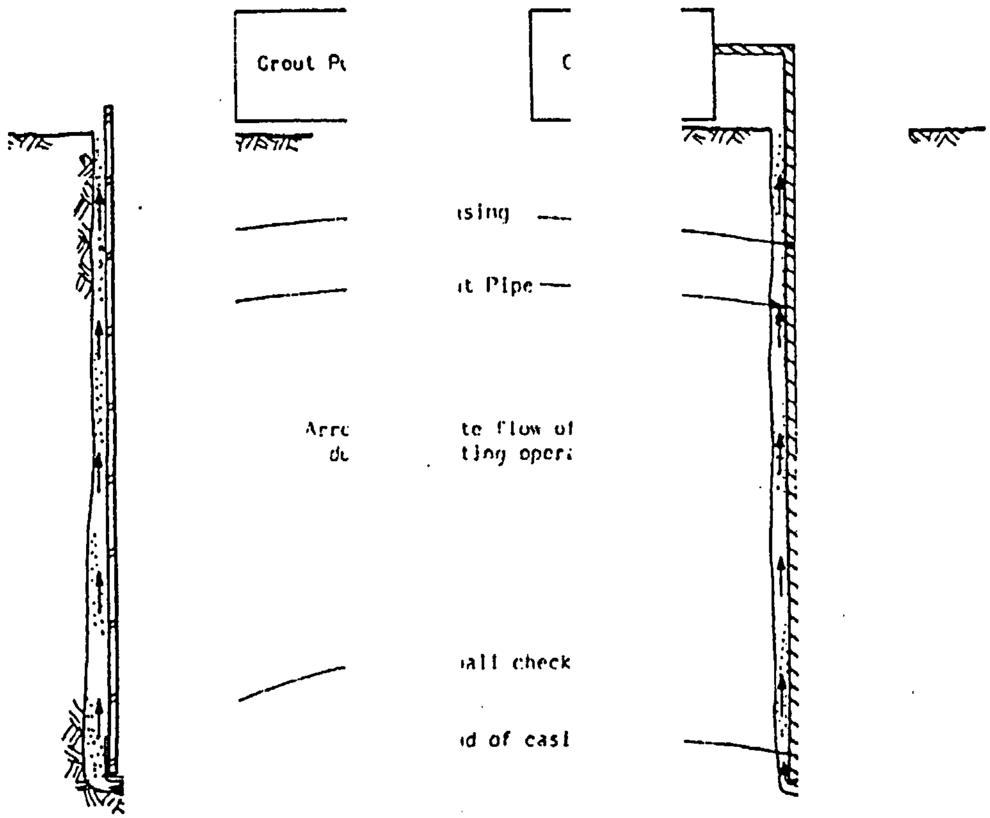


FIG. 4 e Grouting '

4/23/01 jgd

SPECIFICATIONS FOR DRILLING UNCASED BOREHOLES FOR P-S SUSPENSION LOGGING

1. The OYO P-S Suspension Logging Method can be used in either cased or uncased boreholes. Uncased boreholes are preferred because the effects of the casing and grouting are removed. For best results, the borehole must be between 10 and 20 cm in diameter, or 4 to 8 inches.
2. It is recommended that the borehole be drilled using the rotary mud method. Drilling must be done with minimal sidewall disturbance. If you think you would like to use some auger-type drilling method, consider how much damage this does to the borehole wall. The rotary mud (also called rotary wash) method does little damage to the borehole wall, and the drilling fluid (usually a bentonite mix) coats and seals the borehole wall reducing fluid loss and wall collapse. The borehole fluid is required for the logging, and must be well circulated prior to logging.
3. NOTE: A "rathole" of 15 ft is required to obtain data to the full depth desired. This is due to the construction of the OYO P-S suspension tool (see enclosed).
4. GEOVision reserves the right to NOT log a borehole if conditions indicate that there is a strong possibility that we will lose the P-S Suspension logging tool. This is rare, but it can happen. An example is, if there has been significant and continuing collapse in the borehole and attendant loss of circulation. Then the drill string gets stuck, etc. etc. This is why the method of drilling is so important. We strongly recommend rotary mud.

CALIBRATION PROCEDURE FOR

GEOVision SEISMIC RECORDER/LOGGER

Reviewed 02/16/1999

Objective

The timing/sampling accuracy of seismic recorders or data loggers is required for several GEOVision field procedures including Seismic Refraction, Downhole Seismic Velocity Logging, and P-S Suspension Logging. This procedure describes the method for measuring the timing accuracy of a seismic data logger, such as the OYO Model 170 or the Geometrics Strataview. The objective of this procedure is to verify that the timing accuracy of the recorder is accurate to within 1%.

Frequency of Calibration

The calibration of each GEOVision seismic data logger is twelve (12) months. In the case of rented seismic data loggers, calibration must be performed prior to use.

Test Equipment Required

The following equipment is required. Item #2 must have current NIST traceable calibration.

1. Function generator, Krohn Hite 5400B or equivalent
2. Frequency counter, HP 5315A or equivalent
3. Test cables, from item 1 to item 2, and from item 1 to subject data logger.

Procedure

This procedure is designed to be performed using the accompanying Seismograph Calibration Data Sheet with the same revision number. All data must be entered and the procedure signed by the technician performing the test.

1. Record all identification data on the form provided.
2. Connect function generator to data logger (such as OYO Model 170) using test cable
3. Connect the function generator to the frequency counter using test cable.

4. Set up generator to produce a 100.0 Hz, 0.25 volt (amplitude is approximate, modify as necessary to yield less than full scale waveforms on logger display) peak square wave or sine wave. Verify frequency using the counter and initial space on the data sheet.

5. Initialize data logger and record a data record of at least 0.1 second using a 100 microsecond sample period.

6. Measure the recorded square wave frequency by measuring the duration of 9 cycles of data. This measurement can be made using the data logger display device, or by printing out a paper tape. If a paper tape can be printed, the resulting printout must be attached to this procedure. Record the data in the space provided.

7. Repeat steps 5 and 6 three more times using separate files.

Criteria

The duration for 9 cycles in any file must be 90.0 milliseconds plus or minus 0.9 milliseconds, corresponding to an average frequency for the nine cycles of 100.0 Hz plus or minus 1 Hz (obtained by dividing 9 cycles by the duration in milliseconds).

If the results are outside this range, the data logger must be marked with a GEOVision REJECT tag until it can be repaired and retested.

If results are acceptable affix label indicating the initials of the person performing the calibration, the date of calibration, and the due date for the next calibration (12 months).

Procedure Approval

Approved by:

JOHN G. DIEHL	VP
Name	Title
[signature]	2/16/99
Signature	Date

Client Approval (if required):

Name	Title
Signature	Date

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SEISMOGRAPH CALIBRATION DATA SHEET REVISION LOG

DATE	REVISION NUMBER	REASON FOR CHANGE	APPROVED
4/14/98	1.00	NEW GEOVISION PROCEDURE	JGD JGD
		(WAS AGBABIAN PROCEDURE)	
12/8/98	1.10	REVISED 0.25MV TO 0.25V BECAUSE	JGD JGD
		TEST APPARATUS INJECTS SIGNAL	
		AFTER GAIN AMPLIFIERS. ALSO	
		CORRECTED SPELLING ERRORS	
		(COORECT AND SEISMOGRAPG)	
2/16/99	1.20	REVISED "TEST EQUIPMENT	JGD JGD
		REQUIRED" SECTION TO ONLY REQUIRE	
		NIST TRACEABLE CALIBRATION FOR	
		THE FREQUENCY COUNTER. ALSO	
		ADDED INSTRUCTIONS FOR CREATING	
		CALIB. LABEL PER QA PROGRAM.	

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SEISMOGRAPH CALIBRATION DATA SHEET REV 2/18/99

INSTRUMENT DATA

SYSTEM MFR:	OYO	MODEL NO.:	3551
SERIAL NO.:	15014	CALIBRATION DATE:	2/26/02
BY:	R. STELLER	DUE DATE:	2/26/03
COUNTER MFR:	TENMA	MODEL NO.:	72-[illegible]
SERIAL NO.:	MB0000 6378	CALIBRATION DATE:	2/25/02
BY:	MICRO PRECISION CAL.	DUE DATE:	2/25/03
FCTN GEN MFR:	TENMA	MODEL NO.:	72-5085
SERIAL NO.:	MB0000 0378	CALIBRATION DATE:	2/25/02
BY:	MICRO PRECISION CAL	DUE DATE:	2/25/03

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RANGE:	100 msec
DELAY:	0
STACK: 1 (STD)	1
PULSE:	1.6 msec
DISPLAY:	VARIABLE
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AS FOUND 100.0 AS LEFT 100.0

WAVEFORM	FILE NO	FREQUENCY	TIME FOR 9 CYCLES Hn	TIME FOR 9 CYCLES Hr	TIME FOR 9 CYCLES V	AVERAGE FREQ.
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SQUARE	002	100.0	90.0	90.0	90.0	100.0
SINE	003	100.0	90.0	90.1	90.1	99.9
SINE	004	100.0	89.9	90.0	90.0	100.1

CALIBRATED BY: ROBERT STELLER 2/26/02 [signature]

NAME DATE SIGNATURE

OYO

Suspension 170 1.42

15014

ID_NO. : 004
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DEPTH : 0.0 [m]
DATE : 26/02/02 01:35:43 PM
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V-SAMPLE RATE: 100 [μSEC]
PULSE WIDTH : 1.6 [mSEC]
DELAY TIME : 0 [mSEC]

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GAIN :	X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz] :	5	5	5	5	5	5
HCF[Hz] :	20K	20K	20K	20K	20K	20K
STACK :	1	1	1	1	1	1

TRACE SIZE : 1
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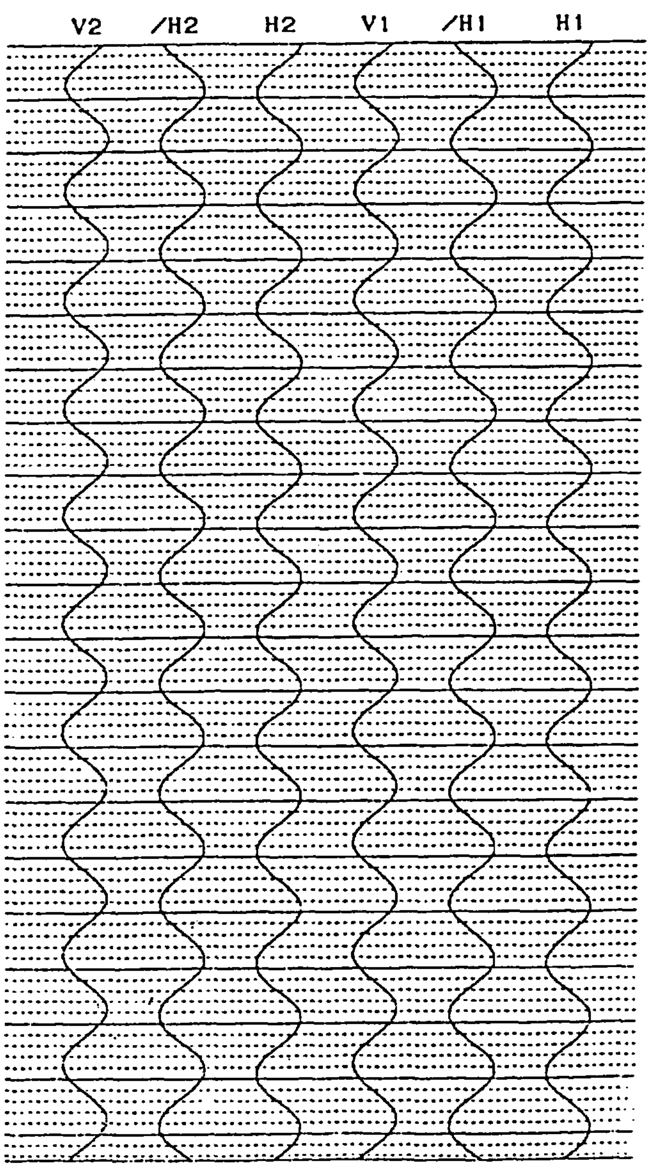

OYO

Suspension 170 1.42

15014

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DEPTH : 0.0 [m]
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V-SAMPLE RATE: 100 [μSEC]
PULSE WIDTH : 1.6 [mSEC]
DELAY TIME : 0 [mSEC]

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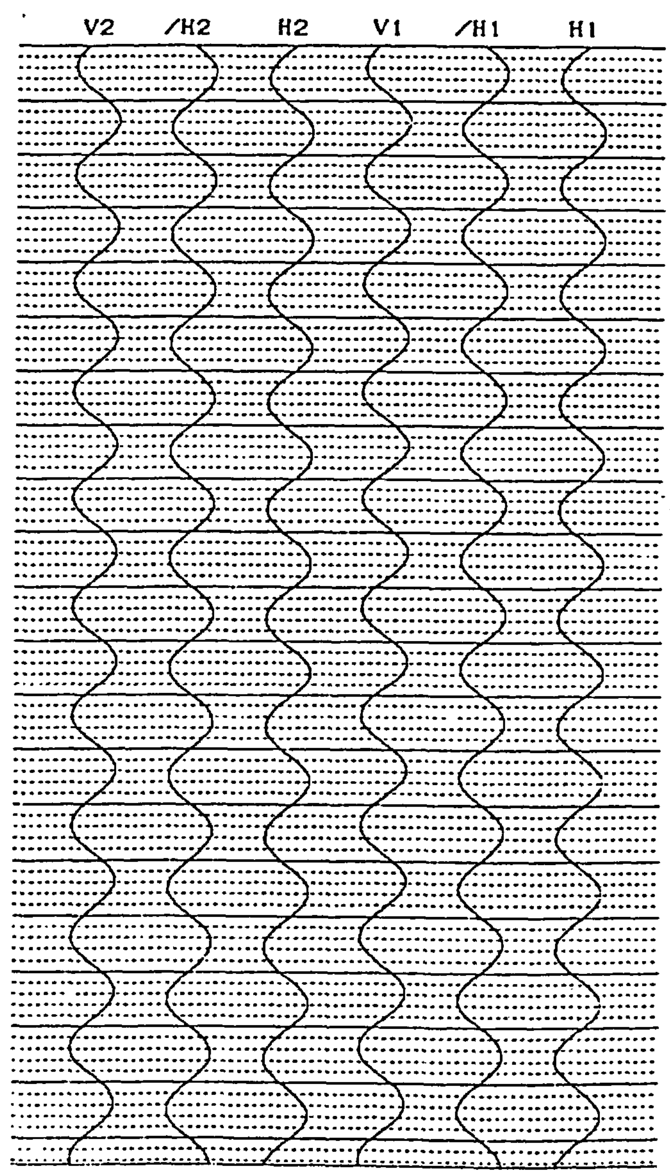
GAIN :	X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz] :	5	5	5	5	5	5
HCF[Hz] :	20K	20K	20K	20K	20K	20K
STACK :	1	1	1	1	1	1

TRACE SIZE : 1
H-TIME SCALE: 1.00 [mSEC/LINE]
V-TIME SCALE: 1.00 [mSEC/LINE]



OYO

15014

Suspension 170 1.42

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V-SAMPLE RATE: 100 [μSEC]
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DELAY TIME : 0 [mSEC]

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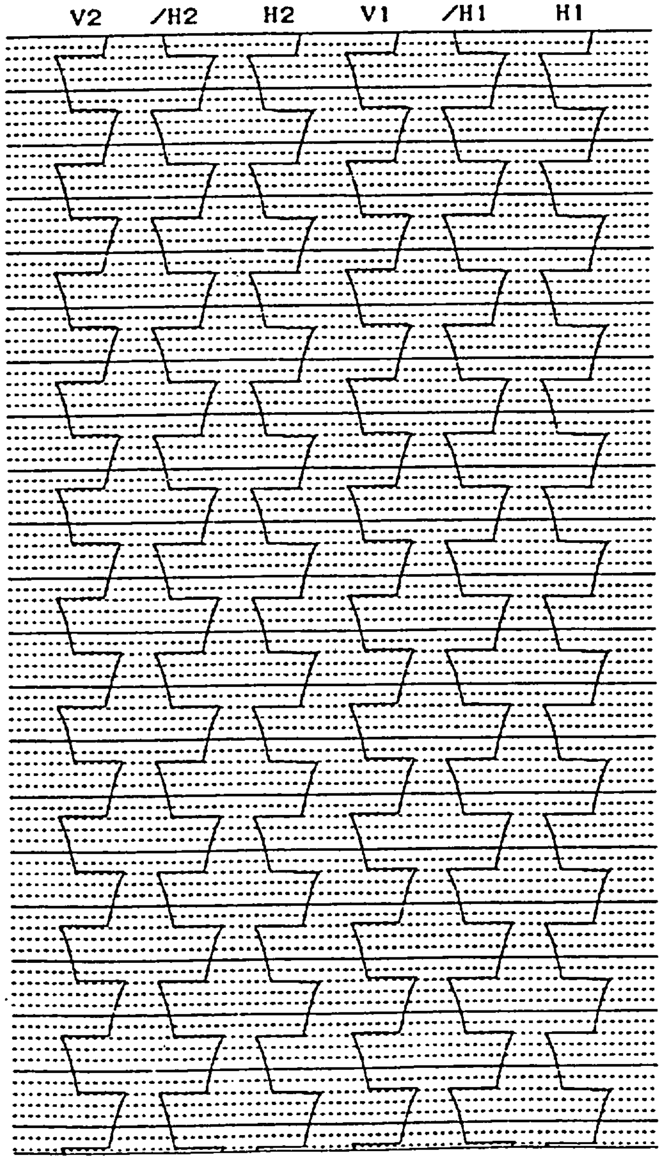
GAIN	:X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz]	: 5	5	5	5	5	5
HCF[Hz]	: 20K	20K	20K	20K	20K	20K
STACK	: 1	1	1	1	1	1

TRACE SIZE : 1
H-TIME SCALE: 1.00 [mSEC/LINE]
V-TIME SCALE: 1.00 [mSEC/LINE]

V2 /H2 H2 V1 /H1 H1



OYO

15014

Suspension 170 1.42

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V-SAMPLE RATE: 100 [μSEC]
PULSE WIDTH : 1.6 [mSEC]
DELAY TIME : 0 [mSEC]

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GAIN	:X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz]	: 5	5	5	5	5	5
HCF[Hz]	: 20K	20K	20K	20K	20K	20K
STACK	: 1	1	1	1	1	1

TRACE SIZE : 1
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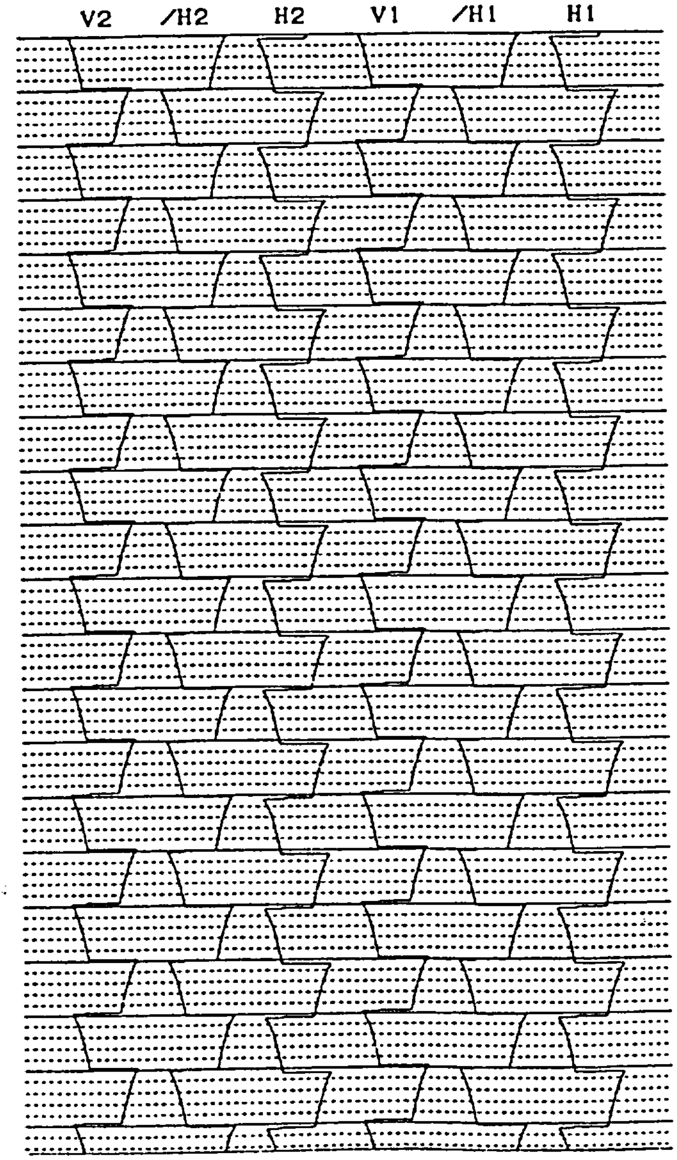
V-TIME SCALE: 1.00 [mSEC/LINE]

V2 /H2 H2 V1 /H1 H1



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SEISMOGRAPH CALIBRATION DATA SHEET REV 2/16/99

INSTRUMENT DATA

SYSTEM MFR: OYO — MODEL NO.: 3331
SERIAL NO.: 12004 — CALIBRATION DATE: 2/26/02
BY: R. STELLER — DUE DATE: 2/26/03

COUNTER MFR: TENMA — MODEL NO.: 72-5085
SERIAL NO.: MB00006378 — CALIBRATION DATE: 2/25/02
BY: MICRO PRECISION CAL — DUE DATE: 2/25/03

FCTN GEN MFR: TENMA — MODEL NO.: 72-5085
SERIAL NO.: MB00006378 — CALIBRATION DATE: 2/25/02
BY: MICROPRECISION CAL — DUE DATE: 2/25/03

SYSTEM SETTINGS:

GAIN: 10
FILTER: 20 KHZ
RANGE: 100 MSEC
DELAY: 0
STACK: 1 (STD) 1
PULSE: 1.6 MSEC
DISPLAY: VARIABLE
SYSTEM: DATE = CORRECT DATE & TIME 2/26/02 1:54 PM

PROCEDURE:

SET FREQUENCY TO 100.0HZ SQUAREWAVE WITH AMPLITUDE APPROXIMATELY 0.25 VOLT PEAK. RECORD BOTH ON DISKETTE AND PAPER TAPE. ANALYZE AND PRINT WAVEFORMS FROM ANALYSIS UTILITY. ATTACH PAPER COPIES OF PRINTOUT AND PAPER TAPES TO THIS FORM. AVERAGE FREQUENCY MUST BE BETWEEN 99.0 AND 101.0 HZ.

AS FOUND 100.0 AS LEFT 100.0

WAVEFORM	FILE NO	FREQUENCY	TIME FOR 9 CYCLES Hn	TIME FOR 9 CYCLES Hr	TIME FOR 9 CYCLES V	AVERAGE FREQ.
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SQUARE	102	100.0	90.0	90.0	90.0	100.0
SINE	103	100.0	90.0	89.9	90.0	100.1
SINE	104	100.0	89.9	90.0	90.1	100.0

CALIBRATED BY: ROBERT STELLER 2/26/02 [signature]
NAME DATE SIGNATURE

OYO

12004

Suspension 170 V1.2

ID_NO. : 103
HOLE NO. : 0
DEPTH : 0.0 [m]
DATE : 26/02/02 01:54:01 PM
SAMPLING : 100 [µSEC]
DELAY : 0 [mSEC]

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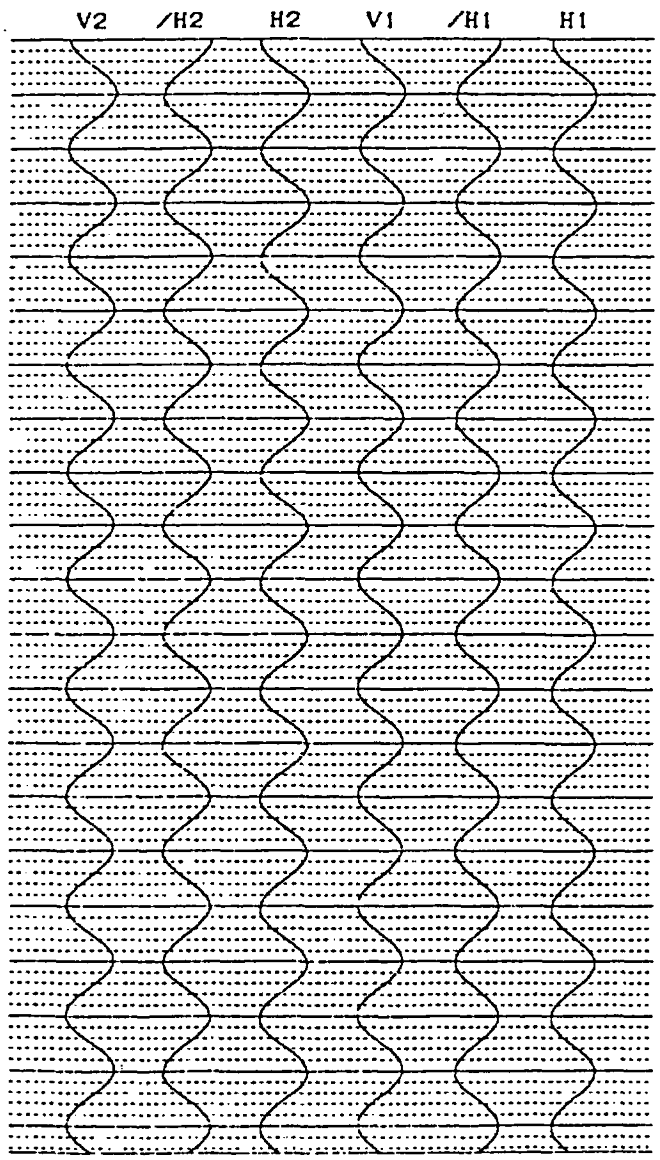
LCF[Hz]	: 5	5	5	5	5	5
HCF[Hz]	: 20K	20K	20K	20K	20K	20K
STACK	: 1	1	1	1	1	1

TRACE SIZE:
TIME SCALE: 1.0 [mSEC/LINE]



OYO

12004

Suspension 170 V1.2

ID_NO. : 104
HOLE NO. : 0
DEPTH : 0.0 [m]
DATE : 26/02/02 01:54:01 PM
SAMPLING : 100 [µSEC]
DELAY : 0 [mSEC]

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GAIN	:X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz]	: 5	5	5	5	5	5
HCF[Hz]	: 20K	20K	20K	20K	20K	20K
STACK	: 1	1	1	1	1	1

TRACE SIZE: 1
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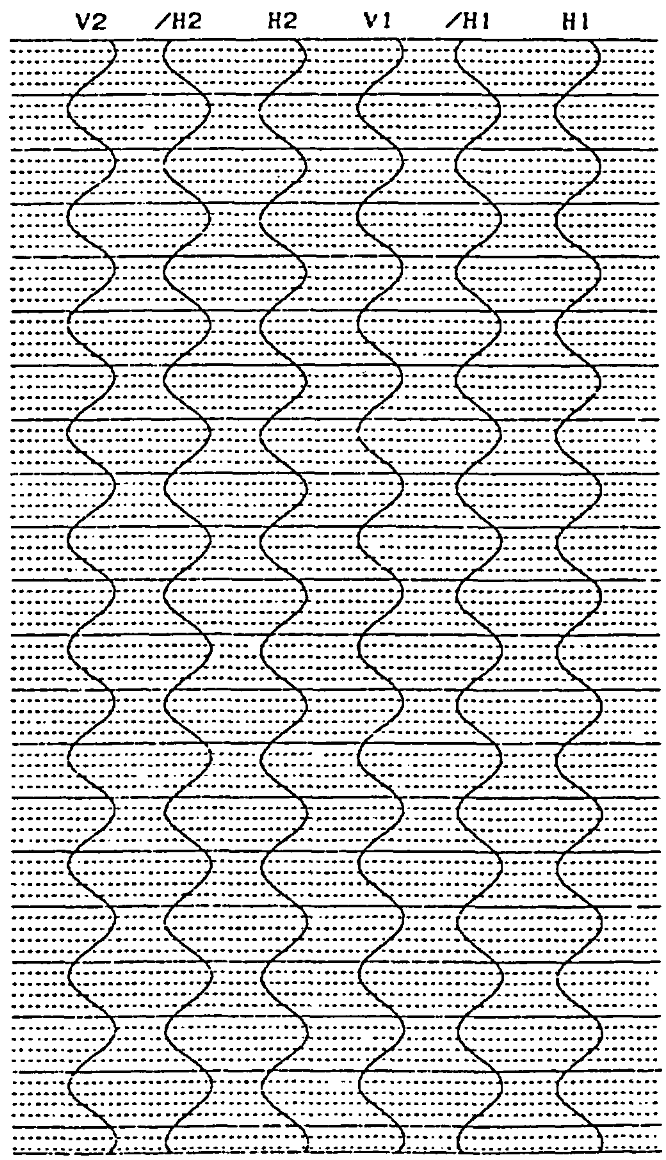

OYO

Suspension 170 V1.2

12004

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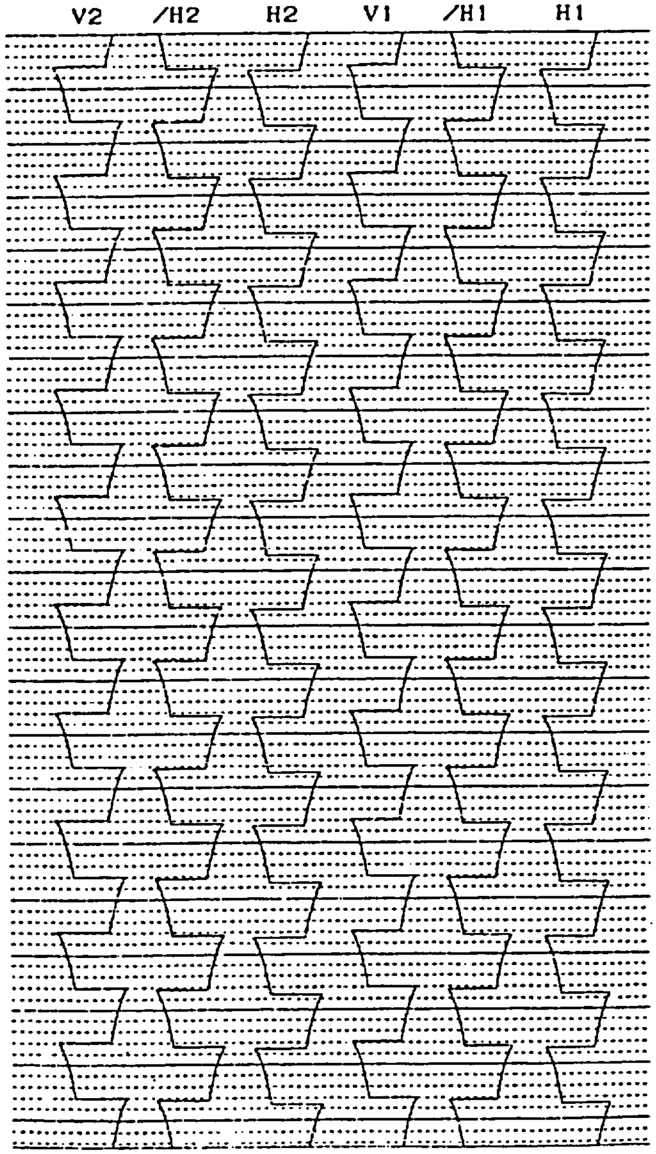
HOLE NO. : 0
DEPTH : 0.0 [m]
DATE : 26/02/02 01:54:01 PM
SAMPLING : 100 [μSEC]
DELAY : 0 [mSEC]

	H1	/H1	V1	H2	/H2	V2
GAIN	:X 10	X 10	X 10	X 10	X 10	X 10
LCF [Hz]	: 5	5	5	5	5	5
HCF [Hz]	: 20K	20K	20K	20K	20K	20K
STACK	: 1	1	1	1	1	1

TRACE SIZE:
TIME SCALE: 1.0 [mSEC/LINE]

V2 /H2 H2 V1 /H1 H1



OYO

Suspension 170 V1.2

12004

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DELAY : 0 [mSEC]

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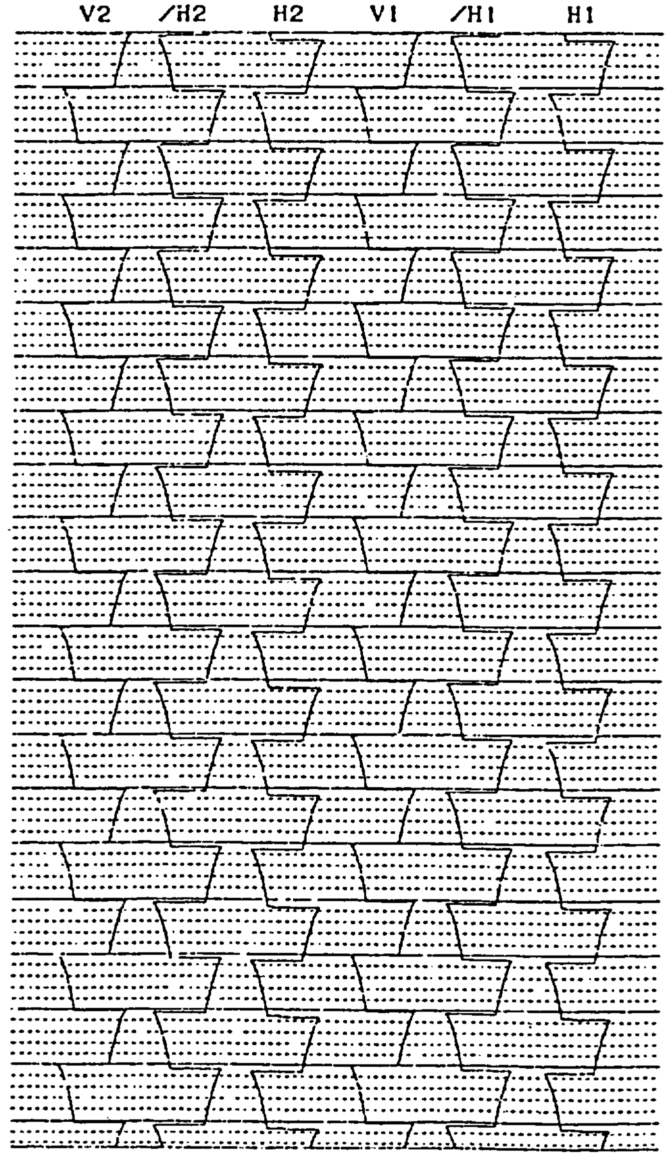
GAIN	:X 10	X 10	X 10	X 10	X 10	X 10
LCF [Hz]	: 5	5	5	5	5	5
HCF [Hz]	: 20K	20K	20K	20K	20K	20K
STACK	: 1	1	1	1	1	1

TRACE SIZE:
TIME SCALE: 1.0 [mSEC/LINE]

V2 /H2 H2 V1 /H1 H1



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SEISMOGRAPH CALIBRATION DATA SHEET REV 2/16/99

INSTRUMENT DATA

SYSTEM MFR:	OYO	MODEL NO.:	3331 A
SERIAL NO.:	19029	CALIBRATION DATE:	2/26/02
BY:	R. STELLER	DUE DATE:	2/26/03
COUNTER MFR:	TENMA	MODEL NO.:	72-5085
SERIAL NO.:	MB00006378	CALIBRATION DATE:	2/25/02
BY:	MICROPRECISION CAL	DUE DATE:	2/25/03
FCTN GEN MFR:	TENMA	MODEL NO.:	72-5085
SERIAL NO.:	MB00006378	CALIBRATION DATE:	2/25/02
BY:	MICRO PRECISION CAL	DUE DATE:	2/25/03

SYSTEM SETTINGS:

GAIN:	10
FILTER:	20 KHZ
RANGE:	100 MSEC
DELAY:	0
STACK: 1 (STD)	1
PULSE:	1.6 MSEC
DISPLAY:	VARIABLE
SYSTEM: DATE = CORRECT DATE & TIME	2/26/02 2:26 pm

PROCEDURE:
SET FREQUENCY TO 100.0HZ SQUAREWAVE WITH AMPLITUDE APPROXIMATELY 0.25 VOLT PEAK. RECORD BOTH ON DISKETTE AND PAPER TAPE. ANALYZE AND PRINT WAVEFORMS FROM ANALYSIS UTILITY. ATTACH PAPER COPIES OF PRINTOUT AND PAPER TAPES TO THIS FORM. AVERAGE FREQUENCY MUST BE BETWEEN 99.0 AND 101.0 HZ.

AS FOUND 100.0 AS LEFT 100.0

WAVEFORM	FILE NO	FREQUENCY	TIME FOR 9 CYCLES Hn	TIME FOR 9 CYCLES Hr	TIME FOR 9 CYCLES V	AVERAGE FREQ.
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SINE	203	100.0	90.0	90.0	90.0	100.0
SINE	204	100.0	90.1	90.1	90.1	99.9

CALIBRATED BY: ROBERT STELLER 2/26/02 [signature]
NAME DATE SIGNATURE

OYO

Suspension 170 4.25 19029

ID_NO. : 204
HOLE NO. : 0
DEPTH : 0.0 [m]
DATE : 26/02/02 02:34:33 PM
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V-SAMPLE RATE: 100 [μSEC]
PULSE WIDTH : 1.6 [mSEC]
DELAY TIME : 0 [mSEC]

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GAIN :	X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz] :	5	5	5	5	5	5
HCF[Hz] :	20K	20K	20K	20K	20K	20K
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TRACE SIZE : 1
H-TIME SCALE: 1.00 [mSEC/LINE]
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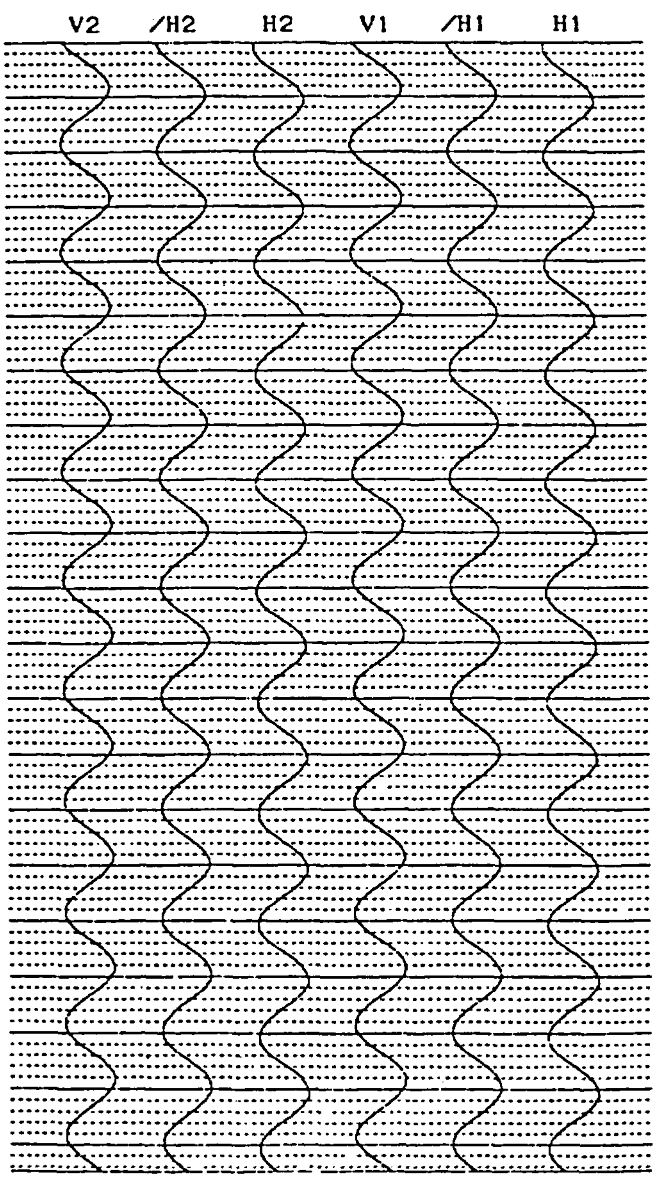

OYO

Suspension 170 4.25 19029

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V-SAMPLE RATE: 100 [μSEC]
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GAIN :	X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz] :	5	5	5	5	5	5
HCF[Hz] :	20K	20K	20K	20K	20K	20K
STACK :	1	1	1	1	1	1

TRACE SIZE : 1
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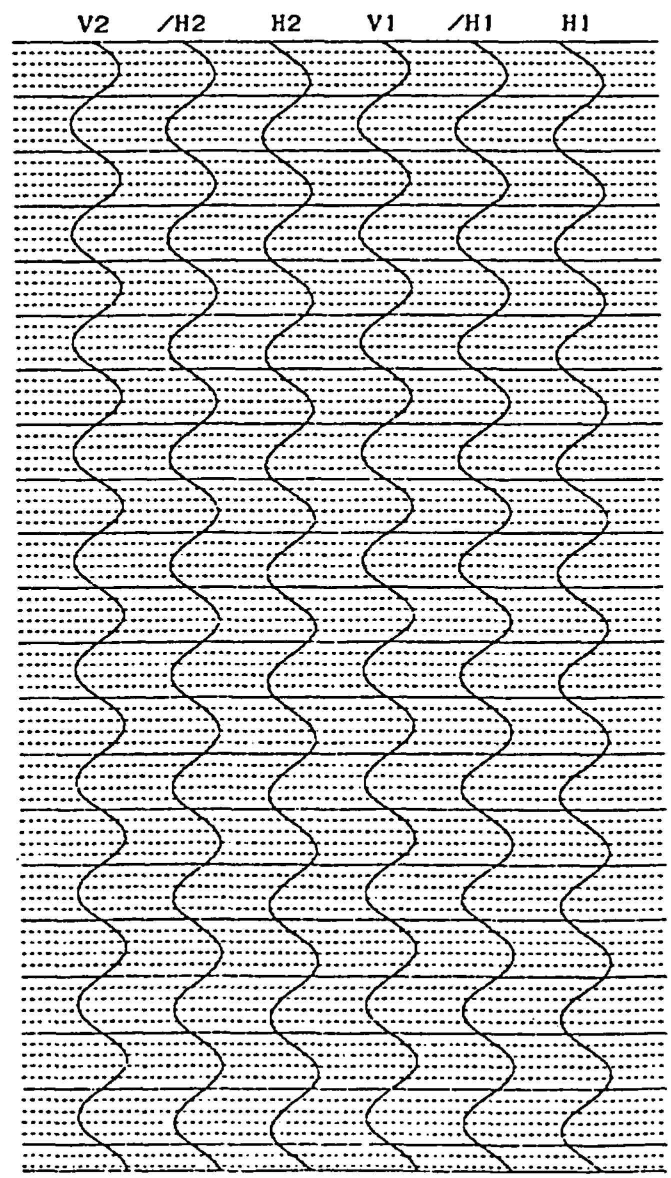

OYO

Suspension 170 4.25 19029

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LCF[Hz] :	5	5	5	5	5	5
HCF[Hz] :	20K	20K	20K	20K	20K	20K
STACK :	1	1	1	1	1	1

TRACE SIZE : 1
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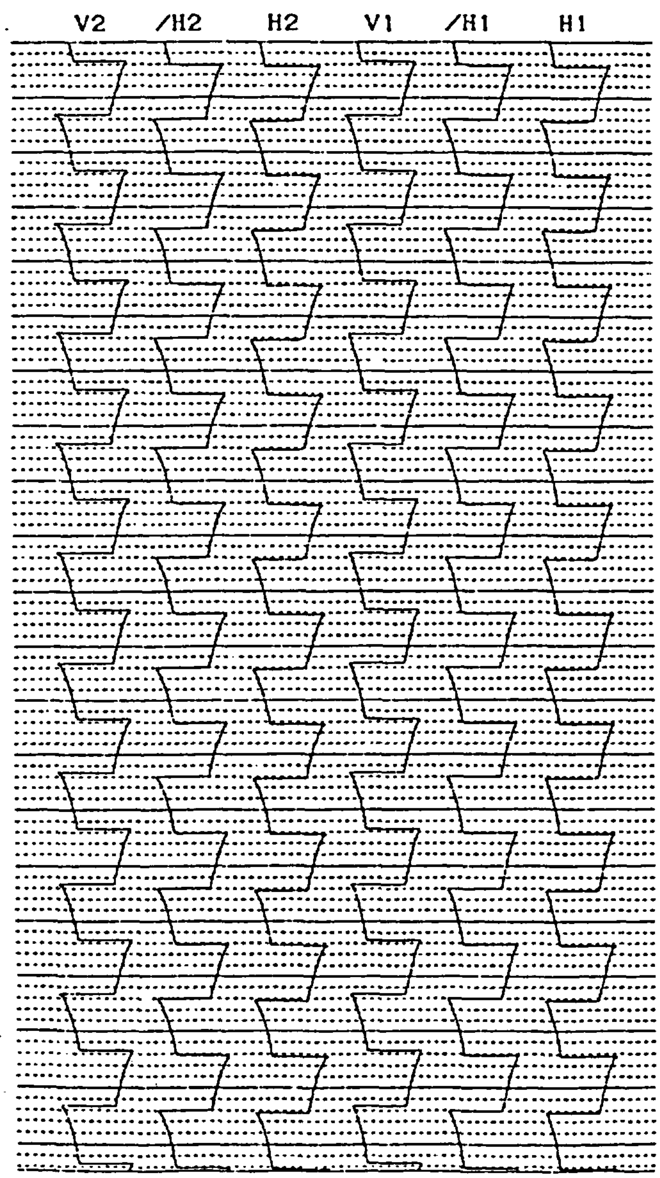
V-TIME SCALE: 1.00 [mSEC/LINE]



OYO

Suspension 170 4.25 19029

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HOLE NO. : 0
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V-SAMPLE RATE: 100 [μSEC]
PULSE WIDTH : 1.6 [mSEC]
DELAY TIME : 0 [mSEC]

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GAIN :	X 10	X 10	X 10	X 10	X 10	X 10
LCF[Hz] :	5	5	5	5	5	5
HCF[Hz] :	20K	20K	20K	20K	20K	20K
STACK :	1	1	1	1	1	1

TRACE SIZE : 1
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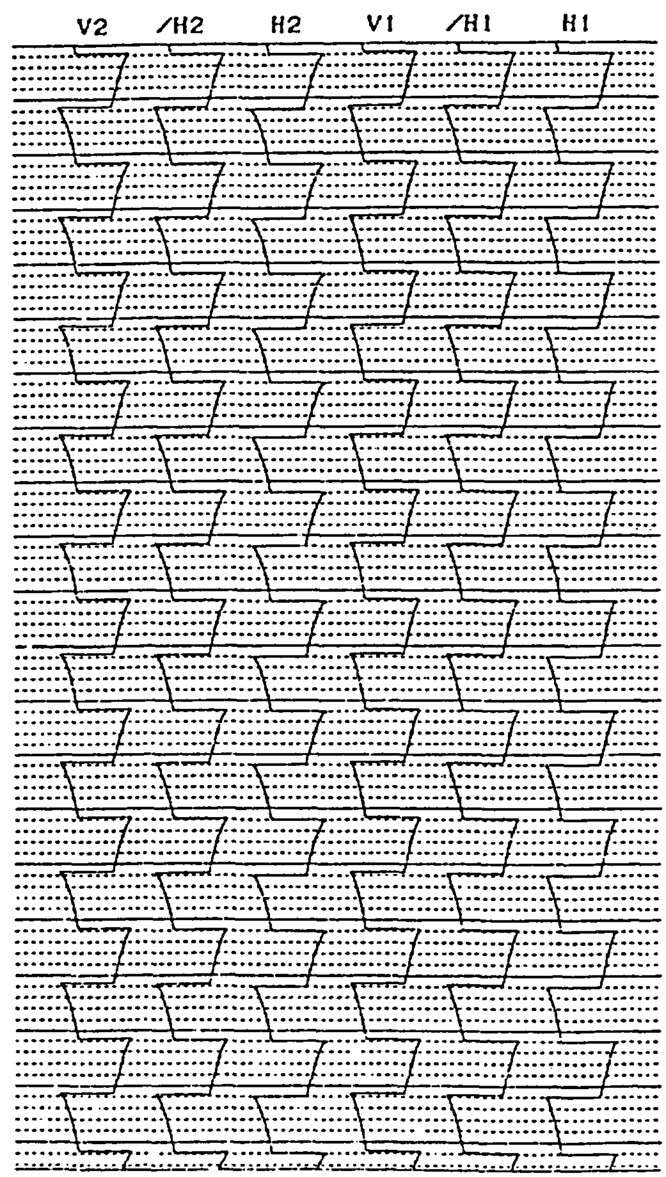


MICRO PRECISION CALIBRATION INC.
11562 Knott Street, Ste. 3, Garden Grove, CA 92841
Ph. 714-901-5659 Fax: 714-901-5649

Calibration Report

Customer: GEOVISION Corona CA 92882

Account: 15214

Instrument: BB9414 Digital Universal Test Center

Mfg: Tenma	Model: 72-5085	Serial #: MB00006378
Size:	Resltn:	Location:

Cust Ctrl:	Dept:	P.O.: 2236-020220-2
Job Number: L16939	Report Number: 115406	Report Date: 022502

Work Performed: Inspected, cleaned, and calibrated. Page 1 of 1

Parts Replaced: None

Received Condition: In tolerance Returned Condition: In tolerance

Function Tested	
Multimeter	Function Generator cont'
AC/DC Volts & Current	Amplitude
Resistance & Capacitance	Sine wave distortion& flatness
Power Supply	Square wave symmetry, rise & fall time
Voltage	Triangle wave linearity
Current	TTL rise & fall time, output level
Ripple	
Frequency Counter	
Frequency range & Accuracy	
Input Sensitivity	
Function Generator	
Frequency	

Ctrl #	Manufacture, Model #, & Description of standards used for calibration	Due Date	Traceability
L8100	L8100 Wavetek 4800A Multifunction Calibr	031202	35951031201
L1600	L1600 Hewlett Packard 34401A Multimeter	040502	97906
T1100	T1100 Hewlett Packard 53131A Counter	060402	100795
P5300	P5300 Tektronix THS710 Oscilloscope w/DMM	022003	114723
K4350	K4350 Hewlett Packard 8903A Audio Analyzer	053102	99604

Services provided conform to ANSI/NCSL Z540-1-1994 (Formerly Mil-Std 45662A) and ISO 10012-1:1992
All work performed complies with MPC Quality System QM 540-94, Rev 1a.

Environmental: 72 Deg F / 42% Rh Test Date: 022502

Uncertainty: Accuracy Ratio > 4:1 Cycle: 12

Cal Procedure: Manufacture Man Due Date: 022503

Technician: ERIC BRADLEY Quality Approval: QC 3

Form Cert 2-25-02

13.5. University of Texas – Dynamic Soil Testing Procedure (105 pages)

ENT0002-PI-05, Rev. 0
ATTACHMENT 5
COVER PAGE

1

Supplemental Record

Appendix 1

Technical Procedures for Resonant Column and Torsional Shear (RCTS) Testing of Soil and Rock Samples

Procedure PBRCTS-1 rev.4, 10 October 2000

Referred to on Pages 2, 43 and 46 of the Scientific Notebook
SN-M&O-SCI-033-V1
Laboratory Dynamic Testing of Rock and Soil Specimens for the Potential Waste Handling Building Site

QA:QA

P.O.# A17376YS0A
UTACED

ENTØØ2-PI-05, REV. 0 2
ATTACHMENT 5

TECHNICAL PROCEDURES
FOR
RESONANT COLUMN AND TORSIONAL SHEAR (RCTS) TESTING OF SOIL AND ROCK SAMPLES

Project: Waste Handling Building Area
Yucca Mountain Project
TRW Environmental Safety Systems, Inc.
Las Vegas, Nevada

Project No. A17376YSOA
Geotechnical Engineering Center
University of Texas
Austin, Texas

QA:QA

P.O.# A17376YS0A
UTACED

RCTS TESTING OF SOIL AND ROCK SAMPLES

1.0 INTRODUCTION

Resonant column and torsional shear (RCTS) equipment shall be employed in this investigation for measurement of the deformational characteristics (shear modulus and material damping in shear) of soil and rock specimens. This equipment has been developed at The University of Texas at Austin over the past two decades (Isenhower, 1979; Lodde, 1982; Ni, 1987; and Kim, 1991). The equipment is of the fixed-free type, with the bottom of the specimen fixed and torsional excitation applied to the top . Both resonant column (RC) and torsional shear (TS) tests can be performed in a sequential series on the same specimen over a shearing strain range from about $10^{-4}\%$ to slightly more than $10^{-1}\%$. The primary difference between the two types of tests is the excitation frequency. In the RC test, frequencies above 20 Hz are required and inertia of the specimen and drive system are needed to analyze the measurements. On the other hand, slow cyclic loading involving frequencies generally below 10 Hz is performed in the TS test and inertia does not enter data analysis.

2.0 RESONANT COLUMN AND TORSIONAL SHEAR EQUIPMENT

2.1 OVERVIEW OF RCTS EQUIPMENT

The RCTS apparatus can be idealized as a fixed-free system as shown in Fig. 1. The bottom end of the specimen is fixed against rotation at the base pedestal, and top end of the specimen is connected to the driving system. The driving system, which consists of a top cap and drive plate, can rotate freely to excite the specimen in cyclic torsion.

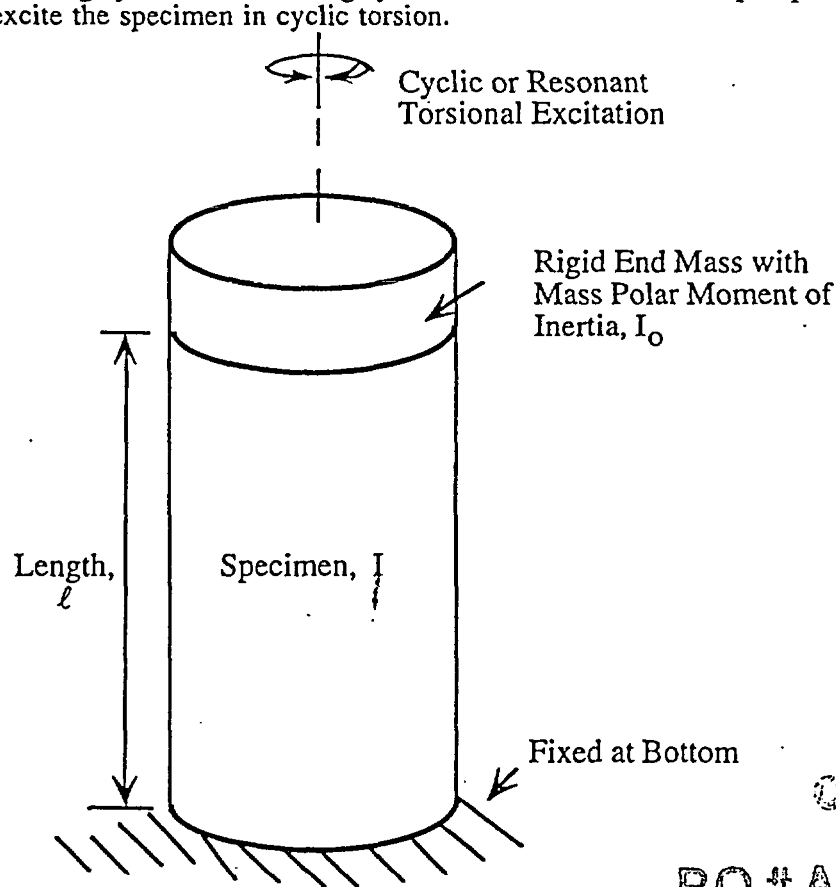


Fig. 1 Idealized Fixed-Free RCTS Equipment

A simplified diagram of a fixed-free resonant column (RC) test is shown in Fig. 2. The basic operational principle is to vibrate the cylindrical specimen in first-mode torsional motion. Harmonic torsional excitation is applied to the top of the specimen over a range in frequencies, and the variation of the acceleration amplitude of the specimen with frequency is obtained. Once first-mode resonance is established, measurements of the resonant frequency and amplitude of vibration are made. These measurements are then combined with equipment characteristics and specimen size to calculate shear wave velocity and shear modulus based on elastic wave propagation. Material damping is determined either from the width of the frequency response curve or from the free-vibration decay curve.

The torsional shear (TS) test is another method of determining shear modulus and material damping using the same RCTS equipment but operating it in a different manner. The simplified configuration of the torsional shear test is shown in Fig. 3. A cyclic torsional force with a given frequency, generally below 10 Hz, is applied at the top of the specimen. Instead of determining the resonant frequency, the stress-strain hysteresis loop is determined from measuring the torque-twist response of the specimen. Proximitors are used to measure the angle of twist while the voltage applied to the coil is calibrated to yield torque. Shear modulus is calculated from the slope of a line through the end points of the hysteresis loop, and material damping is obtained from the area of the hysteresis loop as shown in Fig. 3.

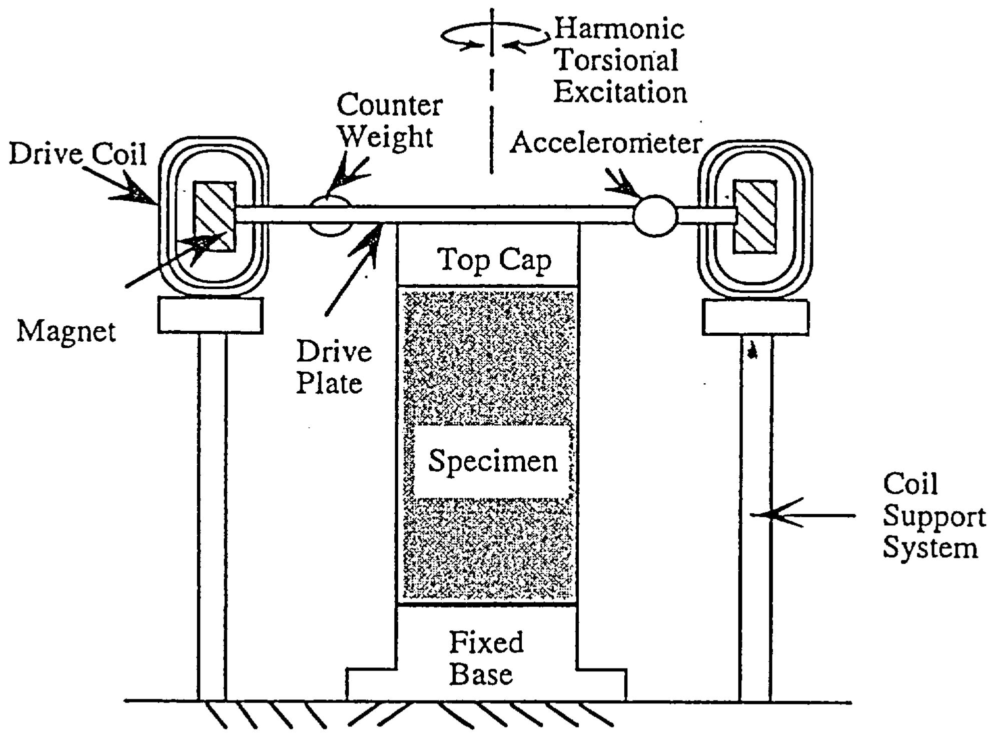
The RCTS apparatus used in this study has three advantages. First, both resonant column and torsional shear tests can be performed with the same set-up simply by changing (outside the apparatus) the frequency of the forcing function. Variability due to preparing "identical" samples is eliminated so that both test results can be compared effectively. Second, the torsional shear test can be performed over a shearing strain range between 5 x 10^{-4}% and about 10^{-1}%, depending upon specimen stiffness. Common types of torsional shear tests, which generate torque by a mechanical motor outside of the confining chamber, are usually performed at strains above 0.01% because of system compliance. However, the RCTS apparatus used in this study generates torque with an electrical coil-magnet system inside the confining chamber, thus eliminating the problem with an external motor. The torsional shear test can be performed at the same low-strain amplitudes as the resonant column test, and results between torsional shear and resonant column testing can be easily compared over a wide range of strains. Third, the loading frequency in the torsional shear test can be changed easily from 0.01 Hz to 10 Hz. Therefore, the effect of frequency on deformational characteristics can be conveniently investigated using this apparatus.

The RCTS apparatus consists of four basic subsystems which are: 1. a confinement system, 2. a drive system, 3. a height-change measurement system, and 4. a motion monitoring system. The general configuration of the RCTS apparatus (without the confinement system) is shown in Fig. 4. The RCTS apparatus was automated by Ni (1987) so that a microcomputer controls the test, collects the data, and reduces results. Computer-aided subsystems are discussed in the following sections. The configuration of the computerized system is shown in Fig. 5.

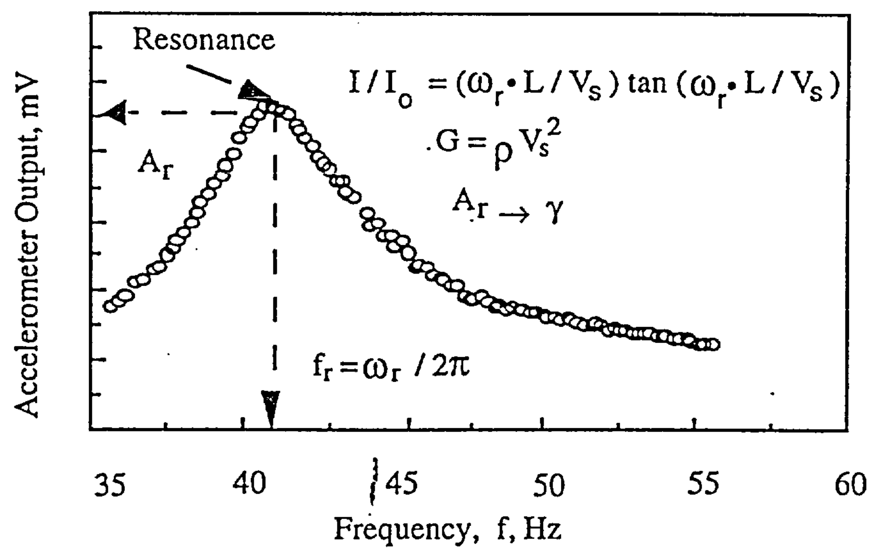
2.2. RCTS Confinement System

The confining chamber is made of stainless steel. A thin-walled (0.6 cm in thickness) hollow cylinder fits into circular grooves machined in 2.5 cm thick base and top plates. Four stainless steel connecting rods (1.28 cm in diameter) are used to secure the base and top plates to the hollow cylinder, and O-rings in the circular grooves are used to seal the chamber. In this configuration, the chamber has been designed to withstand a maximum air pressure of about 200 psi (1379 kPa). To safely test samples at higher confining pressures (pressures on the order of 600 psi (4137 kPa)), the confinement system is modified by adding additional stainless steel rods to secure the cylinder to reinforced top and base plates.

Compressed air is used to confine isotropically the specimen in the RCTS device. The air pressure to the chamber generally is regulated by a Fairchild M 30 regulator and air supplied to the regulator is filtered. At high confining pressures, additional regulators are used. The soil specimen is sealed in a membrane and pore pressure in the specimen is vented to atmospheric pressure.



a) Specimen in the Resonant Column Apparatus
(Confinement Chamber Not Shown)



b) Typical Frequency Response Curve

Fig. 2 Simplified Diagram of a Fixed-Free Resonant Column Test and an Associated Frequency Response Curve

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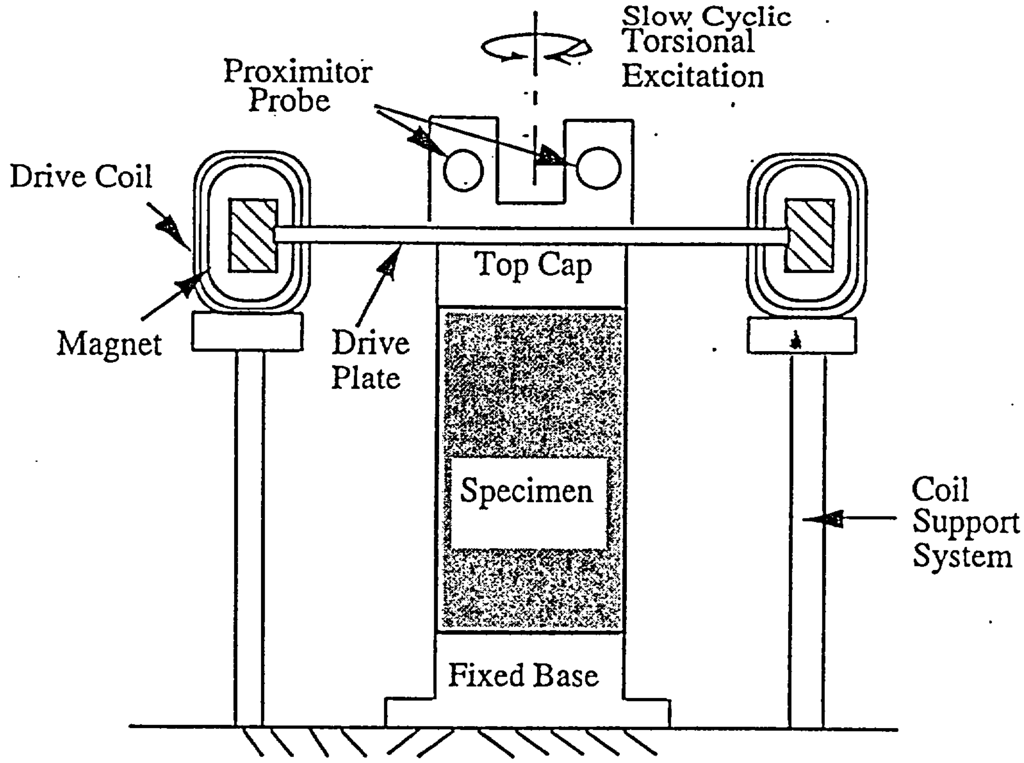
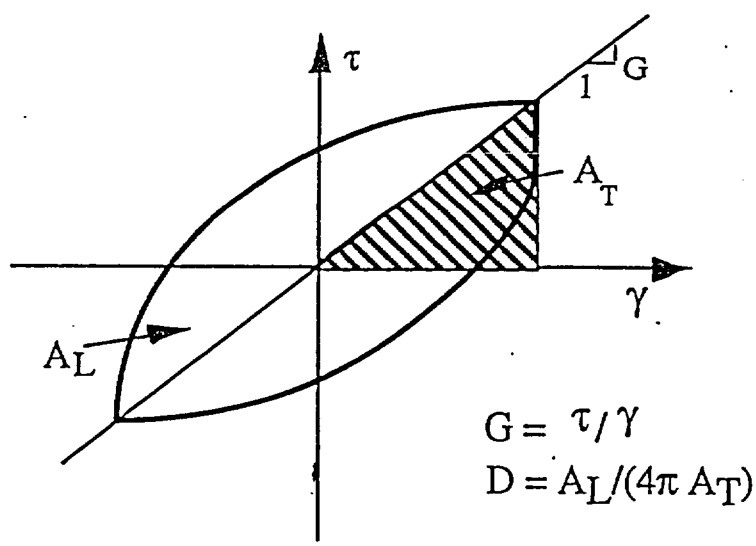


a) Specimen in the Torsional Shear Test Apparatus (Confinement Chamber Not Shown)



b) Measurement of Shear Modulus and Damping Ratio

Fig. 3 Configuration of a Torsional Shear Test and Evaluation of Shear Modulus and Material Damping Ratio

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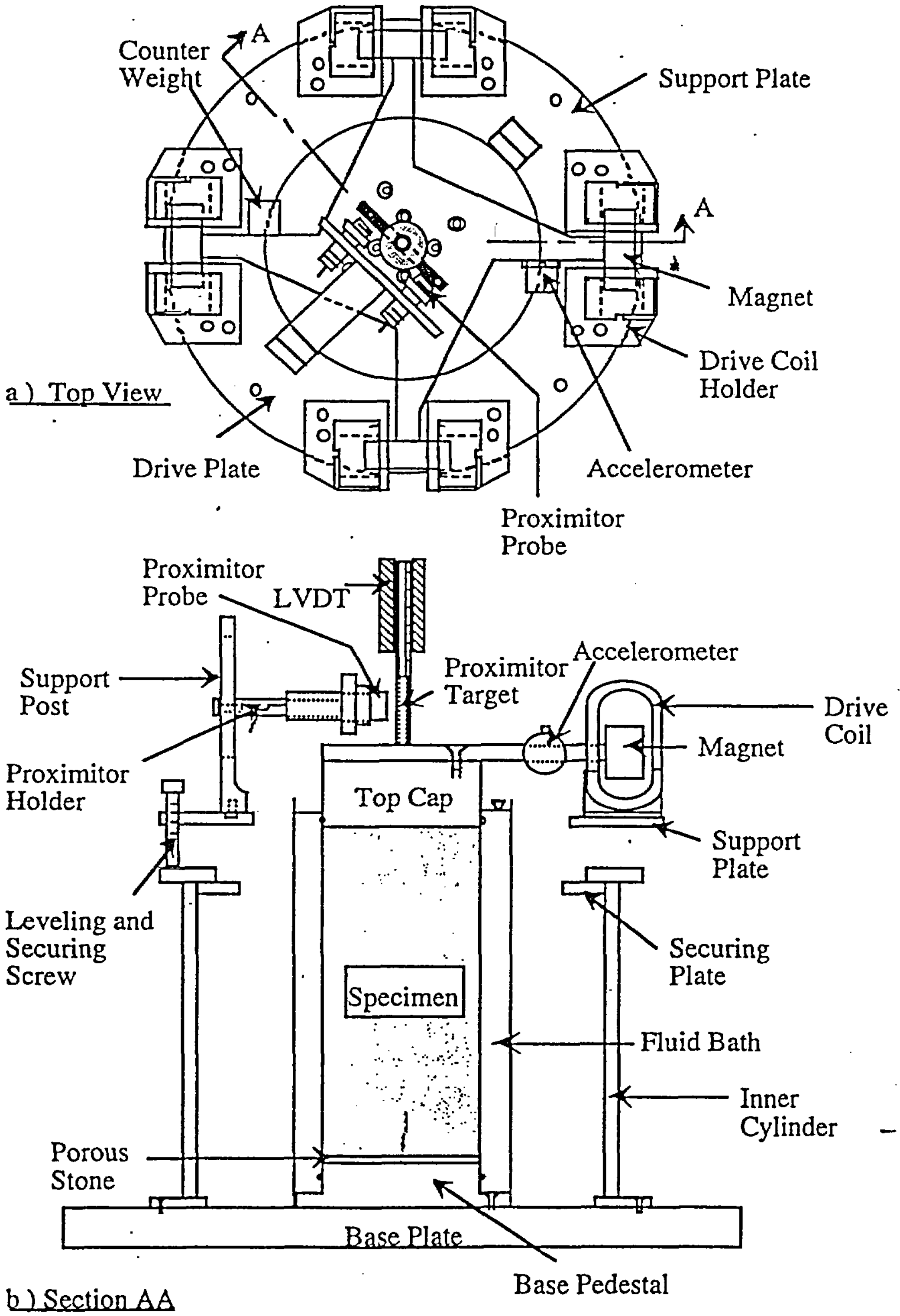

Fig. 4 General Configuration of RCTS Equipment (from Ni, 1987)

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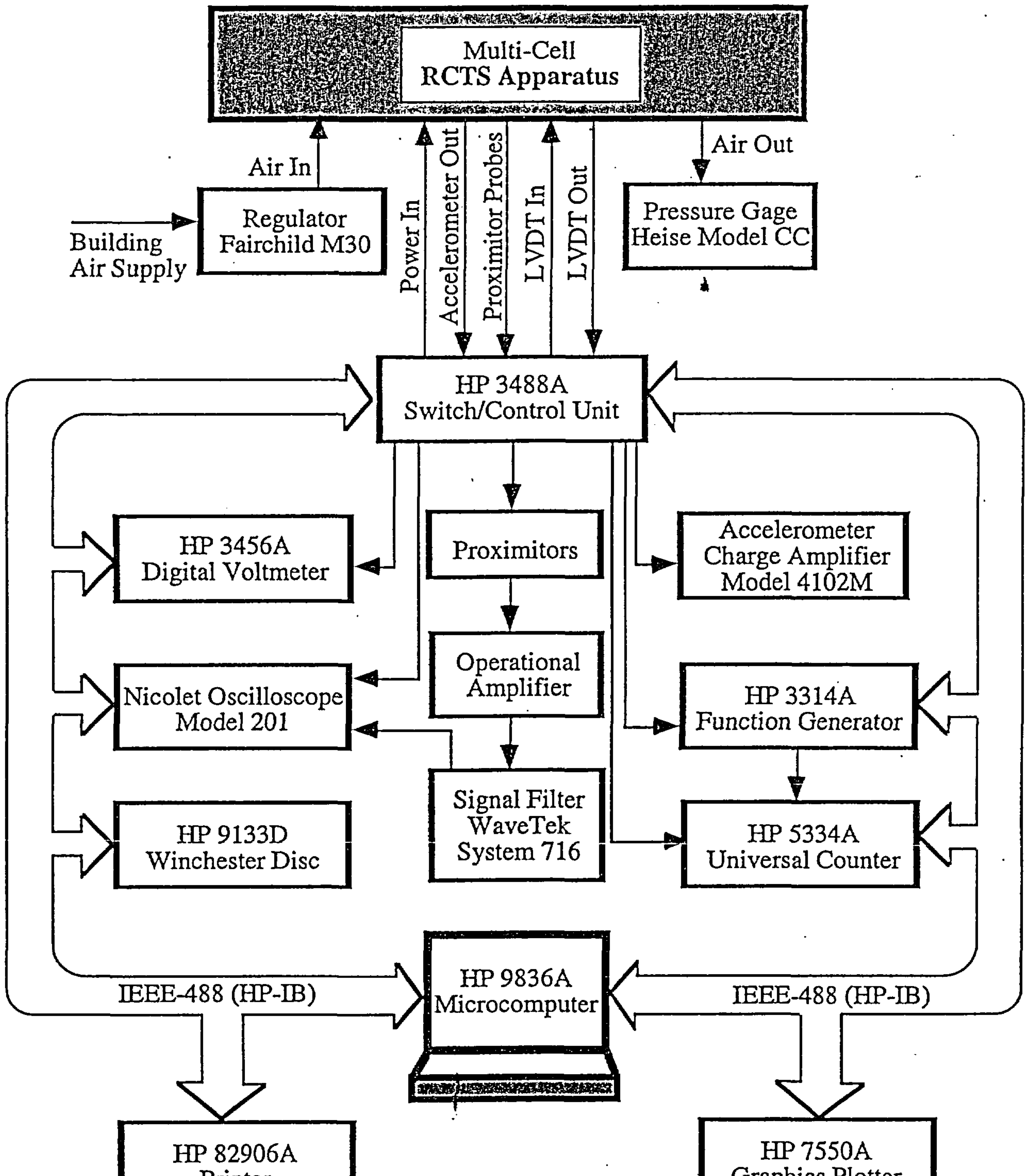

Fig. 5 – Configuration of Computerized RCTS Test Equipment

*Current equipment configuration is presented in Appendix B on page B-2.

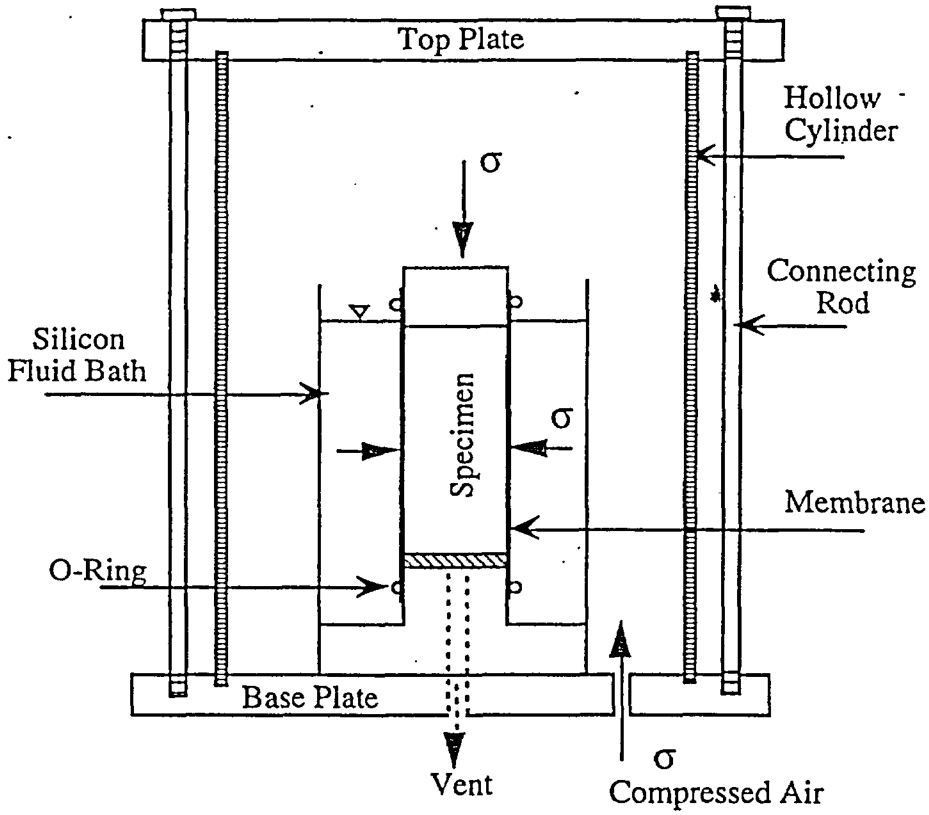

Fig. 6 Simplified Configuration of Confinement System

Inside the confining chamber, the air pressure acts upon a silicon fluid bath which surrounds the sides of the specimen. The purpose of the silicon fluid bath is to retard air migration through the membrane and into the specimen to prevent drying of the specimen. Figure 6 shows the simplified configuration of the confinement system.

The only calibrated portions of the confinement system are the pressure gauges which are used to read the cell air pressure. These gauges are calibrated every six months against reference gauges and electrical pressure transducers.

2.3 Drive System

The drive system consists of a four-armed drive plate, four magnets, eight drive coils, a power amplifier, and a function generator. Each magnet is rigidly attached to the end of one arm of the drive plate as shown in Fig. 4. Eight drive coils encircle the ends of the four magnets so that the drive plate excites the soil specimen in torsional motion when a current is passed through the coils. The maximum torque that the drive system can develop depends on the strength of the magnets, size of the drive coils, resistance of the drive coils, size of the space between the magnets and drive coils, length of the arms of the drive plate, and the electrical characteristics of the function generator and power amplifier. For the three drive systems used in this work, the maximum torque was about 0.60 lb-ft (82 N-cm).

A schematic diagram of the drive system is shown in Fig. 7. The micro-computer activates a function generator (HP 3314A) to input sinusoidal voltage to the drive coils. In the resonant column (RC) test, the function generator performs frequency sweeps with a constant amplitude while in the torsional shear test, a fixed-frequency N-cycle mode is used. For high-amplitude resonant column and torsional shear (TS) tests, the sinusoidal input current is amplified by a power amplifier (HP 6824A) before going to the drive coils.

2.4 Height-Change Measurement System

The height change of the specimen is measured to account for the changes in the length and mass of the specimen during consolidation or swell. This measurement is also used to calculate change in the mass moment of inertia, mass density, and void ratio during testing (by assuming isotropic strain under isotropic confinement and constant degree of saturation). The height change is measured by a linear variable differential transformer (LVDT). The height change measurement system consists of an LVDT (CRL Model SH-200-53R), a function generator (HP 3314A), and a digital voltmeter (HP 3456A). The LVDT core is not in contact with the LVDT coil housing so that no friction occurs during RCTS testing.

The output and calibration factor of an LVDT depend on both the frequency and magnitude of the excitation voltage. The LVDT's are calibrated yearly using micrometers as discussed by Lodde (1982). In this test the computer activates the function generator to generate the input signal in the LVDT coil at a frequency of 500 Hz and a voltage level of 4.77 RMS volts. The output from the LVDT is read with a digital voltmeter. The height change is calculated from the output voltage combined with the calibration factor. The schematic diagram of the height change measuring system is shown in Fig. 8.

Two aspects of the drive in the RCTS equipment system have to be calibrated. First, the mass polar moment of the inertia, I_o, of each drive plate and top cap must be determined. This is done using specimens made of metal rods which are used as fixed-free torsional pendulums as discussed by Isenhower (1979) and Lodde (1982). The second aspect consists of determining the torque - current calibration factor for each drive plate. This process also involves use of the metal rods as discussed by Isenhower and Lodde. These calibrations are performed every nine months.

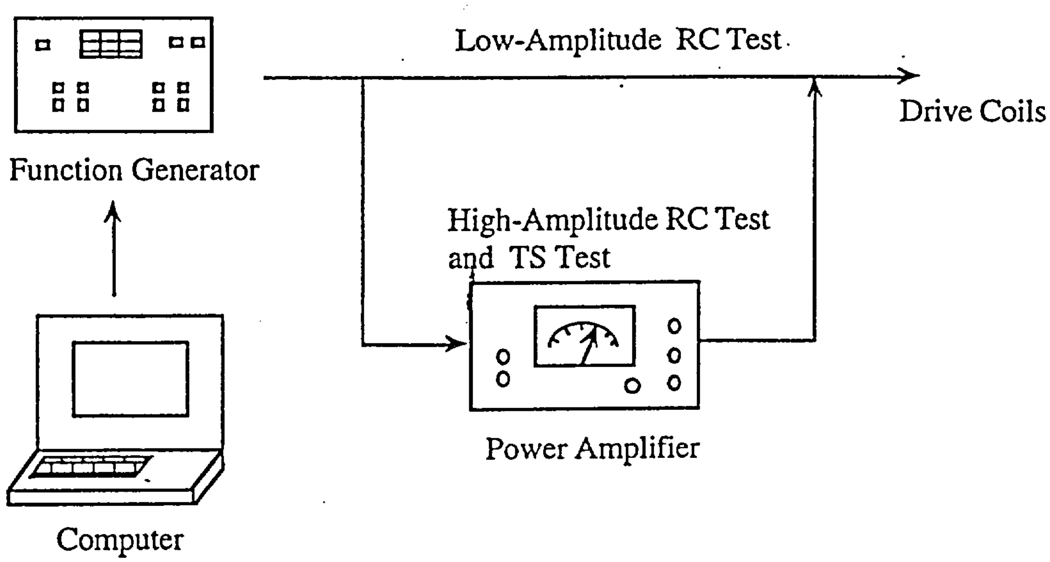

Fig. 7 Schematic Diagram of the Drive System

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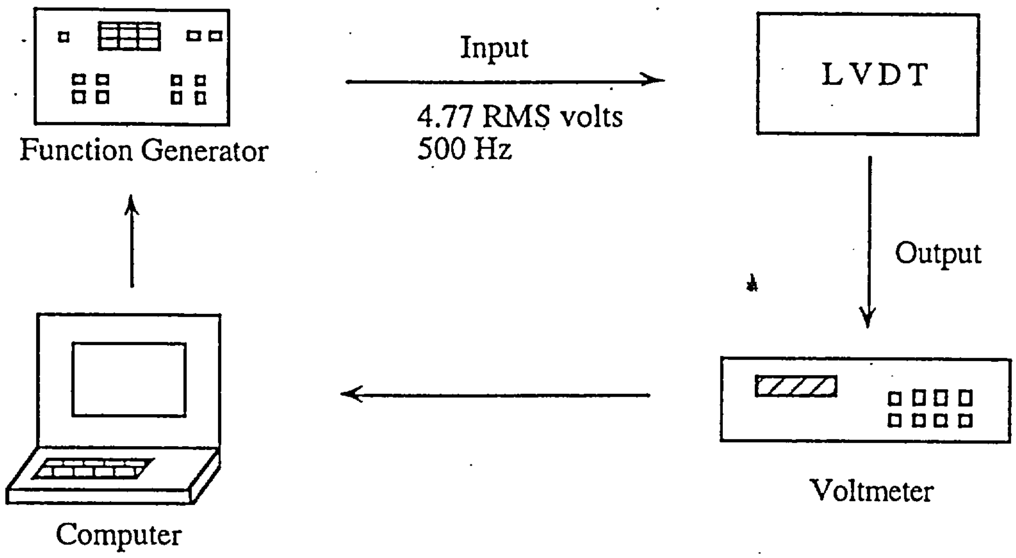

Fig. 8 Schematic Diagram of the Height-Change Measuring System

2.5 Motion Monitoring System

Dynamic soil and rock properties are obtained in the RC test at the resonant frequency which is usually above 20 Hz while torsional shear testing is used to measure the low-frequency (below 10 Hz) cyclic stress-strain relationship of soil. Because of the different frequencies applied in the resonant column and torsional shear tests, different motion monitoring systems are used.

Resonant Column (RC) Test

The motion monitoring system in the RC test is designed to measure the resonant frequency, shearing strain, and free-vibration decay curve. This system consists of an accelerometer (Columbia Research Laboratory Model 3021), a charge amplifier (Columbia Research Laboratory Model 4102M), a frequency counter (HP 5334A), a digital voltmeter (HP 3456A), and a digital oscilloscope (Nicolet 20929-01). The entire system is calibrated yearly using a reference accelerometer (traceable to NBS) and shake table as discussed in Isenhower (1979) and Lodde (1982).

The schematic diagram of the motion monitoring system is shown in Fig. 9. The accelerometer is oriented to be sensitive to torsional vibrations of the drive plate. The charge amplifier conditions the accelerometer output to be linear for all levels of acceleration in the test. The digital voltmeter reads the output voltage from the accelerometer at each frequency which is measured by the frequency counter. The resonant frequency is obtained from the frequency response curve. Once the resonant frequency is obtained, the computer activates the function generator to excite the specimen at the resonant frequency and then suddenly stops the current so that the free-vibration decay curve is recorded by the digital oscilloscope.

The resonant frequency of soil and rock specimens are typically in the range of 20 Hz to 300 Hz with this equipment. To test soils effectively over a wide range of stiffnesses, the search for the resonant frequency is performed in two stages, a rough sweep and a fine sweep. During the rough sweep, a fast logarithmic-linear frequency sweep (16 seconds to sweep from 1 to 170 Hz) is used. The fine sweep is then performed to determine an accurate resonant frequency in the neighborhood where the resonant frequency was found in the rough sweep.

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Torsional Shear (TS) Test

The motion monitoring system in the TS test (3000 Proximitor System) is used to monitor torque-twist hysteresis loops of the specimen. This system consists of two proximitors (Bently Nevada M 20929-01), two proximitor probes (Bently Nevada M 300-00), an operational amplifier (Tektronix TM 504 with AM501), a DC power supply (Lambda M-11-902), an analog filter (WaveTek System 716), a U-shaped target and a digital oscilloscope (Nicolet 20929-01). The U-shaped target is secured to the top of the drive plate, and the two proximitor probes are rigidly attached to the support stand. The entire system is calibrated yearly using a micrometer as discussed in Kim (1991).

A schematic diagram of the motion monitoring system in the torsional shear test is shown in Fig. 10. The function of the proximitor probes is to measure the width of the air gap between the target and the probe tip. Because the proximitor probes do not touch the drive plate, no compliance problems are introduced into the measurement. Two probes are used and the operational amplifier subtracts the signal of one probe from the other so that the effect of bending in the specimen toward the probes can be eliminated. The proximitor system is a very effective low-frequency motion monitoring system which does not introduce any compliance problems into the measurement. With the simultaneous measurement of torque, load-displacement hysteresis loops can be determined.

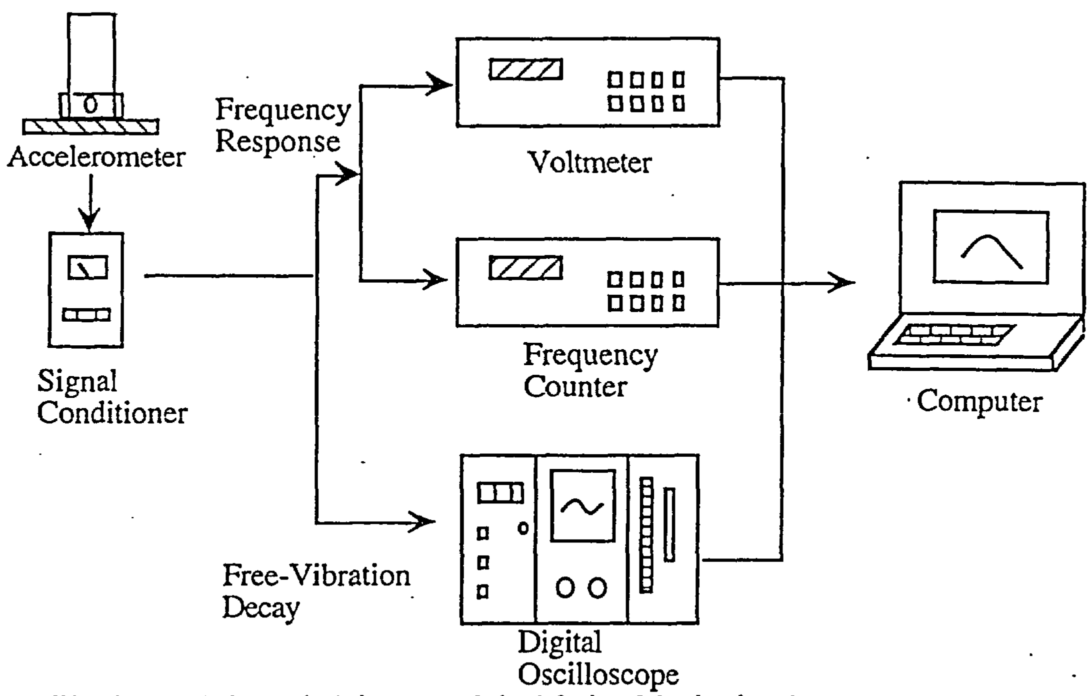

Fig. 9 Schematic Diagram of the Motion Monitoring System in the Resonant Column Test

3.0 METHOD OF ANALYSIS IN THE RESONANT COLUMN TEST

The resonant column test is based on the one-dimensional wave equation derived from the theory of elasticity. The shear modulus is obtained by measuring the first-mode resonant frequency while material damping is evaluated from either the free-vibration decay curve or from the width of the frequency response curve assuming viscous damping.

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3.1 Shear Modulus

The governing equation of motion for the fixed-free torsional resonant column test is :

$$\frac{\Sigma I}{I_o} = \frac{\omega_n \bullet \ell}{V_s} \bullet \tan\left(\frac{\omega_n \bullet \ell}{V_s}\right) \qquad (1)$$

where $\Sigma I = I_s + I_m + \text{---}$

I_s = mass moment of inertia of specimens,
I_m = mass moment of inertia of membrane,
I_o = mass moment of inertia of rigid end mass at the top of the specimen,
ℓ = length of the specimen,
V_s = shear wave velocity of the specimen, and
ω_n = undamped natural circular frequency of the system.

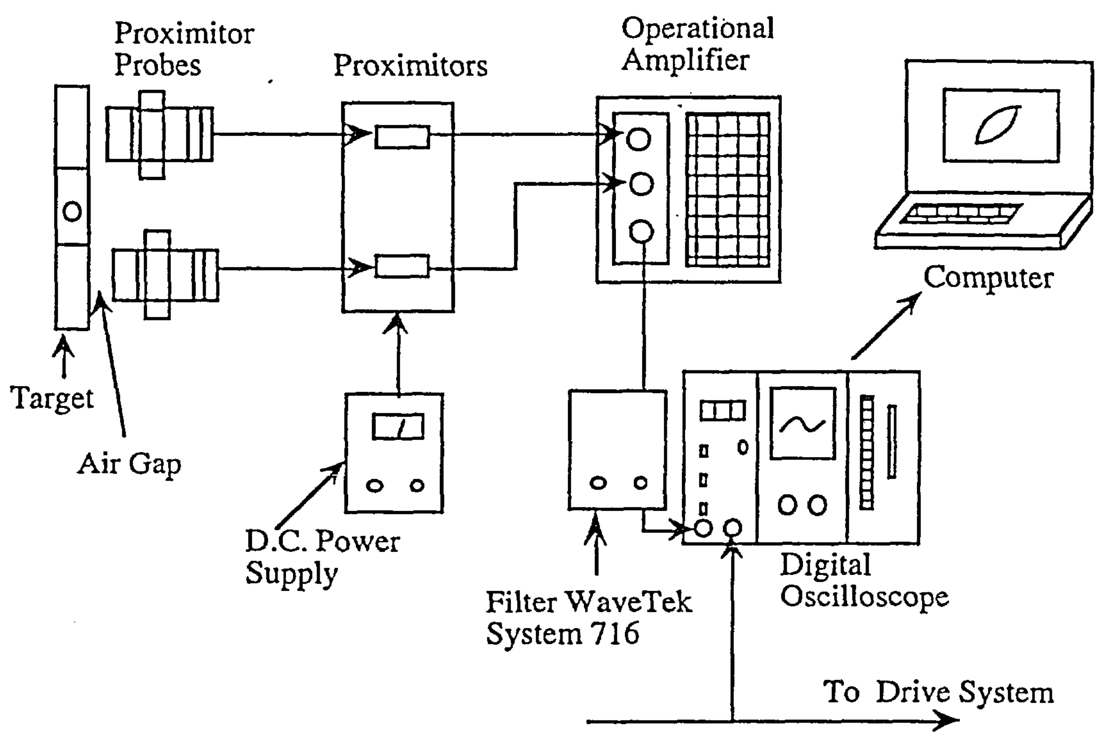

Fig. 10 Schematic Diagram of the Motion Monitoring System in the Torsional Shear Test (3000 Proximitor System)

The value of I_o is known from the calibration of the drive plate. The values of I_s and ℓ are easily determined from the specimen size and weight. Once the first-mode resonant frequency is determined, the shear wave velocity can be calculated from Eq. 1 by assuming that the resonant circular frequency and ω_n are equal.

As noted above and shown in Fig. 2 the resonant circular frequency, ω_r ,is measured instead of undamped natural frequency, ω_n, and ω_r is used to calculate shear wave velocity. If the damping in the system is zero, ω_r and ω_n are equal. The relationship between ω_r and ω_n is :

$$\omega_r = \omega_n \sqrt{1-2D^2} \qquad (2)$$

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A typical damping ratio encountered in the resonant column test is less than 20 percent, which corresponds to a difference of less than 5 percent between ω_r and ω_n. In this study, the damping measured in the resonant column test was usually less than 10 percent, and ω_r can be used instead of ω_n with less than a two percent error.

Once the shear wave velocity is determined, shear modulus is calculated from the relationship:

$$G = \rho \bullet V_s^2 \qquad (3)$$

where ρ is the total mass density of the specimens (total unit weight divided by gravity).

3.2 Shearing Strain

The shearing strain varies radially within the specimen and may be expressed as a function of the distance from the longitudinal axis as illustrated in Fig. 11. The equivalent shearing strain, γ_{eq} or γ, is represented by:

$$\gamma = r_{eq} * \theta_{max} / \ell \qquad (4)$$

where r_{eq} = equivalent radius,

θ_{max} = angle of twist at the top of the specimen, and

ℓ = length of the specimen.

Chen and Stokoe (1979) studied the radial distribution in shearing strain to find a value of r_{eq} for the specimen tested in the RCTS equipment to evaluate an effective strain. They found that the value of r_{eq} varied from $0.82*r_0$ for a peak shearing strain amplitude below 0.001% to $0.79*r_0$ for a peak shearing strain of 0.1% for a solid specimen. These values of r_{eq} have been adopted in this study.

In the resonant column test, the resonant period (T_r, seconds), and output voltage of accelerometer (A_c, volts(RMS)) at resonance are measured. Accelerometer output is changed to the displacement by using the accelerometer calibration factor (CF, volts(RMS)/in./sec^2) assuming harmonic motion. The accelerometer displacement is divided by the distance (D_{ac}, inches) between the location of accelerometer and the axis of the specimen to calculate the angle of twist at the top of the specimen(θ_{max}). The shearing strain is then calculated by:

$$\gamma = r_{eq} \frac{A_c \bullet Tr^2}{4\pi^2 \bullet CF} \bullet \frac{1}{D_{ac}} \bullet \frac{1}{\ell} \qquad (5)$$

3.3 Material Damping

In the resonant column test, material damping ratio can be evaluated from either the free-vibration decay method or from the half-power bandwidth method. Each of these methods is discussed below. It is important to note that, in these measurements, the damping measurement includes material damping in the specimen plus any damping in the equipment. Calibration of equipment damping is discussed in Section 5.

<u>Free-Vibration Decay Method</u>

Material damping in soils and rock specimens can be quite complex to define. However, the theory for a single-degree-of-freedom system with viscous damping is a useful framework for describing the effect of damping which occurs in soil (Richart et al., 1970). The decay of free

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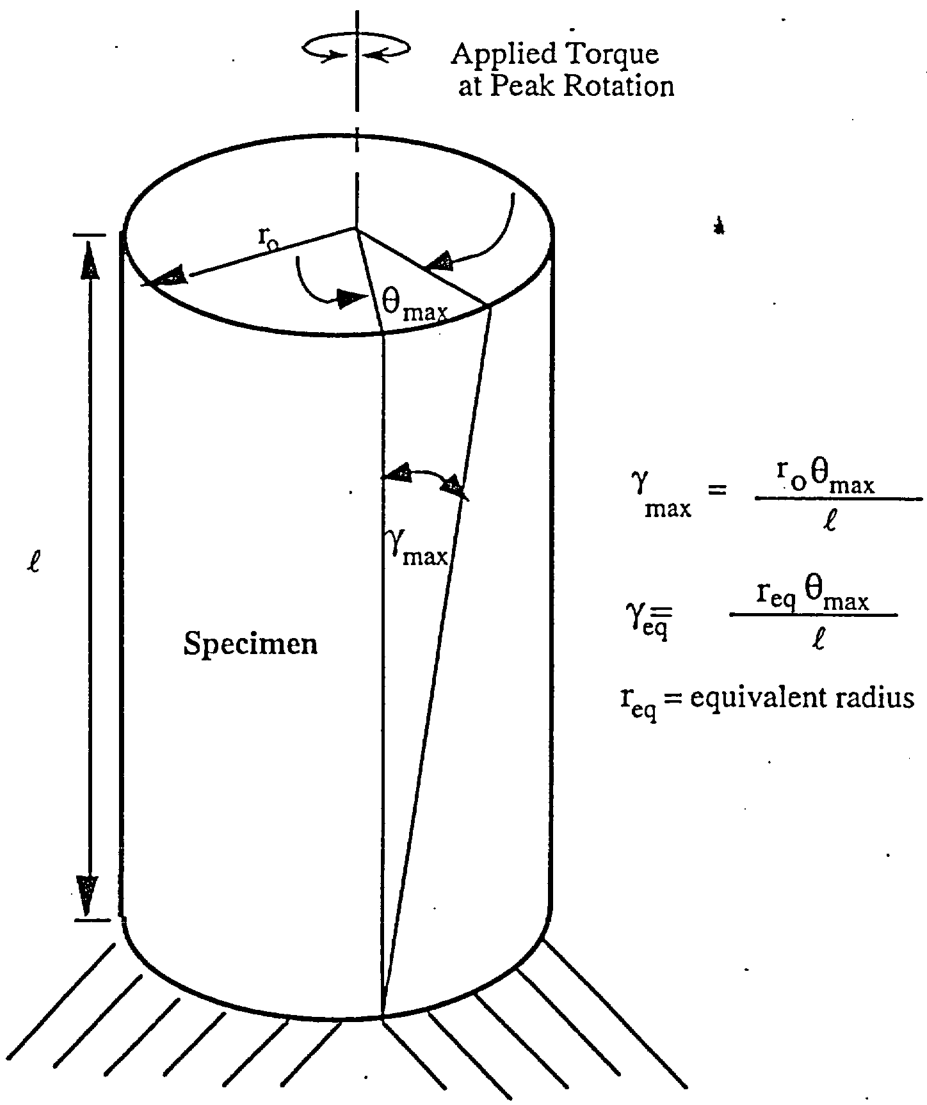

Fig. 11 Shearing Strain in RCTS Specimen Column

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vibrations of a single-degree-of-freedom system with viscous damping is described by the logarithmic decrement, δ, which is the ratio of the natural logarithm of two successive amplitudes of motion as:

$$\delta = \ln\left(\frac{Z_1}{Z_2}\right) = \frac{2\pi D}{\sqrt{1-D^2}} \qquad (6)$$

where Z_1 and Z_2 = two successive strain amplitudes of motion, and
D = material damping ratio.

The free-vibration decay curve is recorded using an oscilloscope by shutting off the driving force while the specimen is vibrating at the resonant frequency. The amplitude of each cycle is measured from the decay curve, and the logarithmic decrement is then calculated using Eq. 6. Material damping ratio is calculated from logarithmic decrement according to :

$$D = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}} \qquad (7)$$

A typical damping measurement from a free-vibration decay curve (from a metal calibration specimen) is shown in Fig. 12.

In this method, it is not certain which strain amplitude is a representative strain for damping ratio calculated by Eq. 7 because strain amplitude decreases during free-vibration decay. In this study, a representative strain amplitude was used as the peak strain amplitude during steady-state vibration for shearing strains below 0.001%. However, at larger strains, the representative strain is smaller than the peak strain, and the average strain determined for the first three cycles of free vibration was used.

Half-Power Bandwidth Method

Another method of measuring damping in the resonant column test is the half-power bandwidth method, which is based on measurement of the width of the frequency response curve near resonance. From the frequency response curve, the logarithmic decrement can be calculated from :

$$\delta = \frac{\pi}{2}\,\frac{f_2^2-f_1^2}{f_r^2}\sqrt{\frac{A^2}{A_{max}^2 - A^2}}\;\frac{\sqrt{1-2D^2}}{1-D^2} \qquad (8)$$

where f_1 = frequency below the resonance where the strain amplitude is A,
f_2 = frequency above the resonance where the strain amplitude is A,
f_r = resonant frequency, and
D = material damping ratio.

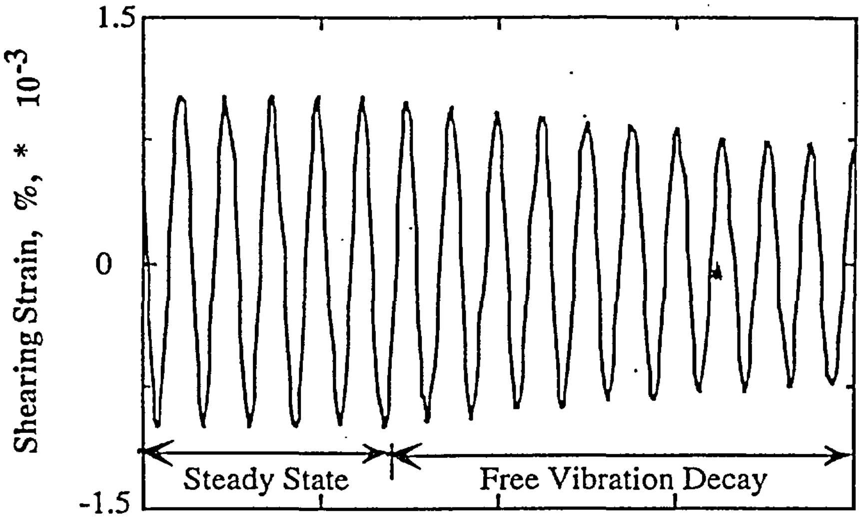
If the damping ratio is small and A is chosen as 0.707 A_{max}, which is called the half-power point, Eq. 8 can be simplified as :

$$\delta \cong \pi \bullet \frac{f_2-f_1}{f_r} \qquad (9)$$

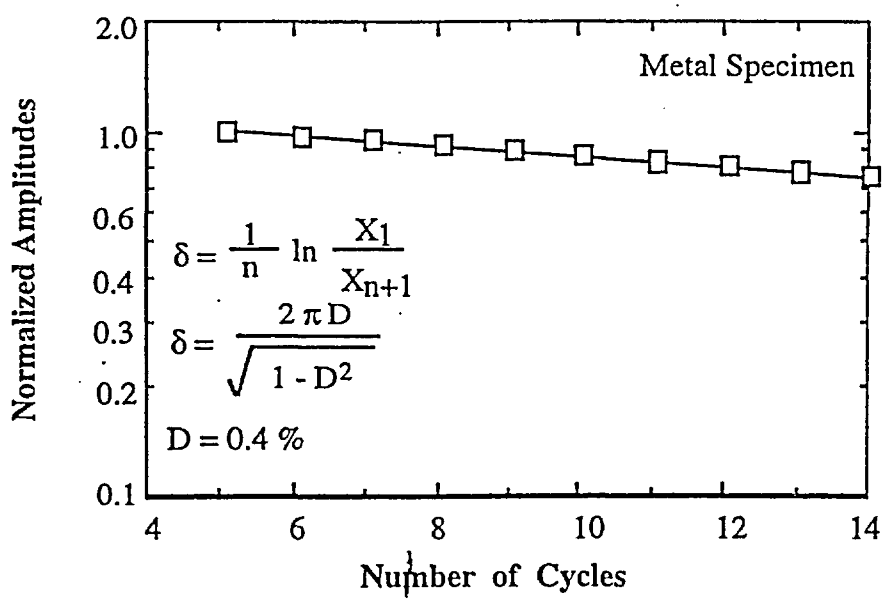
Therefore, the damping ratio can be expressed as :

$$D \cong \frac{f_2-f_1}{2f_r} \qquad (10)$$

A typical damping measurement by the half-power bandwidth method (for a metal calibration specimen) is shown in Fig. 13.



a) Free-Vibration Decay Curve



b) Analysis of Free-Vibration Decay Curve

Fig. 12 Determination of Material Damping Ratio from the Free-Vibration Decay Curve Using a Metal Specimen

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Background noise can be a problem in measuring material damping using the free-vibration decay method at strains less than about 0.001%. On the other hand, background noise generally has a smaller effect on the frequency response curve at strains below 0.001%. Therefore, the half-power bandwidth method is preferred to the free-vibration decay method for making small-strain damping measurements. However, at large strains, symmetry in the frequency response curve is no longer maintained, and a serious error can be introduced in the half-power bandwidth method (Ni, 1987). In this study, both types of damping measurements were made at small-strains in an attempt to obtain good data sets while only the free-vibration decay method was used at larger strains (above 0.001%).

4.0 METHOD OF ANALYSIS IN THE TORSIONAL SHEAR TEST

The torsional shear test is another method of determining the deformational characteristics (modulus and damping) of soil or rock specimens using the same RCTS device. Rather than measuring the dynamic response of the specimen, the actual stress-strain hysteresis loop is determined by means of measuring the torque-twist curve. Shear modulus is calculated from the slope of the hysteresis loop, and the hysteric damping ratio is calculated using the area of the hysteresis loop.

4.1 Shear Modulus

Because shear modulus is calculated from the stress-strain hysteresis loop, shearing stress and shearing strain in the torsional shear test need to be defined.

Shearing Stress

Determination of shearing stress in the torsional shear test is based on the theory of elasticity for circular or tubular rods in pure torsion. Assume that pure torque, T, is applied to the top of the specimen. The torque can be calculated from:

$$T = \int_{r_i}^{r_o} \tau_r (2\pi r)\, r\, dr \qquad (11)$$

where τ_r is the shearing stress at a distance r from the axis of specimen and, r_o and r_i are outside and inside radii, respectively. If the shearing stress is assumed to vary linearly across the radius:

$$\tau_r = \tau_m \bullet (r / r_o) \qquad (12)$$

where τ_m is the maximum shearing stress at $r = r_o$. Eq. 12 can be rewritten as:

$$T = \frac{\tau_m}{r_o} \bullet \frac{\pi}{2} \bullet (r_o^4 - r_i^4) = \frac{\tau_m}{r_o} \bullet J_p \qquad (13)$$

where J_p is the area polar moment of inertia. From Eq. 13, one can write:

$$\tau_m = r_o \bullet \frac{T}{J_p} \qquad (14)$$

Because shearing stress is assumed to vary linearly across the radius, the average torsional shearing stress is defined as:

$$\tau_{avg} = r_{eq} \bullet \frac{T}{J_p} \qquad (15)$$

The value of r_{eq} is the same value as used in the resonant column analysis for calculation of shearing strain (Section 3.2).

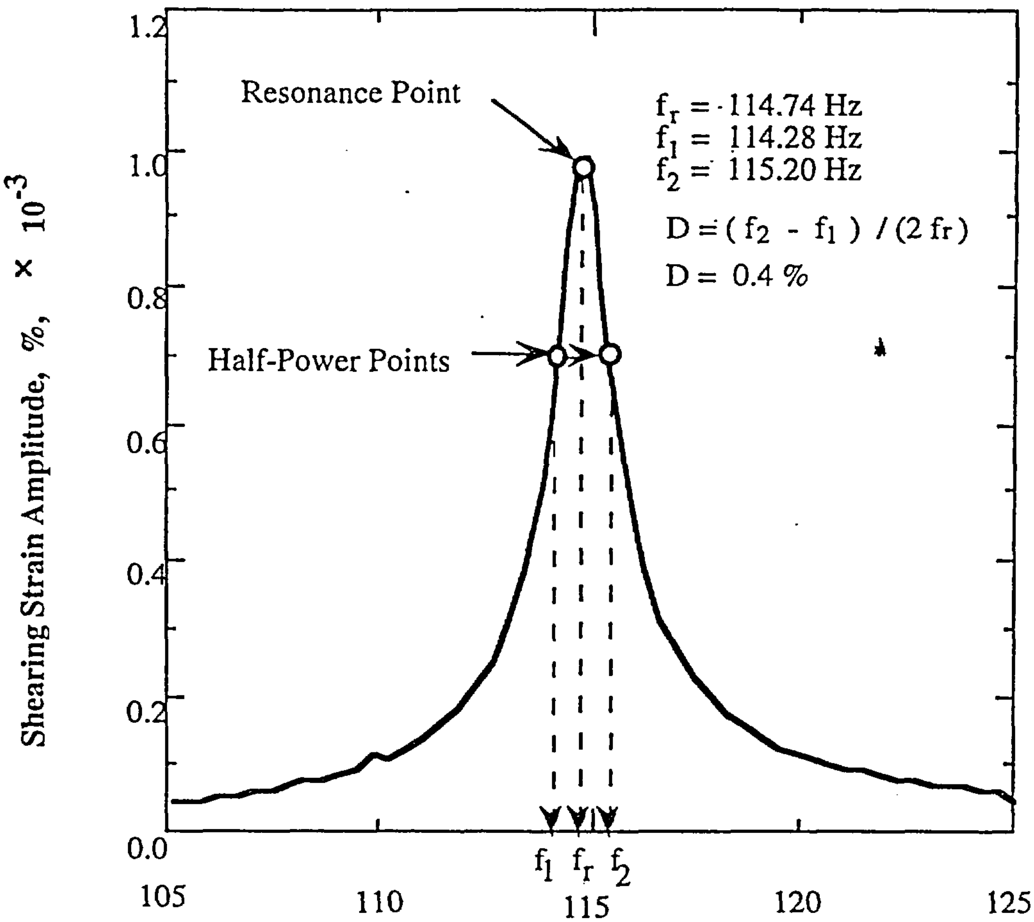

Fig. 13 Determination of Material Damping from the Half-Power Bandwidth Method Using a Metal Specimen

The value of applied torque, T, is calculated from the input voltage applied to the drive system, V_T (Volts), and the torque calibration factor, K_T (torque / Volts). Thus, average shearing stress becomes:

$$\tau_{avg} = r_{eq} \bullet K_T \bullet V_T / J_p \qquad (16)$$

Shearing Strain

Calculation of shearing strain in the torsional shear test follows the same procedure used in the resonant column test. The proximitor system directly measures the displacement (instead of acceleration measured in the resonant test). Hence, the angle of twist (θ) is calculated from the proximitor output voltage ,V_P (volts), and the proximitor calibration factor, K_P (rad / volt). Shearing strain, γ, is then calculated from :

$$\gamma = r_{eq} \sum K_P \bullet V_P / \ell \qquad (17)$$

Shear Modulus

Once the stress-strain hysteresis loop is measured, the shear modulus, G, is calculated from the slope of a line through the end points of the hysteresis loop as shown in Fig. 13. Thus, the shear modulus is calculated from:

$$G = \tau / \gamma \qquad (18)$$

where τ is peak shearing stress and γ is peak shearing strain.

4.2 Hysteretic Damping Ratio

Hysteretic damping ratio in the torsional shear test is measured using the amount of energy dissipated in one complete cycle of loading and the peak strain energy stored in the specimen during the cycle.

In the torsional shear test, the dissipated energy is measured from the area of the stress-strain hysteresis loop. The energy per cycle, W_d, due to a viscous damping force, F_d, is :

$$W_d = \int_o^T F_d \cdot \dot{x}\, dt \qquad (19)$$

where $\dot{x}$ is a velocity and T is a period. For simple harmonic motion with frequency of ω , i.e. $x = A \text{Cos}(\omega t - \phi)$, W_d become:

$$W_d = \pi\, c\, \omega\, A^2 \qquad (20)$$

From the Eq. 20, the viscous damping coefficient can be expressed as :

$$c = W_d / (\pi\ \omega A^2) \qquad (21)$$

The peak strain energy, W_s, stored by the spring is equal to the area under the secant modulus line in Fig. 14 and can be written as:

$$W_s = k\, A^2 / 2 \qquad (22)$$

The critical damping coefficient, C_c, is

$$C_c = 2 \bullet \sqrt{k\, m} = 2\, k / \omega_n \qquad (23)$$

where k is an elastic spring constant, m is a mass, and ω_n is a natural frequency of system. Using Eq. 22, Eq. 23 can be rewritten as :

$$C_c = 4\, W_s / (\omega_n\, A^2) \qquad (24)$$

Therefore, the damping ratio, D, can be expressed as :

$$D = C / C_c = W_d / (4\, \pi\, W_s) * (\omega_n / \omega) \qquad (25)$$

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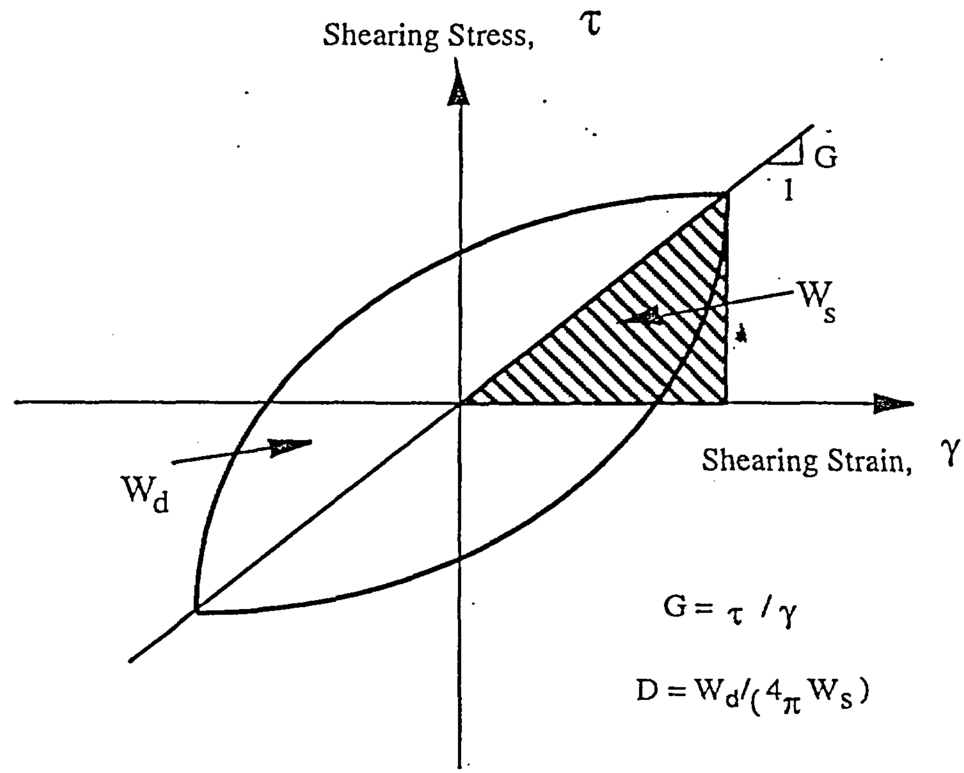


Fig. 14 Determination of Shear Modulus and Damping Rat in the Torsional Shear Test

For soil or rock materials, damping is often assumed to be frequency independent. Therefore, ω_n / ω is ignored and hysteretic damping is written as:

$$D = \frac{1}{4\pi} * \frac{W_d}{W_s} \qquad (26)$$

where W_d is the area of the hysteresis loop and W_s is the area of the triangle as shown in Fig. 13.

5.0 EVALUATION OF RCTS EQUIPMENT COMPLIANCE WITH METAL SPECIMENS

To evaluate the RCTS equipment for system compliance, metal specimens were used. The metal specimens were made of brass and aluminum tubes. Eighteen metal specimens of different sizes and materials were used to obtain different resonant frequencies. Details of the metal specimens are presented in Table 1. It was assumed that the metal specimens should have (essentially) zero damping and that these specimens should exhibit no effect of frequency on stiffness or damping over the complete range of frequencies used in these tests (from about 0.05 Hz to 400 Hz).

Hysteresis loops with one metal specimen measured at a frequency of 0.5 Hz are shown in Fig. 15. The stress-strain curve is linear, resulting in no damping as expected. On the other hand, Figs. 12 and 13 show the damping measurements with the same metal specimen in the resonant column test predict an apparent damping of 0.4% from both the free-vibration decay and half-power bandwidth methods.

QA:QA

Table 1. Metal Specimens Used to Evaluate Equipment Damping Ratio

Specimen Number	Outside Diameter		Inside Diameter		Height		Weight
	inch	cm	inch	cm	inch	cm	gram
1(Brass Tube)	1.000	2.540	0.875	2.223	4.98	12.65	132.35
2(Brass Tube)	0.875	2.223	0.813	2.064	6.96	17.68	79.96
3(Brass Tube)	0.875	2.223	0.813	2.064	8.49	21.56	97.07
4(Brass Tube)	0.750	1.905	0.688	1.746	6.97	17.70	70.72
5(Brass Tube)	0.750	1.905	0.688	1.746	8.49	21.57	85.87
6(Brass Tube)	0.625	1.588	0.563	1.429	6.96	17.68	58.45
7(Brass Tube)	0.625	1.588	0.563	1.429	8.49	21.57	70.94
8(Brass Tube)	0.375	0.953	0.313	0.794	6.94	17.63	33.69
9(Brass Tube)	0.375	0.953	0.313	0.794	8.44	21.45	40.86
10(Brass Rod)	0.313	0.794	0	0	6.92	17.57	74.46
11(Brass Rod)	0.313	0.794	0	0	8.44	21.44	90.30
12(Brass Rod)	0.500	1.270	0	0	7.00	17.78	191.22
13(Brass Rod)	0.750	1.905	0	0	7.00	17.75	429.52
14(Brass Rod)	0.250	0.635	0	0	6.96	17.67	47.53
15(Brass Rod)	1.500	3.810	0	0	7.00	17.78	1731.64
16(Brass Tube)	0.500	1.270	0.438	1.111	6.97	17.71	44.63
17(Brass Tube)	0.500	1.270	0.438	1.111	8.48	21.53	54.29
18(Brass Tube)	1.000	2.540	0.875	2.223	6.97	17.70	178.50

Unit Weight of Brass = 8.49 g/cm^3 (=0.316 lbs/in^3)

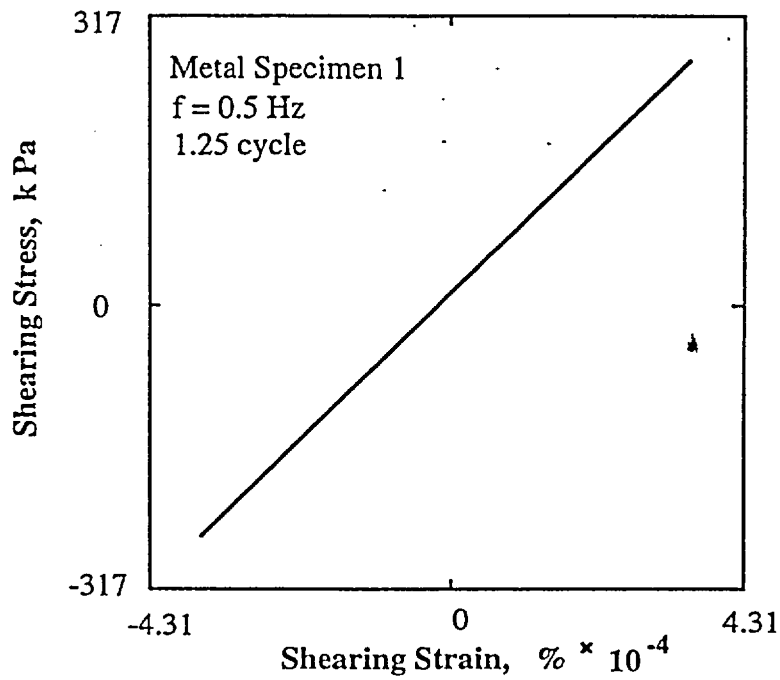


Fig. 15 Hysteresis Loops of Metal Specimen Determined by Torsional Shear Testing at a Frequency of 0.5 Hz

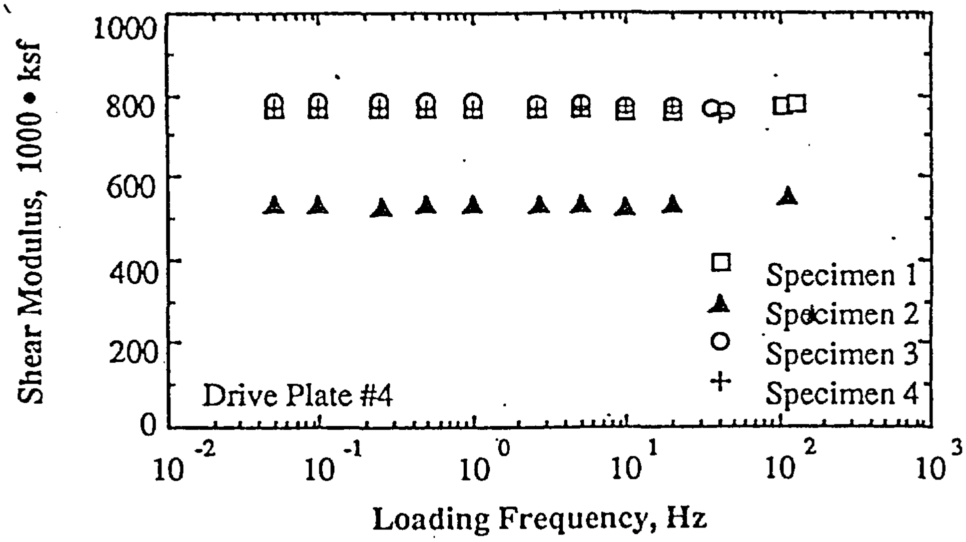
The variations in shear modulus and damping ratio with loading frequency for four of the metal specimens are plotted in Fig. 16. The shear modulus of each metal specimen determined from the RCTS equipment is independent of loading frequency as expected. Therefore, shear modulus can be measured properly with RCTS equipment over a wide frequency range without any compliance problem.

On the other hand, the damping ratio measured by the RCTS equipment is affected by the loading frequency. For frequencies less than or equal to 0.5 Hz, damping ratio evaluated by the torsional shear test is essentially zero as expected. In this frequency range, material damping can be evaluated without any equipment correction. For higher frequencies, however, non-zero damping values are obtained with all metal specimens in the torsional shear as shown in Figs. 16b and 17. In this case the apparent material damping increases significantly as the excitation frequency increases from 1 to 10 Hz. Strain amplitude has little effect on the damping values as shown in Fig. 17. These values of apparent material damping are considered to be due to a compliance problem with the complete RCTS system (back-EMF generated by the drive system) and are, therefore, subtracted from all damping measurements in the torsional shear test at the same frequencies when soil specimens are tested.

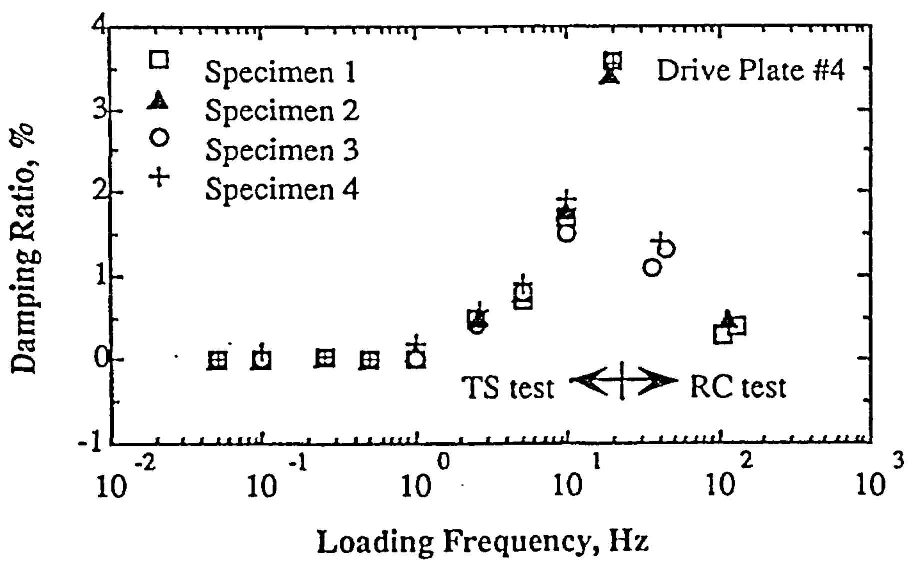
It should be noted that excitation frequencies in the torsional shear test never exceeded 0.1 times the resonant frequency of the soil or rock specimen. This approach was followed so that dynamic amplification did not affect the TS measurements. Even in this case, however, corrections were made for minor dynamic amplification which occurs near 0.1 times the resonant frequency.

In the resonant column test, non-zero damping values were obtained at all resonant frequencies as seen in Figs. 16b and 18. Equipment damping values ranged from about 3.5% at 20 Hz to about 0.4% at 200 Hz. These resonant frequencies are in the frequency range where all soil testing was conducted. Just as in the TS test, the values of equipment damping measured with the metal specimens were subtracted from the damping measurements in all RC tests with soil or rock specimens at the same resonant frequencies. Strain amplitude had a negligible effect on equipment damping as shown in Fig. 19.

QA:QA



a) Variation in Shear Modulus



b) Variation in Material Damping Ratio

Fig. 16 Variation in Shear Modulus and Material Damping Ratio with Loading Frequency Determined for Metal Specimens (from Kim, 1991)

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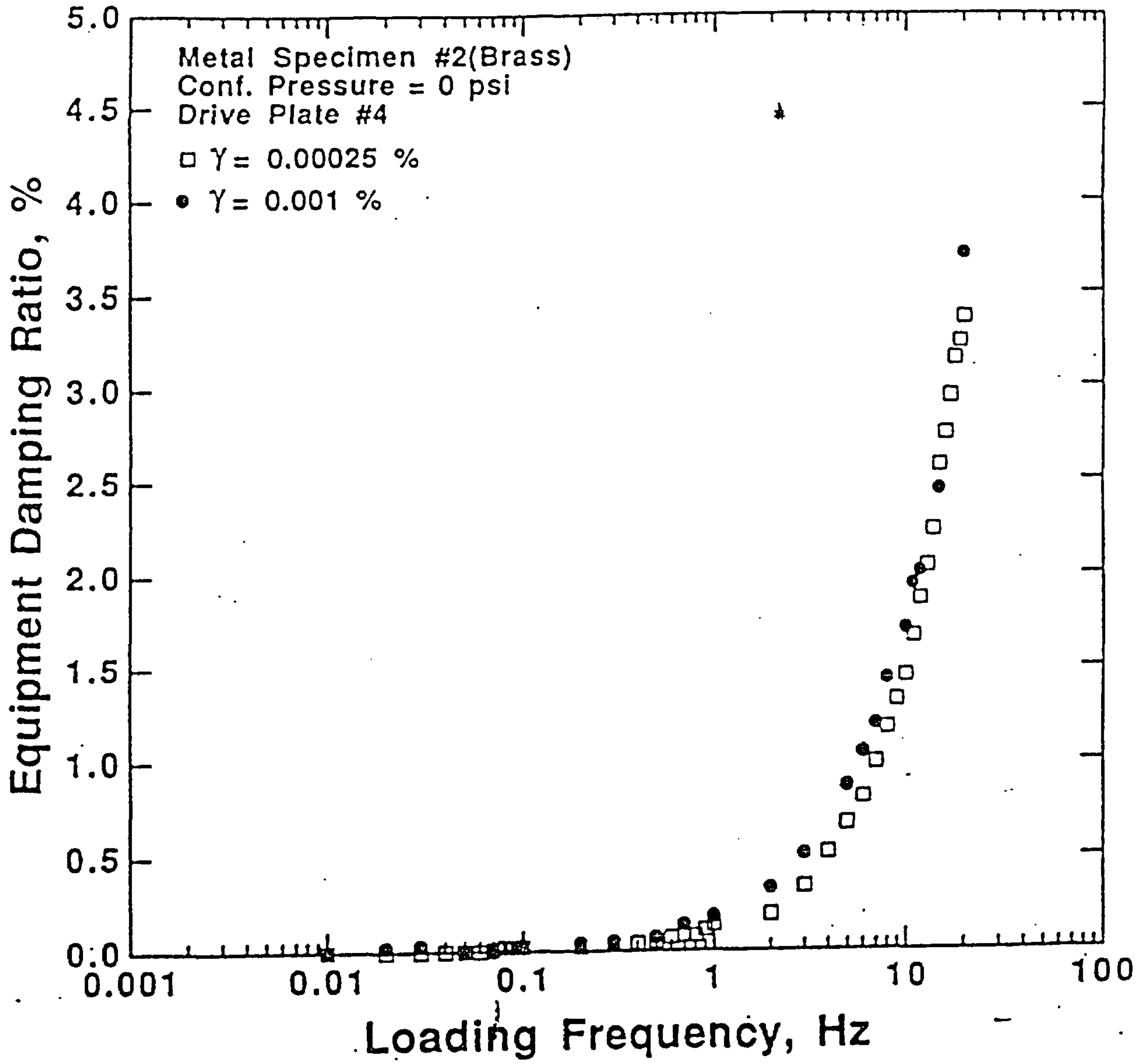

Fig. 17 Measured Damping Ratio for Metal Specimen #2 in the Torsional Shear Test

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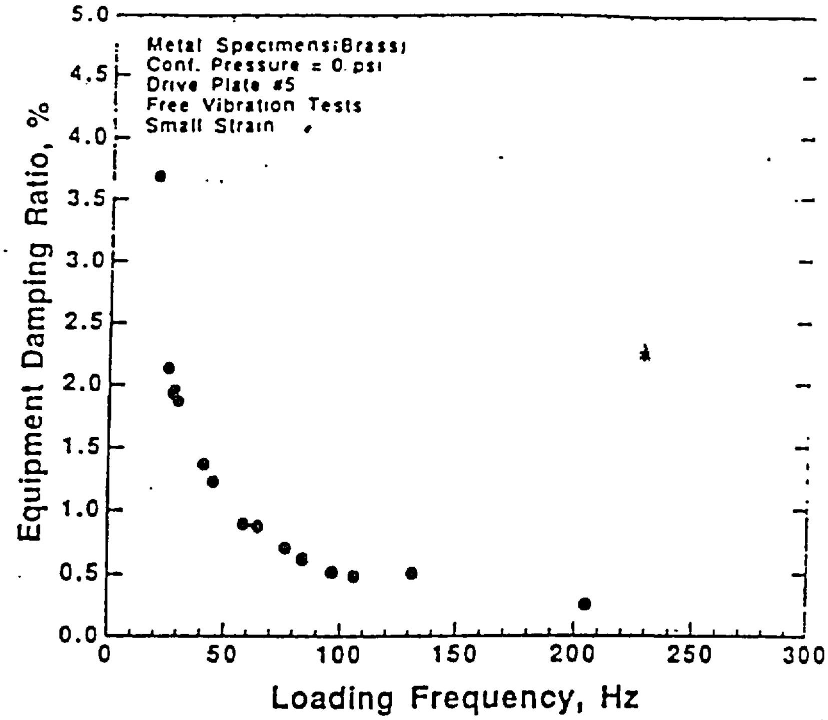
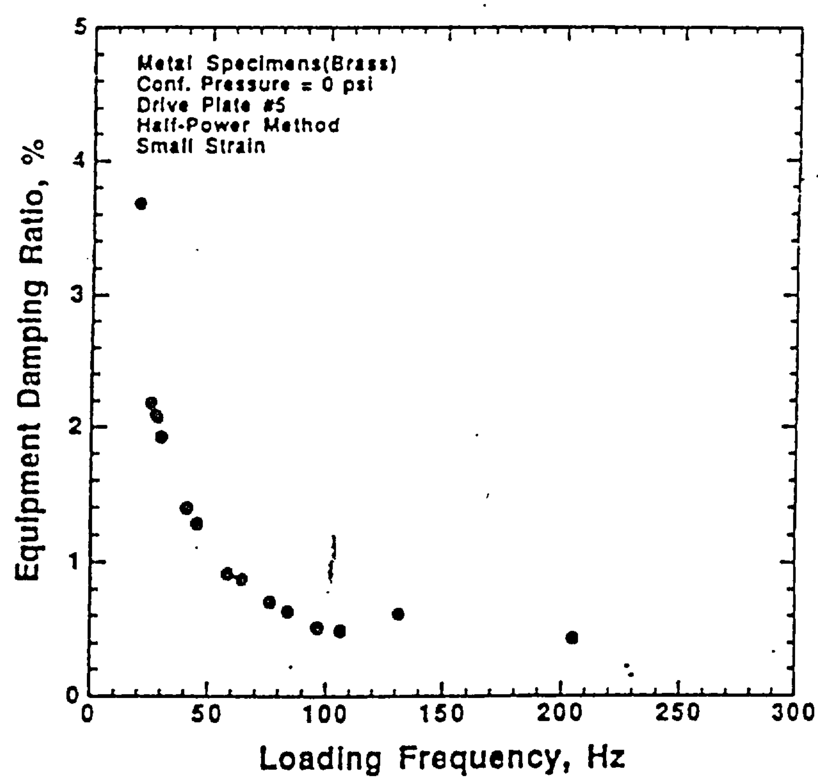


a. Damping from the Free-Vibration Decay Curve



b. Damping from the Half-Power Bandwidth

Fig. 18 Equipment Damping Measured in the Resonant Column Test

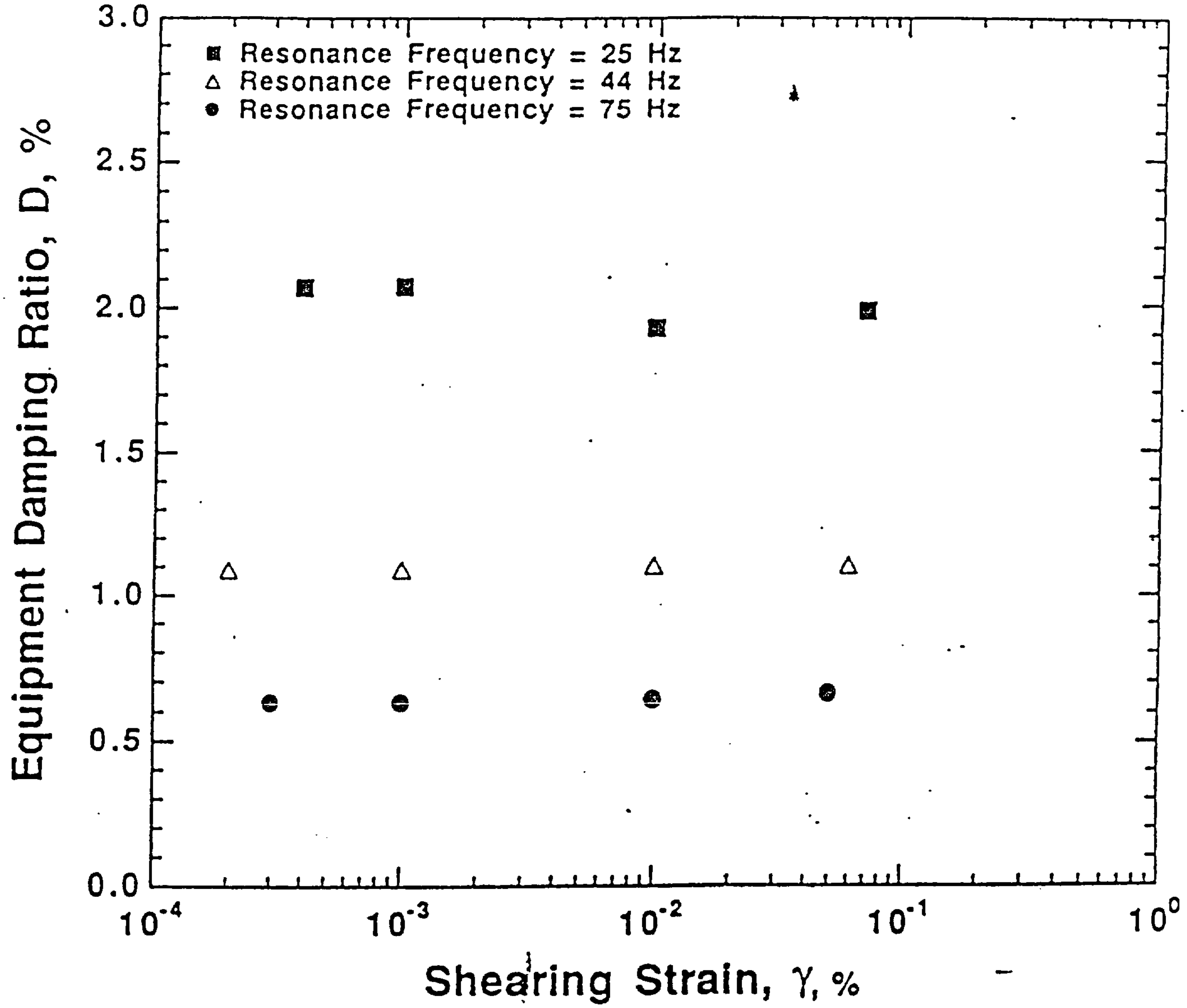


Fig 19 Effect of Strain Amplitude on Equipment Damping Measured in the Resonant Column Test

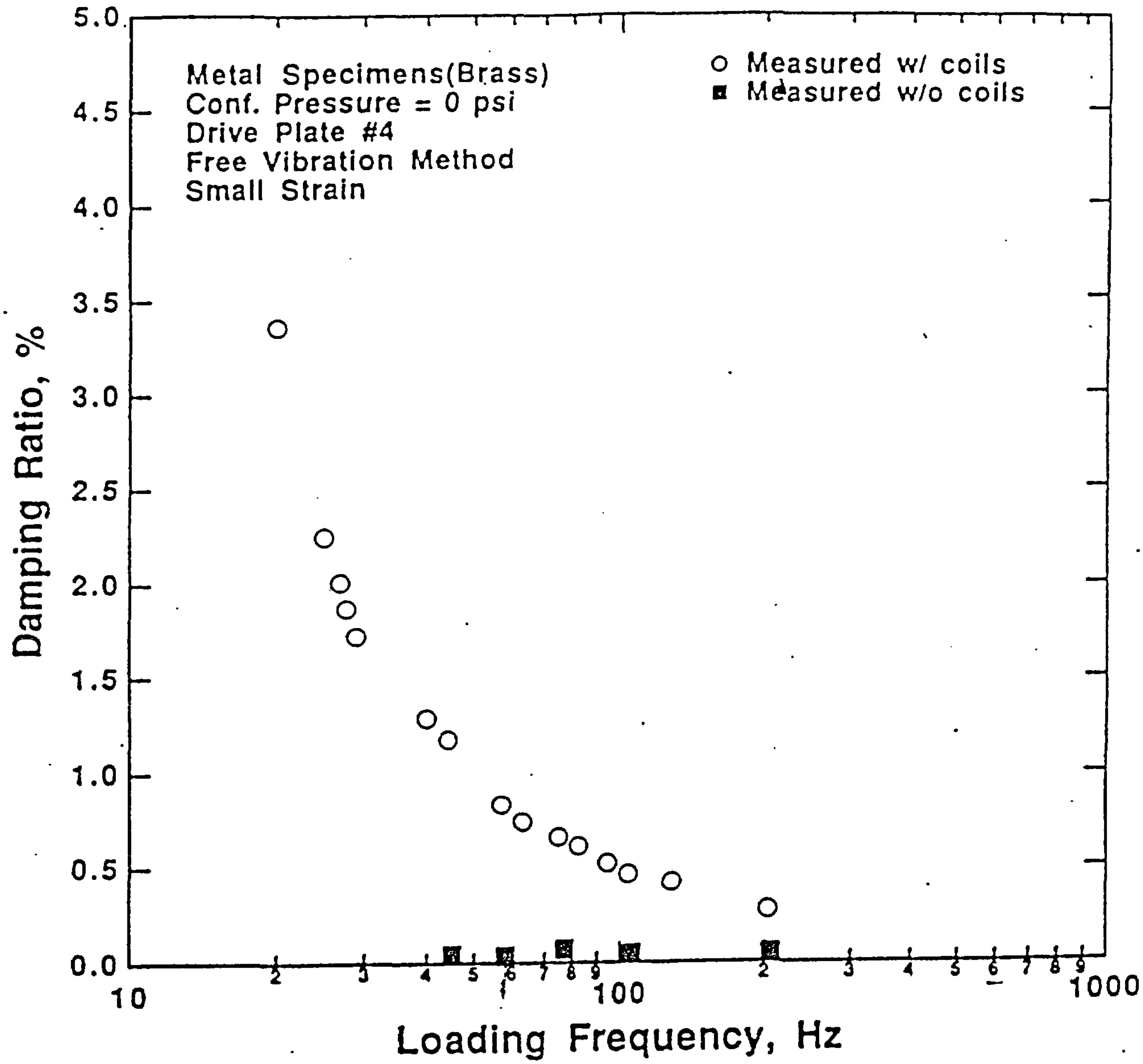


Fig. 20 Comparison of Equipment Damping Measured in Free Vibration RC Tests With and Without the Electrical Coils

Finally, to be sure that coil-magnet interaction was the cause of the equipment damping problem, free-vibration tests were conducted with the RC equipment. In this case, however, all coils were removed which required that the drive plate be excited by hand in free vibration. The resulting tests with drive plate #4 are given in Fig. 20 by the solid square symbols. As seen, damping values less than 0.1% were measured. These values are considered to equal zero in this work, indicating the coil-magnet interaction is mainly the cause of the equipment damping.

6.0 COMPUTER PROGRAMS AND DATA OUTPUT

As noted in Section 2.1 and in Fig. 5, the RCTS equipment is controlled and calculations are performed by a microcomputer. Computer programs RCTEST and TSTEST are used to perform the dynamic and cyclic testing, respectively. These two computer programs are included as Attachment 1 for RCTEST (pages 33 through 62) and Attachment 2 for TSTEST (pages 63 through 66). The programs were developed by Ni (1987) and used extensively by Kim (1991). Each program automatically gives a hard-copy output every time testing is performed (without exception). Examples of typical outputs are presented in Attachments 3 and 4 for RCTEST and TSTEST, respectively (pages 67 and 68). All hard copies are stored in the laboratory with the Chain of Custody forms.

7.0 INTACT SPECIMEN CONSTRUCTION

(Checklist on pages 29 and 30)

8.0 RCTS TEST PROCEDURES

(Checklist on pages 31 and 32)

9.0 REFERENCES

Chen, A.T.F., Stokoe, K.H., II (1979), "Interpretation of Strain Dependent Modulus and Damping from Torsional Soil Tests," Report No. USGS-GD-79-002, NTIS No. PB-298479, U.S. Geological Survey, 46 pp.

Isenhower, W.M. (1979), "Torsional Simple Shear/Resonant Column Properties of San Francisco Bay Mud," Geotechnical Engineering Thesis, GT 80-1, University of Texas, Dec., 307 pp.

Kim, D.-S. (1991), "Deformational Characteristics of Soils at Small to Intermediate Strains from Cyclic Tests," Ph.D. Dissertation, The University of Texas at Austin, pp. 341

Lodde, P.F. (1982), "Shear Moduli and Material Damping of San Francisco Bay Mud," M.S. Thesis, The University of Texas at Austin, June, 295 pp.

Ni, S.-H. (1987), "Dynamic Properties of Sand Under True Triaxial Stress States from Resonant Column/Torsional Shear Tests," Ph.D. Dissertation, The University of Texas at Austin, 421 pp.

Richart, F.E.,Jr., Hall, J.R.,Jr. and Woods, R.D. (1970), Vibrations of Soils and Foundations, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 414 pp.

Checklist for Setting Up An Intact Soil Specimen for RCTS Testing

Project No.____________ Test No.________ Sample No._______

Performed by______________________ Date_________________

Checked by______________________ Date_________________

Preparing Specimen

_____ 1. Clean base pedestal, porous stone, and base plate.

_____ 2. Place base pedestal on base plate and secure using screws. Ensure that drainage holes on pedestal and plate are correctly aligned.

_____ 3. Saturate all water lines to the base of the sample (if required).

_____ 4. Coat the sides of the top cap and base pedestal with vacuum grease.

_____ 5. Place membrane in the membrane spreader, prepare water content cans, prepare carrying mold and fill out initial data sheet (Attachment 5).

_____ 6. Remove desired thin-walled sample tube.

_____ 7. Select portion of the tube using X-rays.

_____ 8. Remove wax from tube, determine soil type (cohesive or cohesiveless) and cut tube with appropriate tube cutter.

_____ 9. Re-label subdivided tube, re-wax, cap, tape, and return unused portion of the tube sample to control area.

_____ 10. Clean each end of the subdivided tube and remove any obstructions before extruding.

_____ 11. Extrude vertically, wrap with plastic wrap, and carry to trimmer in sample holding mold.

_____ 12. Visually inspect to ensure that specimen is undisturbed and intact.

_____ 13. Carefully place sample in trimming mold, and trim to desired diameter using razor and wire saws.

_____ 14. Place specimen in appropriate holding mold, and trim excess soil from ends.

_____ 15. Again, visually inspect sample to ensure that it is undisturbed and intact.

_____ 16 Weigh shavings from the side, top, and bottom of the trimmed specimen for water content measurements.

_____ 17. Weigh sample and mold before placing sample on base pedestal.

_____ 18. Measure the height of the sample using a cathometer in three different places. Measure the diameter of the sample in three places using a pi-tape.

QA:QA

Checklist - Intact Soil Samples

_____ 19. Secure a strip of filter paper around the base of the sample and the base pedestal to prevent membrane puncture. Repeat this procedure at the junction of the top of the specimen and the top cap.

_____ 20. Apply a vacuum to the membrane expander and place membrane over the specimen. Gently detach the membrane from the expander.

_____ 21. Apply a small seating vacuum pressure of about 1 to 2 psi to the sample.

_____ 22. Using the O-ring expander, place O-rings around the top cap and base pedestal to seal the membrane.

_____ 23. Add an additional membrane and O-rings to the sample (if necessary).

Assembling the Cell

_____ 24. Clean and apply vacuum grease the bottom of the inside of the fluid chamber and install. Apply vacuum grease to the base of the chamber on the outside.

_____ 25. Pour silicon fluid around the sample.

_____ 26. Affix the RCTS ring stand to the base plate with appropriate screws.

_____ 27. Align the screw holes of the drive plate with those of the top cap and gently tighten the four securing screws.

_____ 28. Carefully and accurately center the magnets in the drive coils and secure the coil plate by tightening the two securing screw plate screws.

_____ 29. Attach proximitor target to drive plate and proximitors to the fixed post. Adjust the proximitors to correct distance from target (voltage = 7.0 v ± 0.1 v).

_____ 30. Attach LVDT to the fixed post, properly align, and adjust the height of the core to an output voltage of 4.0 v ± 0.1 v.

_____ 31. Clean and grease the confining chamber sealing O-ring in the base plate. Place the confining chamber onto the base plate.

_____ 32. Attach all electrical connections through the confining chamber and obtain an initial LVDT reading. Run small strain RC test to ensure equipment is in working order. Visually inspect the resonance and vibration decay curves.

_____ 32. Clean and grease the confining chamber O-ring and attach the top plate to the confining chamber. Screw in the four (or eight) locking rods to the base plate and tighten the bolts to secure the confining cell.

_____ 33. Apply required confinement and begin RCTS testing, as described on the RCTS Test Procedures Checklist.

Checklist for RCTS Test Procedures

Project No.__________ Test No._______ Sample No._______

Performed by_________________ Date________________

Checked by__________________ Date________________

Low-Amplitude RC Test Procedure Isotropic Confining Pressure = ____psi

______1. Calculate the estimated mean effective in situ stress, σ_m. Determine the pressure levels to be used based on σ_m. Often five pressure levels are used; 0.25, 0.5, 1, 2 and 4 times σ_m.

______2. Check to be sure all cables are properly connected for RC test.

______3. Before $0.25\sigma_m$ is applied, run RCTEST Program with an input voltage of 10-15 mV which induces shearing strains less than 0.001 % to the specimen. Confirm that complete system is operating properly (i.e. on the monitor screen).

______4. Close valve for confining pressure line to the cell and set the pressure level to be applied to the sample using pressure regulator and pressure gauge.

______5. Schedule 1-hour to 1-day test (depending on type of soil) using RCTEST Program.

______6. Apply first confining pressure at scheduled time and simultaneously disconnect the vacuum line.

______7. Check the shearing strain to make sure that testing is in the linear range ($\gamma <$ 0.001%). Lower input voltage if γ is too high before the second test starts.

______8. Repeat Step 7 if necessary.

______9. Frequently check by visual observation to be sure that testing is running properly.

High-Amplitude RC Test Procedure Isotropic Confining Pressure =_____psi

______1. Connect cable from Function Generator to the input of the Power Amplifier. Use fixed-gain setting of 20 times.

______2. Connect cable from output of the Power Amplifier to the Switch/Control Unit.

______3. Perform high-amplitude testing following the RCTEST Program. Begin with 0.5mV input setting and double (or slightly more) input for each strain-amplitude increase.

______4. Once shearing strain reaches $\approx$ 0.001%, perform low-amplitude tests ($\gamma \approx 5\text{x}10^{-4}\%$) by using appropriate input voltage between each high-amplitude test to check the degree of degradation due to high-amplitude straining.

______5. Repeat Steps 3 and 4 until input voltage reaches 1500 mV or signal on the Oscilloscope shows non-sinusoidal shape which indicates one of the three symptoms :

a). Magnets touch coils. Therefore test is concluded.

b). LVDT Core touches inner wall of LVDT frame and testing is stopped.

c). Displacement exceeds appropriate range for RC test and conclude.

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Checklist for RCTS Test Procedures

Project No.____________ Test No.________ Sample No.________

Performed by____________________ Date________________

Checked by____________________ Date________________

Torsional Shear Test Procedure Isotropic Confining Pressure ________psi

______1. Follow the Steps 1 and 2 in High-Amplitude RC Test Procedure. Connect the two cables from proximitors to the input of the DC Shifter. Output of DC Shifter is connected to the Digital Voltmeter.

______2. Zero the proximitor output using DC Shifter. Connect output from DC Shifter to Operational Amplifier.

______3. Connect the output cable from the Power Amplifier to channel 3 of the WaveTek Filter. Connect the output cable from Operational Amplifier to channel 2 of the WaveTek Filter. Connect two output cables from WaveTek Filter to the Nicolet Oscilloscope.

______4. Set the appropriate settings for Cut-Off Frequency and Amplification Factor in the WaveTek Filter. Set the appropriate settings for Voltage range, Time per point and Trigger Mode in the Nicolet Oscilloscope.

______5. Start running TSTEST program and follow the instructions on the screen. To determine the effect of cyclic loading on the sample, 10 cycles of loading at a frequency of 0.5 Hz are usually input for each strain increase. To evaluate the effect of frequency, testing is normally performed at two strain levels ($\gamma = 0.001\%$ and $\gamma = 0.01\%$) at frequencies of 0.05, 0.1, 0.5, 1.0, 5.0 and 10 Hz, with 4 cycles of loading at each frequency.

______6. For the first test, use an input voltage of 0.01 volts, an excitation frequency of 0.5 Hz and 10 cycles of loading.

______7. Double the input voltage for each strain increase until the shearing strain reaches $\approx 0.001\%$.

______8. Once the shearing strain reaches $\approx 0.001\%$, evaluate the effect of frequency as described in Step 5. Use same the input voltage as used to obtain a shearing strain of $\approx 0.001\%$

______9. After performing Step 8, double the input voltage for each strain increase until the shearing strain reaches $\approx 0.01\%$. Then, follow Step 8 maintaining a shearing strain level $\approx 0.01\%$.

______10. Double the input voltage for each strain increase until input voltage reaches 1.3volts or signals on the Oscilloscope shows non-sinusoidal shape which indicates one of the three symptoms described in Step 5 of High-Amplitude RC Test Procedure.

QA:QA

ATTACHMENT 1

USER'S GUIDE FOR PROGRAM RCTEST

A.1 LOADING THE PROGRAM

To load the program in the computer, simply type:

Load "RCTEST"

and then press the "ENTER" key.

A.2 PROGRAM ENTRY

The program use interactive procedures to input all data required to run the resonant column test. Before running this program the specimen should be prepared in a triaxial cell. All information of specimen and cell should be recorded on a laboratory data sheet(as shown on the next page).

When the specimen is ready for testing, the operator presses the "RUN" key. The operator is then ready to run the program by answering the question asked by the computer. The entry question is

Welcome to RCTEST. Enter one of the following commands :

R = return to present test series

A = access RCTEST softkeys

I = initialize counters, data and schedule of new test sample

N = new pressure level

There are four possible entries. Operator have to decide which entry should be entered according to the status of the test. These four entries will be explained in the following sections with examples.

1. Initialization Entry This response is called initialization entry because in this case the computer has no information about the test specimen. This response should be used whenever the specimen has been prepared and is ready to be tested for the first time. Input "I" for the entry question. The operator should then input the following data in order to have the computer perform the resonant column test.

The University of Texas at Austin - Soil Dynamics Laboratory
Resonant Column and Torsional Shear Test

Project No. 0201-213-5 Test No. UT43C Sample No. 22
Performed by Seon Keun Hwang Date 8/27/93
Checked by Mark Raymond Twede Date 8/27/93

Site Location : OTRC Date Started : 8/27/93
Sample Depth : 25.5 ft Boring Number : CATAZ-1
Cell No. : 4 Visual Sample Classification : soft light gray clay
Drive Plate No.: 9 LVDT No. : 4 Top Cap No. : 2 Accel. No. : 5
Proximitor No. : 4 Pressure Gage No. : 279327

Water Content Determination

Proximitor Reading(Y/R)

	Top	Sides	Bottom
Tare Number		127D	
Weight of Tare (g)		20.59	
Weight of Tare + Wet Soil(g)		59.34	
Weight of Tare + Dry Soil(g)		45.55	
Weight of Water (g)		13.79	
Weight of Dry Soil (g)		24.96	
Water Content, %		55.20	
Average Water Content, %		55.20	

$$\bar{\sigma}_m = \frac{(1+2K_o)}{3}\{h_w\gamma_t + (h_t - h_w)(\gamma_t - \gamma_w)\}$$

Weight of Sample + Mold (g) = 707.7
Weight Mold (g) = 389.2
Weight of Sample before testing (g) = 318.5

Dimension of Sample before Testing

	Height (cm)	Outside Dia. (cm)	Isotropic Confining Pressure, σ_0, psi								
0 ° or Top	26.39-16.78	4.997		2.0	5.0	10	21	42			
120 ° or Middle		4.997	RC-LAT								
240 ° or Bottom		5.000	TS								
Average	9.61	4.998	RC-HAT								

Specific Gravity : 2.72 Density : - Initial LVDT Reading (V) : 5.4758
Seating Pressure Applied (Vacuum) : 2 psi
Description of Specimen and Comments

QA:QA

a) Initialize the data files. This resets the counter of the RESULT file to zero. Also set all the control variables to their default values. They are as the follows:

F_{ma} = -1 (do rough sweep search)
G_{sto} = 0 (not to store graphic data file in the diskette)
I_{adc} = 0 (use Nicolet oscilloscope to get free vibration decay curve)
N_{sp} = -1 (do rough sweep search from frequency step no. 1)
N_{sw} = 1 (do only downgrade fine sweep search)
T_o = TIMEDATE store current clock time in seconds
V_{pp} = 22 (power output level is 22 mv)

These input steps will be:

```
Enter Cell Number :
==>  4

Are you sure(initialize only at the beginning)? (Y/N) Y
==>  Y
```

b) Input the specimen and testing cell information according to the laboratory data sheet as requested by the computer. The input is shown in the following steps:

```
Is initial sample data stored in a SOIL_DATA file? (Y/N) N
==>  N

Enter title of test :
==>  UT43C--Sample No. 22--25.5ft--Soft Light Gray Clay

Enter Drive Plate Number :
==>  9

Is Proximitor Target attached on the Drive Plate? (Y/N)
==>  Y
```

Enter one of the following Top Cap Numbers :

1. = 1.500 in. solid.
2. = 2.000 in. solid.
3. = 2.100 in. hollow.
4. = 2.500 in. hollow(for isotropic loading).
5. = 2.500 in. solid.
6. = 2.800 in. solid.
7. = 2.875 in. solid.
8. = 3.000 in. solid.
9. = 2.500 in. hollow(for anisotropic loading).
10. = 2.000 in. Stainless Steel solid(for cemented sand)
11. = 1.000 in. Stainless Steel solid(for rock specimen).
12. = 1.875 in. Stainless Steel solid(for rock specimen).
13. = 2.000 in. Stainless Steel solid(for rock specimen).
14. = 3.000 in. Stainless Steel solid(for rock specimen).
15. = 4.000 in. Stainless Steel solid(for rock specimen).
16. = 2.000 in. Brass solid for Metal Specimen(Inner position).
17. = 2.000 in. Brass solid for Metal Specimen(Outer position).

==> 2

Enter LVDT Number :

==> 4

Enter one of the following Accelerometer Numbers :

1. = Serial No. 3878
2. = Serial No. 2919
3. = Serial No. 2963
4. = Serial No. 3877
5. = Serial No. 3879
6. = Serial No. 3873
7. = Serial No. 2018
8. = Serial No. 2017
9. = Serial No. 2016
10. = Serial No. 2057
11. = Serial No. 2120
12. = Serial No. 2140

==> 5

Enter the following specimen information--

Height(cm) :
==> 9.61

Outside Diameter(cm) :
==> 4.998

Inside Diameter(cm) :
==> 0

Mass(gm) :
==> 318.5

Water Content(decimal) :
==> 0.552
Specific Gravity :
==> 2.72

Enter initial LVDT output in volts :
==> 5.4758

Enter time in minutes assumed for 100 % primary consolidation :
(usually 50 = sand, 1000 = clay)
==> 1000

Anisotropic loadings in this test series? (0 = no, 1 = yes)
==> 0

Pressure Transducer to monitor cell pressure? (0 = no, 1 = yes)
==> 0

Following additional testing information is necessary to perform Low-amplitude resonant column tests. Input the desired cell pressure level, followed by the time schedule for performing the resonant column test at this pressure level.

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The program has three default time schedules used to perform the resonant column test. They are designed to fit a period of one hour, one day, or one week. There are six default readings for a period of one hour. They are at 10, 20, 30, 40, 50, and 60 minutes, there are twenty-one default readings for a period of one day. They are 2, 7, 12, 17, 25, 35, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, and 1440 minutes. There are twenty-eight default readings for a period of one week. They are 2, 7, 12, 17, 25, 35, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1200, 1440, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, and 10080 minutes. The operator can select one of the default time schedule to be used for his particular specimen. The operator may also designate an alternate time schedule to run the resonant column test for a specific specimen. To select an alternate time schedule simply input the number of readings and all of the reading times. The interactive input is as follows:

```
        UT43C--Sample No. 22--25.5ft--Soft Light Gray Clay
        The test no. in this test series is 1

    What is the confining pressure Pc in psi in this pressure level?
    ==>  2

    Do you want to use default time to get readings?
    ==>  Y

        ****** Default Reading Time Schedule *******
                 1.  for one hour (6 readings)
                 2.  for one day (21 readings)
                 3.  for one week (28 readings)

        Please select 1 or 2 or 3
    ==>  1

        The present time is 20:40:57 .
    What is the beginning time for this pressure level? (type: hr, min, sec)
    ==>  20,42,0
```

Time Schedule for Cell 1 (Beginning time is 20:42: 0)

Test No.	Time for test(min)	(Hr:Min: Sec)	Index	Pressure (psi)
1	10	20:52: 0	0	2
2	20	21: 2: 0	0	2
3	30	21:12: 0	0	2
4	40	21:22: 0	0	2
5	50	21:32: 0	0	2
6	60	21:42: 0	0	2

What is power output level for LA test in mv?
(default 22 mv for clean sand)
==> 18

The no. of sweep?
(1 = downgrade sweep, 2 = downgrade and upgrade sweep)
==> 1

Which instrument is used to get free vibration decay?
(0 = Nicolet oscilloscope, 1 = ADC)
==> 0

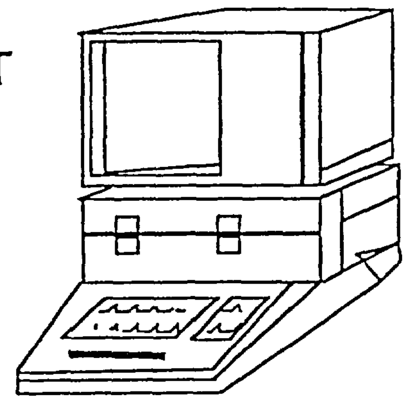
Will you store graphic data files? (0=no, 1=yes)
==> 0

Printer address? (1 = Monitor, 701, 717 or ... = Printer)
==> 701

When data input is completed, the computer will search the most recent running time T_{run}. The running time T_{run} will be loaded into the computer memory and will be displayed on the screen (as shown in Fig. A. 1). The clock is activated to run until the clock time is equal to the running time T_{run}, at which point the computer performs the resonant column test. Once the execution is complete, the computer will search for the next running time, thereby creating an execution cycle until all the tests have been completed. After performing the final scheduled test, computer displays Fig. A. 2 to inform the operator that it has carried out all the tests planned at specified pressure level.

SOIL DYNAMICS LAB

RESONANT COLUMN TEST
IS IN PROGRESS



NEXT READING
AT 20:52:0
FOR CELL 4

20:41:50 ← real time clock

softkeys assigned

Mod Init Data	Time Schedules	Test Results	Ctrl Status	Stop
RC_Setup	Calc Tx_Stress	Run LAT	Run HAT	Check LVDT Rdg

Fig. A. 1 Display on the Screen When Computer is Timing to Run Resonant Column Test

QA:QA

P.O.# A17370...

UTACED

* ALL DONE*
Computer
is
available now.

To clear monitor, Type: GRAPHICS OFF & (EXECUTE)

(No part of resonant column equipment can be moved out of this lab.)

SCRATCH	LOAD"	CAT	RE-STORE"	LIST

Fig. A. 2 Display on the Screen When Computer all the Schedule Tests

2. Access to Softkeys Entry

When the program is running, ten softkeys assigned to control the program execution will be displayed on the front panel along with their labels as shown in Fig. A. 4. The keys can also be accessed by inputing "A" for the entry question(Fig. A. 3 is displayed on the screen). All softkeys can be used to initiate the program execution to perform their specific purposes. The function of the softkeys are as follows:

Mod Init_Data: To modify the specimen data and cell information for a specified testing cell.

Time Schedules: To display the time schedule of resonant column test for a specified testing cell.

Test Results: To check and list the resonant column test results for a specified testing cell.

Ctrl Status: To check and modify the testing control variables stored in the file TIME_SCHE.

Stop: To stop the execution of the resonant column test.

RC_Setup: To check the equipment system setup and addresses.

Calc Tx_Stress: To calculate the triaxial stresses for a hollow specimen.

Run LAT: To perform a low-amplitude resonant column test for a specified testing cell immediately. With this key the low-amplitude test of any cell can be performed at any time other than the scheduled testing time.

Run HAT: To perform the high-amplitude resonant column test for a specified testing cell immediately.

Check LVDT Rdg: To check LVDT output readings for a specified testing cell.

Three examples will be presented to show the use of the softkeys.

Example 1: When the key Mod Init_Data is pressed,

```
Enter the cell number of the initial data to modify:
==>  1

     UT43C--Sample No. 22--25.5ft--Soft Light Gray Clay
will you modify title?
==>  N
```

QA:QA

K0	K1	K2	K3	K4
Mod Init_Data	Time Schedules	Test Results	Ctrl Status	Stop
RC_Setup	Calc Tx_stress	Run LAT	Run HAT	Check LVDT Rdg
K5	K6	K7	K8	K9

Fig. A. 3 Assigned Softkeys with Labels

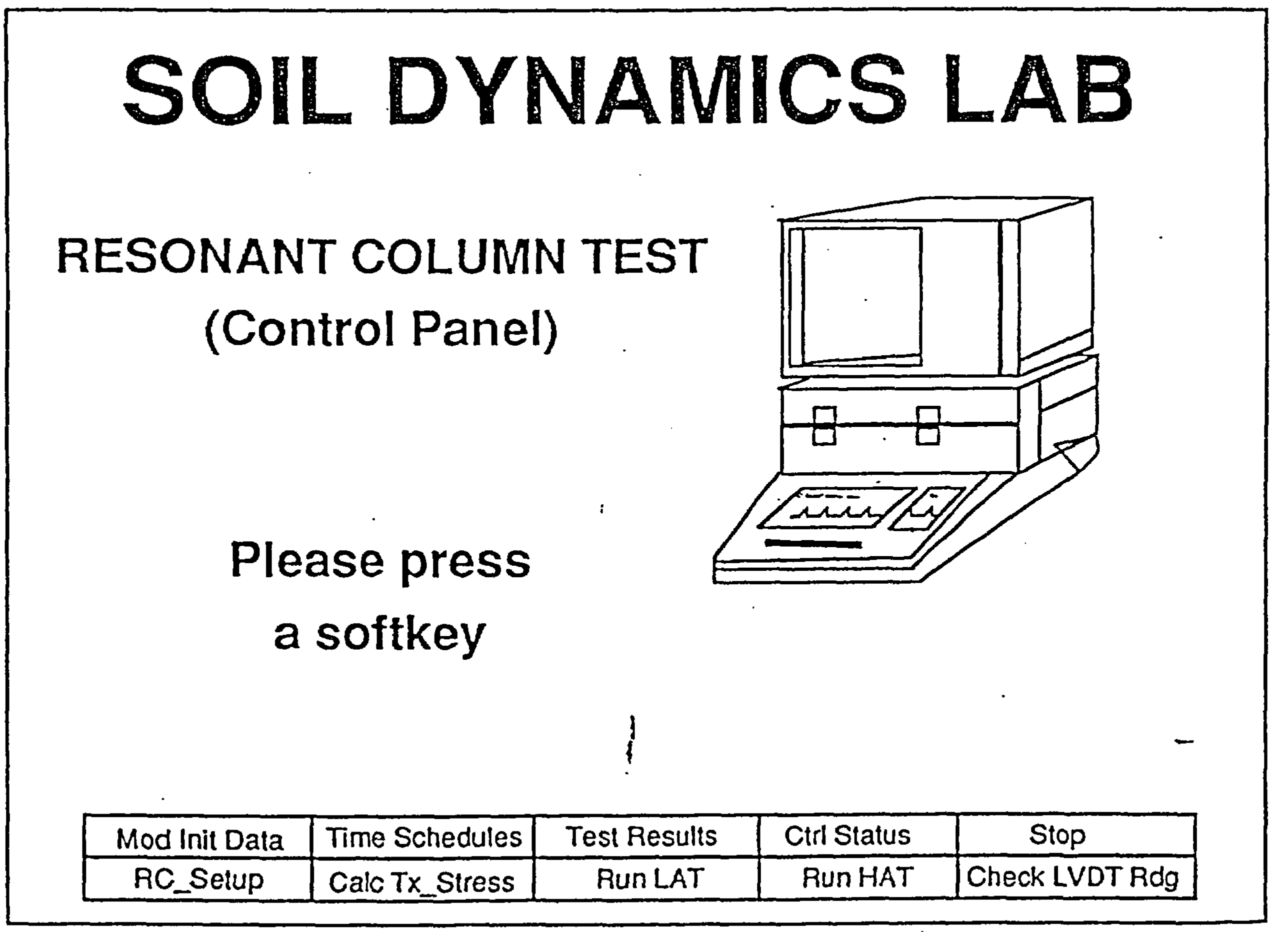


Fig. A. 4 Display on the Screen Access to Sofkeys Entry is Chosen

QA:QA

Drive Plate No. = 9
Will you modify this value?
==> N

Top Cap No. = 2
Will you modify this value?
==> N

LVDT No. = 4
Will you modify this value?
==> N

Loading condition(0 = isotropic, 1 = anisotropic) = 0
Will you modify this value?
==> N

Pressure Transducer Index(0 = no, 1 = yes) = 0
Will you modify this value?
==> N

Accelerometer No. = 5
Will you modify this value?
==> N

Height(cm) = 9.61
Will you modify this value?
==> N

Outside Diameter(cm) = 4.998
Will you modify this value?
==> N

Inside Diameter = 0
Will you modify this value?
==> N

Weight(gm) = 318.5
Will you modify this value?
==> N

Water Content = 0.552
Will you modify this value?
==> N

Specific Gravity = 2.72
Will you modify this value?
==> Y

New value?
==> 2.65

Initial LVDT output voltage(volts) = 5.4758
Will you modify this value?
==> N

Time index(min.) = 50
Will you modify this value?
==> N

Is Proximitor Target attached on the Drive Plate? (Y/N)
==> Y
Repeat?
==> N

Example 2: When the key Ctrl Status is pressed,

Which cell will you access to?
==> 4

1. Total number of tests scheduled: 6
2. Total number of tests performed: 0
3. Confining Pressure level no.: 1
4. Beginning time of test: 2.11374481801E+11
5. Number of rough sweep level: -1
6. Resonant frequency of previous LA test: -1
7. Max. Accelerometer output in the previous test: 0
8. Index for storing graphic data: 0
9. Number of fine sweep level: -1
10. Power output level(mv): 18
11. Instrument for free vibration decay(0 = Nicolet, 1 = ADC): 0
12. Resonant frequency of previous HA test: 0
13. Printer address(1 = screen, 701 = printer): 701

Input the No. of parameter to be changed(0 to stop)?
==> 13

Input the new value of parameter?
==> 1

1. Total number of tests scheduled: 6
2. Total number of tests performed: 0
3. Confining Pressure level no.: 1
4. Beginning time of test: 2.11374481801E+11
5. Number of rough sweep level: -1
6. Resonant frequency of previous LA test: -1
7. Max. Accelerometer output in the previous test: 0
8. Index for storing graphic data: 0
9. Number of fine sweep level: -1
10. Power output level(mv): 18
11. Instrument for free vibration decay(0 = Nicolet, 1 = ADC): 0
12. Resonant frequency of previous HA test: 0
13. Printer address(1 = screen, 701 = printer): 1

Input the No. of parameter to be changed(0 to stop)?
==> 0

QA:QA

Example 3: Performing High-Amplitude Test

High-amplitude test can be carried out at any time by pressing softkey "Run HAT" in any entry mode. The operator has two data input options to run the high-amplitude test. The first option is called step by step mode. In this mode the computer will perform the resonant column test after the operator has input one pair values of V_{pp} and A_{cfr}. The computer performs the test depending on the values of V_{pp} and A_{cfr}. The second option is called semi-auto mode. In this mode the computer will continue to perform the resonant column test until all tests are completed. The computer uses the defaulted series of V_{pp} and A_{cfr} values. The default values of V_{pp} are 0.5, 1, 2.5, 5, 12, 27, 65, 155, 350, 850, 2000, 4500 mv, respectively. A input example for step mode follows:

Press the softkey Run HAT

Cell Number:
==> 4

Will you store graphic data from HA test? (0 = no, 1 = yes)
==> 0

Re-enter the previous test series? (Y or N)
==> N

What is the confining pressure Pc in psi in this pressure level?
==> 2

The no. of sweep?
(1 = downgrade sweep, 2 = downgrade and upgrade sweep)
==> 1

Which instrument is used to get free vibration decay?
(0 = Nicolet oscilloscope, 1 = ADC)
==> 0

Will you store graphic data files? (0 = no, 1 = yes)
==> 0

QA:QA

Printer address? (1 = Monitor; 701, 717 or ...= printer)
==> 701

Vpp? in mv(input 0 to stop)
==> 1

Accelerometer output factor?
==> 1

The operator can perform the HA test as many times as necessary to achieve the intended strain amplitude level by changing input voltage and accelerometer output factor.

3. New Pressure Level Entry. The third response to the initial question asked by the computer is called new pressure level entry. In this case input "N" for this entry. The operator should choose this response to set the time schedule for a new cell pressure level.

What is the number of cell that you are going to run?
==> 4

UT43C--Sample No. 22--25.5ft--Soft Light Gray Clay
The test no. in this test series is 2

What is the confining pressure Pc in psi in this pressure level?
==> 5.2

The pressure level Pc = 5.20 psi
Do you want to use default time to get readings?
==> Y

******* Default Reading Time Schedule *******
1. for one hour (6 readings)
2. for one day (21 readings)
3. for one week (28 readings)

Please select 1 or 2 or 3
==> 1

The present time is 21:48:48

What is the beginning time for this pressure level? (Type: hr, min, sec)

==> 21,50,0

Time Schedule for Cell 1 (Beginning time is 21:50: 0)

Test No.	Time for test (min)	(Hr:Min: Sec)	Index	Pressure (psi)
1	10	22: 0: 0	0	5.20
2	20	22:10: 0	0	5.20
3	30	22:20: 0	0	5.20
4	40	22:30: 0	0	5.20
5	50	22:40: 0	0	5.20
6	60	22:50: 0	0	5.20

What is power output level for LA test in mv?

(22 mv for clean sand)

==> 22

The no. of sweep?

(1 = downgrade sweep, 2 = downgrade and upgrade sweep)

==> 1

Which instrument is used to get free vibration decay?

(0 = Nicolet oscilloscope, 1 = ADC)

==> 0

Will you store graphic data files? (0 = no, 1 = yes)

==> 0

Printer address? (1 = Monitor; 701, 717 or ... = printer)

==> 701

4. <u>Returning Entry</u>. Whenever the computer is interrupted to be used for other purposes. The operator should choose this option to let the computer continue running this program. In this case the operator answers "R" to the question. The computer will search for the most recent running time and be ready to perform the next scheduled resonant column test.

A.3 EXAMPLE TEST

As a demonstration of how to perform a resonant column test using this program, an example is shown in sequence on the next several pages. When the specimen is ready for testing, the operator should input the necessary data according to the laboratory sheet as explained in the previous section.

RESONANT COLUMN TEST - SOIL DYNAMICS LABORATORY - UNIVERSITY OF TEXAS AT AUSTIN
----- PROGRAM RCTEST VERSION 1.0 -----

Date 7 SEP 1993 Time: 12: 46: 09
Title: UT43C--Sample No. 22--25.5ft--Soft Light Gray Clay
Pressure level no. = 5, Confining pressure Pc = 20.8 psi
Pressure Gage No. : 279327
LVDT: Input = 4.772 volts Output = 4.0335 volts

Frequency Sweep to Determine Resonant Frequency and Damping Ratio:
Input Voltage : RMS = 31.83 mv PEAK-TO-PEAK = 45.01 mv
Rough max. accel. output = 67 mv, Freq. = 71.886 Hz, Period = 13.915 msec

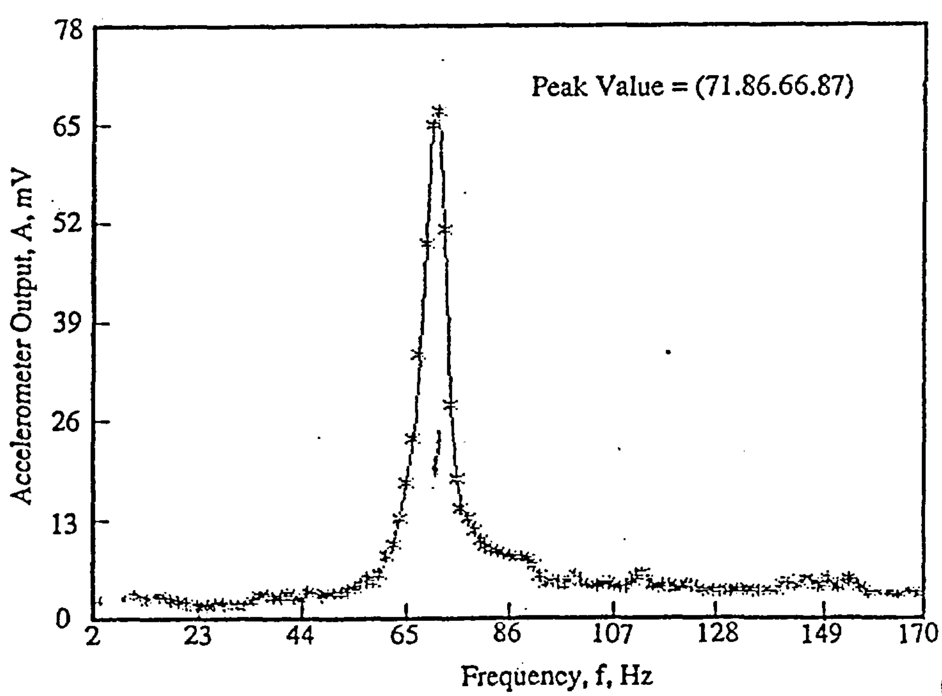


Fig. A. 5 Result of Rough Sweep Search

QA:QA

P.O.# A17376YS0A
UTACED

Fine max. accel. output = 82.8 mv, Freq. = 67.508 Hz, Period = 14.813 msec
Damping Ratio (by Half Power Method) = 1.563 %

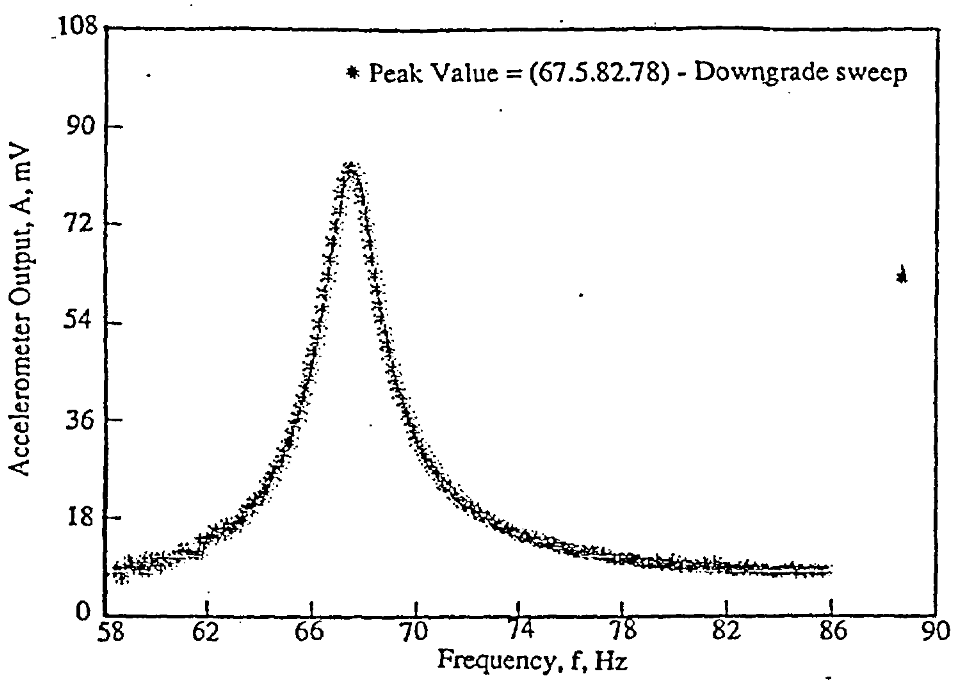


Fig. A. 6 Result of Fine Sweep Search

Damping Ratio From The Free Vibration Decay Curve at Resonance(67.51 Hz):

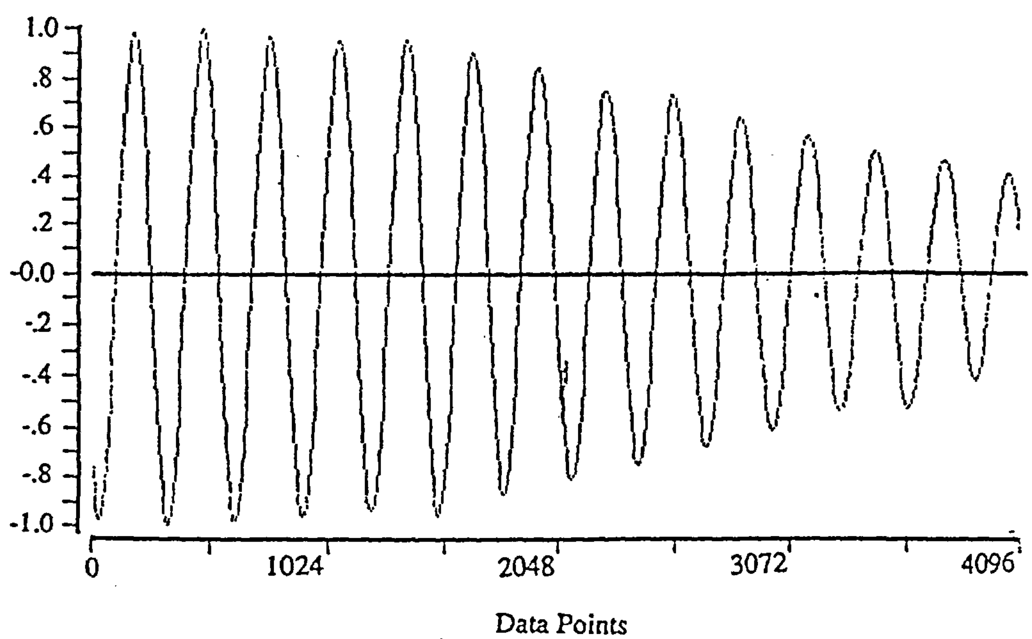


Fig. A. 7 Time Domain Data of Free Vibration Decay Curve

QA:QA
P.O.# A17376YS0A
UTACED

Peak No = 13, No. of peak points for calc. Dr = 7

443 407 373 351 315 280 249 233

Correlation = - 0.9960 Damping Ratio = 1.5388 %

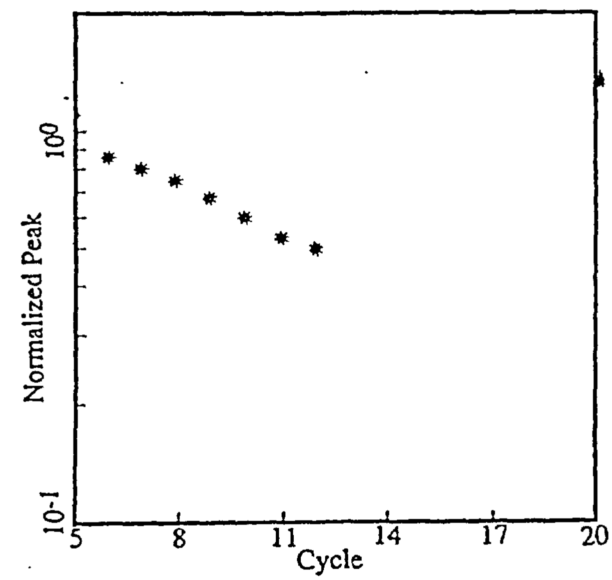


Fig. A. 8 Plot Log Peaks of Free Vibration Decay Curve Versus Number of Cycles

(Continues to get free vibration curve)

(figure which is similar to Fig. A. 7 is omitted)

Peak No = 17, No. of peak points for calc. Dr = 7

430 388 360 321 291 266 232 227

(figure which is similar to Fig. A. 8 is omitted)

Correlation = - 0.9940 Damping Ratio = 1.5202 %

(Continues to get free vibration curve)

(figure which is similar to Fig. A. 7 is omitted)

Peak No = 17, No. of peak points for calc. Dr = 7

444 387 364 311 279 255 239 227

(figure which is similar to Fig. A. 8 is omitted)

Correlation = - 0.9878 Damping Ratio = 1.5006 %

The avg. Damping Ratio is 1.520 %

Time	Cell	LVDT	Mac Ac	Reson.	Void	Shear	Shear	Damping		Vs
	pres.	Output	Output	Freq.	Ratio	Strain	Modulus	FV	HP	
min.	psi	V	mV	Hz	%	%	psf	%		fps
6790	20.8	4.0335	83	67.51	1.352	8.554E-04	1.849E+06	1.52	1.56	742

RC_SETUP

The purpose of this program is to check the setup of all the testing equipment used in the resonant column test at the beginning of testing.

```
**********************************
*     SYSTEM CONFIGURATION       *
*            FOR                 *
*    RESONANT COLUMN TEST        *
**********************************
                            Address
External Plotter ------------------705
External Printer ------------------701
3456A DVM -------------------------722
3314A Function Generator ----------707
5334A Frequency Counter -----------703
3488A Switch/Control Unit ---------709
```

Fig. A.9 Display on the Screen After Computer Checks the Configuration of Equipment

This program, which can be accessed by the softkey when the data acquisition program RCTEST is running, is run to check the address of equipment and the connections of the interface bus. Output display is shown in Fig. A. 9. If no error occurred, the computer will automatically continue the execution of program RCTEST.

TIMELIST

The purpose of this program is to list time schedules for running a resonant column test. It provides the operator with information concerning the availability of computer to perform other computations.

This program can be accessed by softkey on the keyboard shown on Fig. A. 4 during testing. When the operator presses the assigned softkey, it activates program execution. By inputting the cell number on the keyboard, the operator requests a screen print out of the time schedule at a specific test cell (as shown in Fig. A. 10). To stop program execution and to return to the main RCTEST program, the operator enter "0".

```
Which cell do you ask for its running time schedule? (Type 0 to stop)
==>  2
```

TIME SCHEDULE for Cell 2 (BEGINNING TIME IS 15: 0: 0)

Test No.	Time for test(min)	(Hr:Min: Sec)	Index	Pressure
1	10	15:10: 0	0	28.00
2	20	15:20: 0	0	28.00
3	30	15:30: 0	0	28.00
4	40	15:40: 0	0	28.00
5	50	15:50: 0	0	28.00
6	60	16: 0: 0	0	28.00
7	70	16:10: 0	1	56.00
8	80	16:20: 0	0	56.00
9	90	16:30: 0	0	56.00
10	100	16:40: 0	0	56.00
11	110	16:50: 0	0	56.00-
12	120	17: 0: 0	0	56.00
13	130	17:10: 0	0	56.00

This cell have 10 more testings. Next running time is at 15:40: 0

Fig. A. 10 Output Example of Program TIMELIST

QA:QA

Which cell do you ask for its running time schedule?
(Type 0 to terminate)
==> 0

RCRESULT

This program displays the test results of a specified testing cell and enables the operator to verify the results.

This program can be accessed by softkey on the keyboard during testing (as shown on the Fig. A. 4). To run this program the operator simply presses the softkey assigned. After the operator inputs the desired testing cell number, the computer will display on the monitor or print out all test results previously performed by the computer. To stop execution of this program one simply hits "0".

SET_RST

The purpose of this program is to create result files manually. RESULT files are created manually whenever the data storage system fails by accident or the computer data acquisition is not available at that time. Data input is interactive. Data, (such as accelerometer output level, resonant period, LVDT output reading, damping ratio, etc.), are entered on the keyboard upon computer request. No other calculations are done in this program. The program will create RESULT files in the mass storage system. Accurate dynamic soil properties will be calculated by the program Re_RST.

EDIT_RST

The purpose of this program is to correct data errors on SOIL_DATA file and RESULT files. In cases where erroneous data are stored in a RESULT file or SOIL_DATA file, this program can be used to recall the erroneous data and to correct them. Keywords used for this purpose are listed as follows:

1) D = Delete line
2) I = Insert line
3) M = Modify the whole line
4) S = Substitute data
5) Q = Quit the editor

RESULT and SOIL_DATA files can be easily corrected with these keywords. After the operator quits the editor, a new data file will replace the old data file.

QA:QA

Re_RST

The purpose of this code is to accurately calculate dynamic soil properties, such as shear modulus after a RESULT data file has been created or modified. If EDIT_RST is used to correct data or if SET_RST is used to create data, only the necessary data is corrected or created. No calculations are performed in these two programs. Program Re_RST is used to do calculations and store the final results in RESULT files.

HP_IBM

The purpose of this program is to create two destiny files(one in binary format and another in ASCII format) to store SOIL_DATA and RESULT files together for easy access.

When all the resonant column tests(i.e. Low-amplitudes, High-amplitudes tests at several different pressure levels) is carried out, they are saved into different RESULT files. The program first creates two data files, which is named by the operator. Secondly, the program gains access to SOIL_DATA file and RESULT files to store them into two newly generated files. The binary data file will be used in the HP computer and ASCII data file is transferred to the Macintosh computer through IBM computer using two softwares(Standard Data Format Utilities and Apple File Exchange). Final plots are made in the Macintosh computer using graphic software(Igor 1.27).

RCFILE_RST

The purpose of this program is to create SOIL_DATA and RESULT files in the HP computer using binary data file saved in the diskette with program HP_IBM.

RCREDUCE *

The purpose of this program is to sort test results from a resonant column test using the microcomputer. The program calculates several parameters using the binary data file created by program HP_IBM. The program also includes a plotting subroutine which enables the operator to make preliminary plots.

PLOTGF *

The purpose of this program is to retrieve graphic data saved in the diskette and to display them on the monitor. When the resonant column test is performed, the result of tests may be stored in a graphic data file if requested by the operator at the beginning of testing. An advantage of storing the graphic data is that the operator can check the test results whenever questionable data appear in a RESULT file.

* These programs are not currently in use.

QA:QA

ATTACHMENT 2

A COMPUTER-AIDED TORSIONAL SHEAR TEST EXAMPLE USING PROGRAM TSTEST

To have testing program in the computer, simply type:

LOAD "TSTEST"

and then hit the key "ENTER". Make sure a diskette is the disk drive to store the test results, otherwise program will not perform the test properly. Following is a complete interactive testing example.

To start the testing, press the "RUN" key.

Cell No. ?

==> 4

What is the address of printer that you're going to use?

For Performing tests: Enter 701

For Data Reduction: Enter 1

Printer is? (1 = monitor, 701 = printer)

==> 701

Will you read data in Disc ? [Y, N, or S (stop), or P (partial file to recalculate)]

==> N

TORSIOAL SHEAR TEST-SOIL DYNAMICS LABORATORY-UNIVERSITY OF TEXAS AT AUSTIN

-------------- PROGRAM TSTEST VERSION NO. 2.0 ------------

DATE: 7 SEPT 1993 TIME: 21:10:06

Title: UT43C--Sample No. 22--25.5ft--Soft Light Gray Clay

Pressure level no. = 5, Confining pressure Pc = 20.8 psi

Pressure Gage No. 279327

Are you going to test metal specimen? (Yes = Y, No = N)

==> N

QA:QA

(Getting LVDT Reading before Applying torque to the sample)
LVDT Input Voltage = 4.7719 vlts   LVDT Output Voltage = 4.0291

*** Run torsional shear test by Manual ***

1. Connect cables. -- Proximitor output to chan. A of Nicolet oscilloscope.
   -- Excitation input to chan. B of Nicolet oscilloscope.

Frequency = ? Hz., Vpp = ? volts, and no. of cycles of oscillation?
==> 0.5,0.02,10

2. Press LCL-key on the keyboard of Function Generator.
3. To count no. of cycles, set Frequency Counter on LOCAL, TOT START A, AC.
4. Set Nicolet Oscilloscope storage control to LIVE, HOLD LAST and AUTO mode.
5. Manual trigger Function Generator: press INT-key twice.
6. Wait until required no. of cycles displayed on the oscilloscope.
7. Press CONTINUE to proceed the data by computer.

==> (Press) CONTINUE

(Getting LVDT Reading after Applying torque to the sample)
LVDT Input Voltage = 4.7719 vlts   LVDT Output Voltage = 4.0290

(Transferring data from Nicolet oscilloscope to computer)
Voltage range setting (1/2 of full range - V): Va, Vb and time per point setting - ms?
==> 0.4   1.0   20

What are the setting of PREFILTER GAIN of amplifiers S1 and S2?
==> 10,1

Which cycle you are going to pick up ?
==> 1.25

Input a file name to save data.
==> UT43C72

QA:QA

(Data are being saved into the dikette)

File name to save this data is UT43C72

Will you plot shear stress vs. shear strain?.

==> Y

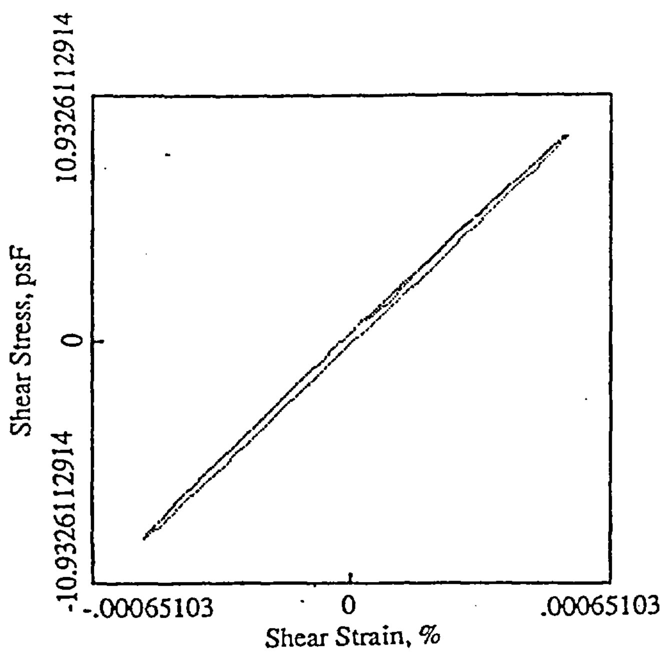


Fig. A. 11 Stress versus Strain Plot from Torsional Shear Test of Sample

Proximity Calibration Factor = 1.33909E-03 rad/volt

Torque Calibration Factor = 1.48830E-02 ft-lb/volt

LVDT Calibration Factor = 0.0043598 inch/volt

Frequency is 0.50 Hz Cycle no. = 1.25

Smoothing 0 times.

Max. shear strain = 5.425274E-04 Max. shear stress = 9.11051 psf

Frequency is 0.50 Hz

Max. shear strain = 5.425274E-04 %

Shear Modulus = 1.673749E+06 psf

Damping Ratio = 1.439 %

Will you dump this plot to printer or plotter? (1 = printer, 5 = plotter, else = No)

==> 0

QA:QA

Continue with curve smoothing ?

==> Y

(figure which is similar to Fig. A. 11 is omitted)

Smoothing 1 times.

Max. shear strain = 5.417998E-04 Max. shear stress = 9.11051 psf

Frequency is 0.50 Hz

Max. shear strain = 5.417998E-04 %

Shear Modulus = 1.676351E+06 psf

Damping Ratio = 1.436 %

Will you dump this plot to printer or plotter? (1 = printer, 5 = plotter, else = No!)

==> 0

Continue with curve smoothing ?

==> N

Will you read data in Disc ? [Y, N, or S (stop), or P (partial file to recalculate)]

To continue the testing with different conditions (i.e. strain amplitude, loading frequency, number of loading cycles), enter "N" to the last question asked and proceed with appropriate answers to the program.

Performed by: Shon Keun Hwang
Checked by: K. H. Stokoe
Date: 20 Sept 93

ATTACHMENT 3

HAND CALCULATION SHEET

A. Resonant Column Test Results: Low-Amplitude Test($\gamma <$ 0.001%)

Test results used for confirming the computations performed by the computer program, RCTEST, are presented below. The following information from one sample tested from Savannah River Site is :

Project Number : AA891070
Depth : 79 ft (24 m)
Boring Number : CDF1
Sample Number : PS-5A
Test Number : UT39I
Confining Pressure : 140 psi
Type of Test Performed : Low-Amplitude Resonant Column Test
Time : 1335 minutes

Test results (at a time of 1335 minutes after applying a confining pressure of 140 psi) performed by computer program "RCTEST" are as follows:

Measured by Computer Program:

a) Accelerometer Output = 111 mv
b) Resonant Frequency, f_r = 101.529 Hz
c) LVDT Output = 3.242 volts

Measured by Hand:

a) Accelerometer Output = 110 mv
b) Resonant Frequency, f_r = 101.3 Hz
c) LVDT Output = 3.242 volts

Calculated by Computer Program:

d) Void Ratio, e = 0.919
e) Shearing Strain, $\gamma = 4.954 \times 10^{-4}$ %
f) Shear Modulus, $G = 3.885 \times 10^3$ ksf
g) Shear Wave Velocity, V_s = 1064 fps
h) Damping Ratio from Half-Power Bandwidth Method = 3.275 %
i) Damping Ratio from Free-Vibration Decay Curve = 3.221 %

1. Known Constants of Sample(Before Applying Isotropic Confining Pressure):

a) D_{outo} : Initial Outer Diameter of Sample
= 5.15 cm = 5.15(cm) / 2.54(cm/in.) / 12(in/ft) = **0.1690 ft**

b) D_{into} : Initial Inner Diameter of Sample
= 0.0 cm = 0.0(cm) / 2.54(cm/in.) / 12(in/ft) = **0.0 ft**

c) H_{tsamo} : Initial Height of Sample
= 10.22 cm = 10.22(cm) / 2.54(cm/in.) / 12(in/ft) = **0.3353 ft**

d) W_{tsamo} : Initial Weight of Sample
= 366.5 gm = 366.5 (gm)/453.6(gm/lbs) = **0.8080 lbs**

e) W_{csamo} : Initial Water Content of Sample
= **31.1 %**

f) G_s : Specific Gravity of Sample(Assumed)
= 2.65

g) V_{lvdto} : Initial LVDT Reading
= 4.6219 volts

2. Calibration Factors of Testing Device:

a) D_p : Mass Polar Moment of Inertia of Drive Plate No. 5
= 0.00208760 ft-lbs-sec^2 **

b) T_c : Mass Polar Moment of Inertia of Top Cap(Dia. = 2 in.)
= 0.00005056 ft-lbs-sec^2 **

c) F_{ac} : Calibration Factor of Accelerometer No. 3878
= 2.5234 volts/g (for a setting of 70.9 pcmb/g
on Charge Amplifier No. 4102M)**

d) F_{lvdt} : Calibration Factor of LVDT No. 3
= 0.0040263 ft/volt**

3. Unknowns:

a) Dry Unit Weight, γ_d
b) Void Ratio, e_o and e
c) Initial Degree of Saturation, S_r
d) Shear Wave Velocity, V_s
e) Shear Modulus, G
f) Shearing Strain, γ
g) Damping Ratio from Frequency Response Curve, D_{hp}
h) Damping Ratio from Free-Vibration Decay Curve, D_{fv}

4. Hand Calculations for Initial Conditions (Before Any Confinement):

a) Dry Unit Weight, γ_d, pcf:

$$\gamma_d = \frac{\text{Dry Weight of Sample}}{\text{Volume of Sample}}$$

$$= \frac{\dfrac{W_{tsamo}}{(1+W_{csamo})}}{\text{Volume of Sample}}$$

$$= \frac{0.8080/(1+0.311)}{\pi \times 0.1690^2 \times 0.3353/4}$$

$$= 81.94 \text{ pcf } (82.0 \text{ pcf})^*$$

** RC Test Version 2.1 and TS Test Version 3.1 have new calibration factors.

D_p = 2.0630E-03 ft lb sec^2
T_c = 5.09296E-05 ft lb sec^2
F_{ac} = 2.741 pkV/g (for a setting of 70.9 pcmb / g on Charge Amplifier No. 4102M)
F_{lvdt} = 3.768E-03 ft/V

* Numbers printed out in computer program.

QA:QA

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b) Void Ratio, e_o:

$$e_o = \frac{G_s \times \gamma_w}{\gamma_d} - 1 = \frac{2.65 \times 62.4}{81.94} - 1 = 1.018 \ (1.018)^*$$

c) Degree of Saturation, S_{rsamo}, %:

$$S_{rsamo} = \frac{W_{csamo} \times G_s}{e_o} = \frac{31.1 \times 2.65}{1.018} = 81.0\ \%\ (81.0\ \%)^*$$

d) Volume of Sample(V_{olo}):

$$V_{olo} = D_{outo}^2 \times \pi / 4 \times H_{tsamo}$$
$$= 0.1690^2 \text{ ft} \times \pi / 4 \times 0.3353 \text{ ft}$$
$$= 0.00752 \text{ ft}^3 \ (0.00752 \text{ ft}^3)^*$$

e) Dry Weight of Sample(W_{tdry}):

$$W_{tdry} = W_{tsamo} / (1 + W_{csamo})$$
$$= 0.8080 \text{ lbs} / (1 + 0.311)$$
$$= 0.6163 \text{ lbs}$$

f) Volume of Solid(V_{solid}):

$$V_{solid} = W_{tdry} / (G_s \times \gamma_w)$$
$$= 0.6163 \text{ lbs} / (2.65 \times 62.4 \text{ lbs/ft}^3)$$
$$= 0.00373 \text{ ft}^3$$

4. Hand Calculations at Confinement Time = 1335 minutes:

a) Length of Sample(H_t):

$$H_t = H_{tsamo} - (V_{lvdt} - V_{lvdto}) \times F_{lvdt}$$
$$= 0.3353 \text{ ft} - (4.6219 - 3.242) \text{ volts} \times 0.0040263 \text{ ft/volt}$$
$$= 0.3297 \text{ ft}$$

b) Outer Diameter of Sample(D_{out}): (assuming isotropic strain for isotropic confinement)

$$D_{out} = D_{outo} \times (H_t / H_{tsamo})$$
$$= 0.1690 \text{ ft} \times (0.3297 \text{ ft} / 0.3353 \text{ ft})$$
$$= 0.1662 \text{ ft}$$

c) Volume of Sample(V_{olume}):

$$V_{olume} = D_{out}^2 \times H_t \times \pi / 4$$
$$= 0.1662^2 \text{ ft} \times 0.3297 \text{ ft} \times \pi / 4$$
$$= 0.00715 \text{ ft}^3$$

d) Total Weight of Sample(W_{eight}) (assuming S_r remains constant):

$$W_{eight} = W_{tsamo} - ((V_{olo} - V_{olume}) \times S_{rsamo} \times \gamma_w)$$
$$= 0.8080 \text{ lbs} - ((0.00752 \text{ ft}^3 - 0.00715 \text{ ft}^3) \times 0.809 \times 62.4 \text{ lbs/ft}^3)$$
$$= 0.7893 \text{ lbs}$$

* Numbers printed out in computer program.

QA:QA

e) Void Ratio(e):

$e = (Volume - V_{solid}) / V_{solid}$

$= (0.00715\ ft^3 - 0.00373\ ft^3) / 0.00373\ ft^3$

$= 0.917\ (0.919)$*

f) Shear Wave Velocity(V_s):

Mass Polar Moment of Inertia of Sample(I):

$I = Weight \times D_{out}^2 / (8 \times g)$

$= 0.7895\ lbs \times 0.1662^2\ ft^2 / (8 \times 32.2\ ft/sec^2)$

$= 0.00008464$ ft-lbs-sec^2

Mass Polar Moment of Inertia of Drive Plate and Top Cap(I_o):

$I_o = Dp + Tc = 0.00208760$ ft-lbs-sec^2 + 0.0000505614 ft-lbs-sec^2

$= 0.00213816$ ft-lbs-sec^2

$I / I_o = 0.00008464 / 0.00213816$

$= 0.03958385$

Solving for β from equation $I / I_o = \beta \times \tan\beta$

$\beta \approx 0.197654$

β(rad)	β ×tanβ
0.1970	0.03931896
0.1980	0.03972448
0.1975	0.03952145
0.1976	0.03956201
0.1977	0.03960260
0.19765	0.03958230
0.19766	0.03958636
0.197655	0.03958433
0.197654	0.03958393

Since $\beta = \omega_n \times H_t / V_s$ and for Small Damping Ratios, $f_n \approx f_r$

$Vs = (2 \times \pi \times f_r) \times H_t / \beta$

$= (2 \times \pi \times 101.529\ Hz) \times 0.3297\ ft / 0.197654$

$= 1064.1$ fps (1064 fps)*

g) Shear Modulus(G):

$G = \rho \times V_s^2$

$= (Weight / Volume \times g) \times V_s^2$

$= (0.7893\ lbs / (0.00715\ ft^3 \times 32.2\ ft/sec^2)) \times (1064.1\ fps)^2$

$= 3882$ ksf (3885 ksf)*

* Numbers printed out in computer program.

h) Shearing Strain, γ, %:

$$\gamma = C \times \gamma_{out} \times 100\ \%$$

where,

γ : Equivalent Shearing Strain of Specimen(%)

γ_{out} : Shearing Strain at the Outer Edge of Specimen(%)

$$C = \frac{r_{eq}}{r_{out}} = (\frac{2}{3} \text{ for a Solid Specimen})^{*+}$$

r_{eq} : Equivalent Radius of Specimen(ft)

r_{out} : Radius of Specimen(ft) for Solid Specimen $= \frac{D_{out}}{2}$

$$\gamma_{out} = \frac{z_{out}}{H_t}$$

where,

z_{out} : Horizontal Displacement at the Outer Edge of Specimen(ft)

H_t : Height of Specimen(ft)

$$z_{out} = \frac{r_{out} \times z_a}{r_a}$$

where,

r_{out} : Horizontal Radius of Specimen(ft)

z_a : Displacement at the Location of Accelerometer(ft)

r_a : Distance from the Center of Specimen to the Location of Accelerometer(ft) (= 2 in. = 0.1667ft)

$$\ddot{z}_a = \frac{\sqrt{2} \times (32.2\ \text{ft}/\text{sec}^2)/g \times \frac{V_a}{1000}}{F_{ac}}$$

where,

$\ddot{z}$: Acceleration of the Accelerometer(ft/sec^2)

V_a : Output Voltage(RMS) of the Accelerometer(mv)

g : Acceleration of Gravity (= 32.2 ft/sec^2)

F_{ac} : Calibration Factor of the Accelerometer($= 2.5234 \frac{v}{g}$)

$$\ddot{z}_a = z_a \times \omega^2$$

* Chen, A. T. F. and Stokoe, K. H., II (1979), "Interpretation of Strain-Dependent Modulus and Damping from Torsional Soil Tests," Report No. USGS-GD-79-002, NTIS No. PB-298479, U.S. Geological Survey, pp 46.

+ RC Test Version 2.1 and TS Test Version 3.1 use $\bar{C}$ = 0.82 to 0.79, depending upon the strain amplitude.

QA:QA

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$$\ddot{z}_a = z_a \times \left(2 \times \pi \times f_r\right)^2$$

where,

ω : Angular Frequency of the Specimen($= 2 \times \pi \times f_r$)
f_r : Resonant Frequency of Specimen(Hz).

$$z_a = \frac{\ddot{z}_a}{4 \times \pi^2 \times f_r^2}$$

$$z_a = \frac{\sqrt{2} \times 32.2 \times V_a}{2.5234} \times \frac{1}{4 \times \pi^2 \times f_r^2} \times 10^{-3}$$

$$z_{out} = \frac{r_{out}}{2/12} \times \frac{\sqrt{2} \times 32.2 \times V_a}{2.5234} \times \frac{1}{4 \times \pi^2 \times f_r^2} \times 10^{-3}$$

$$\gamma = \frac{2}{3} \times \frac{1}{H_t} \times \frac{D_{out}/2}{2/12} \times \frac{\sqrt{2} \times 32.2 \times V_a}{2.5234} \times \frac{1}{4 \times \pi^2 \times f_r^2} \times 10^{-1}\ \%$$

$$\gamma = \frac{2}{3} \times \frac{1}{0.3297} \times 3 \times 0.1662 \times \frac{\sqrt{2} \times 32.2 \times 111}{2.5234} \times \frac{1}{4 \times \pi^2 \times 101.529^2} \times 10^{-1}\ \%$$

$\gamma = 0.0004963\ \%\ (0.0004954\ \%)$*

i) Damping Ratio from Frequency Response Curve, D_{hp}:

Test results used for hand calculations to confirm computations of damping ratios by computer program, RCTEST, are taken from a different sample than used above because original data for Savannah River sample was only stored in terms of final results (not the complete response curve).

Hand Reading from Frequency Response Curve (See Fig. A. 12):

$A_{max} = 110.58$ mv(110.67 mv)*
$f_r = 84.6$ Hz(84.89Hz)*
$0.707\ A_{max} = (0.707 \times 110.58$ mv$) = 78.18$ mv
$f_1 = 83.8$ Hz (from recorded curve) at $0.707\ A_{max}$
$f_2 = 85.9$ Hz (from recorded curve) at $0.707\ A_{max}$

* Numbers printed out in computer program.

QA:QA

$$D_{hp} \cong \frac{f_2 - f_1}{2 \times f_r}$$

$$\cong \frac{85.9 - 83.8}{2 \times 84.6} \times 100\ \%$$

$$\cong 1.24\%(1.30\%)\ *$$

j) Damping Ratio from Free-Vibration Decay Curve, D_{fv}:

$$\delta = \ln\left(\frac{Z_1}{Z_2}\right)$$

$$D = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}}$$

where,
δ : Logarithmic Decrement
Z_1, Z_2 : Two Successive Peaks from Free-Vibration Decay Curve
D : Damping Ratio

No. of Cycle	Peak, Zi	Logarithmic Decrement	Damping Ratio, %
1	3.90	-	-
2	3.70	0.05264	0.84
3	3.35	0.09937	1.58
4	3.15	0.06156	0.98
5	2.75	0.13580	2.16
6	2.70	0.01835	0.29
7	2.40	0.11778	1.87
8	2.25	0.06454	1.03
9	2.10	0.06899	1.10
10	1.95	0.07411	1.18

Average Damping Ratio = 1.23 %(1.29 %)*

* Numbers printed out in computer program.

QA:QA

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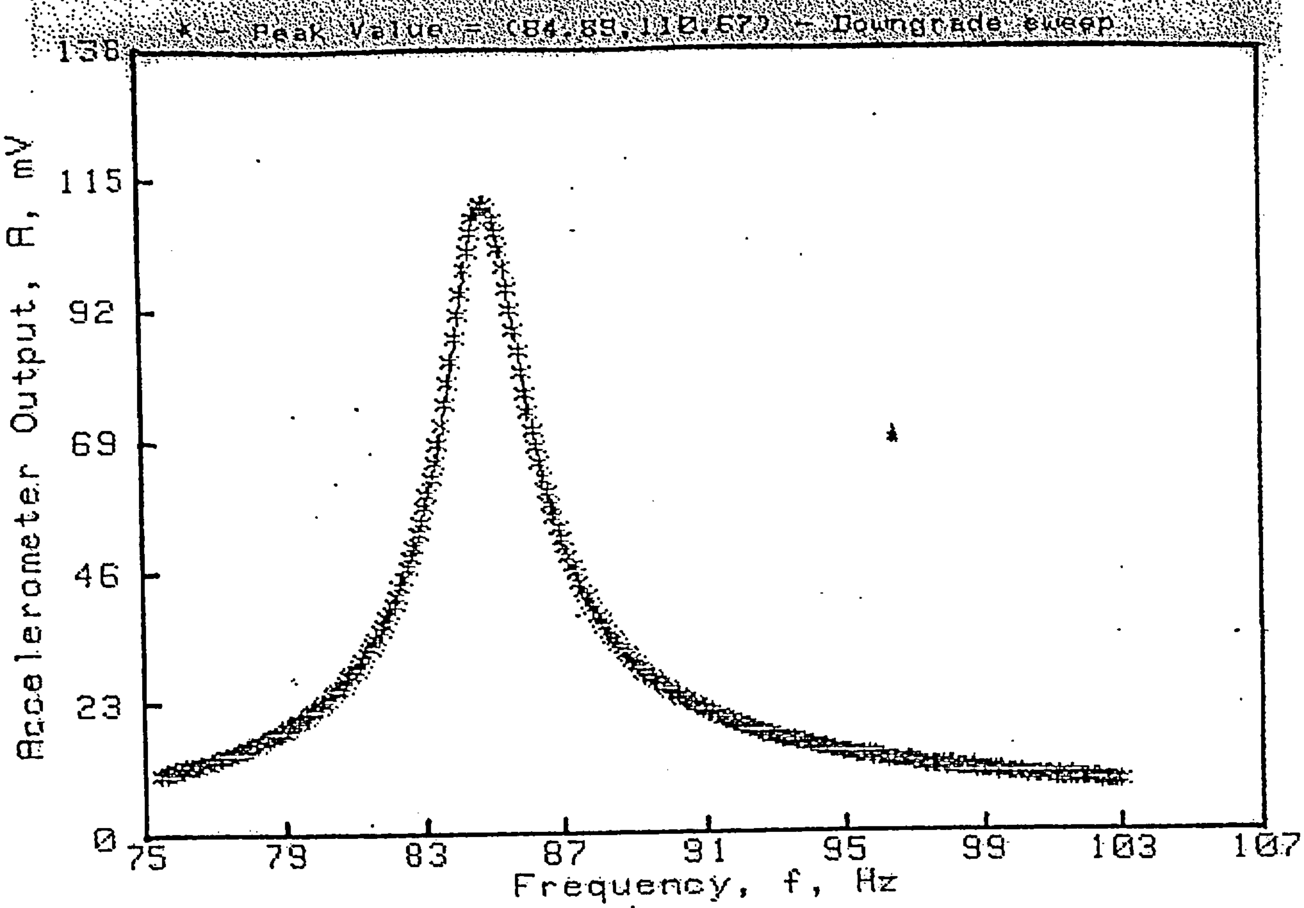

Fig. A.12 Frequency Response Curve

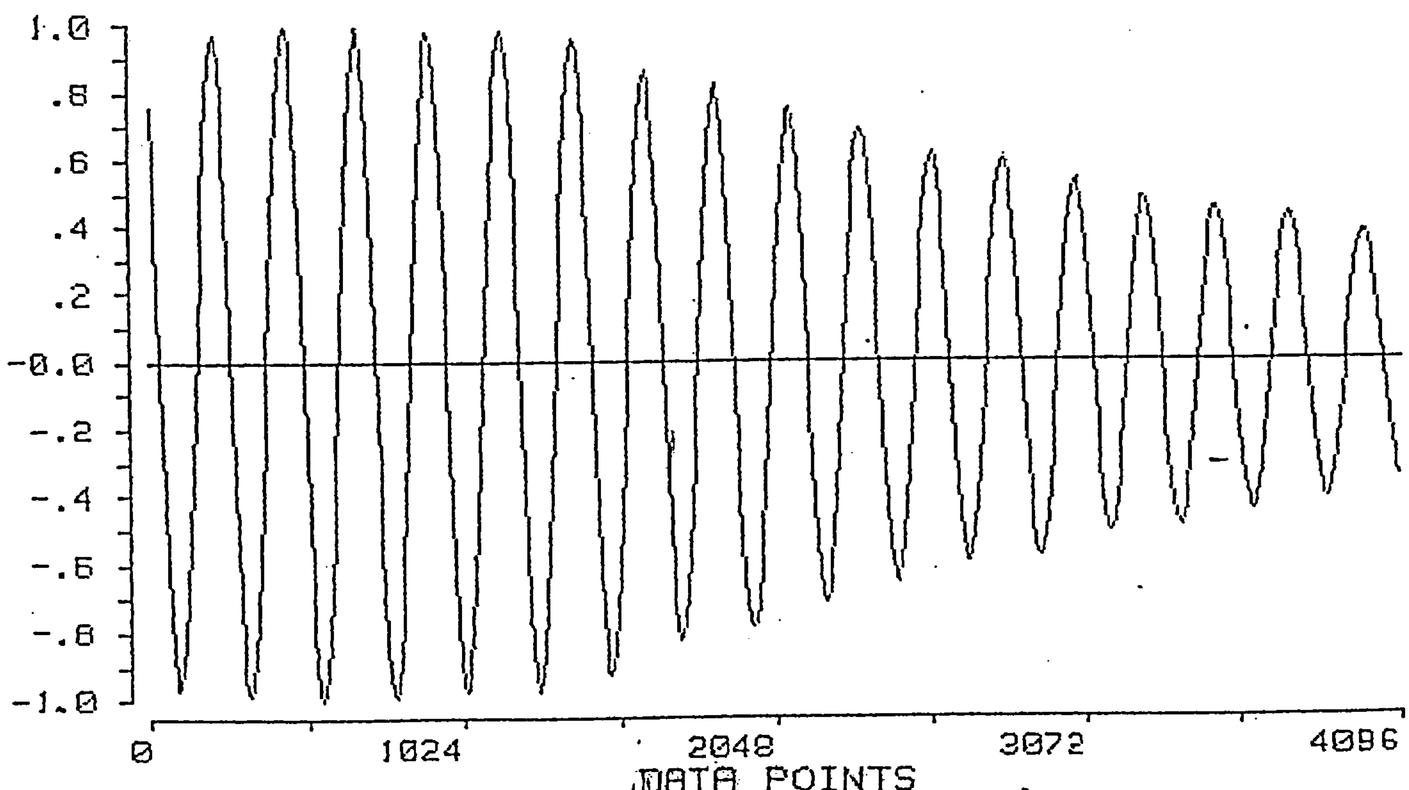

Fig. A. 13 Free-Vibration Decay Curve

QA:QA

Performed by: Jeon Keun Hwang
Checked by: K. H. Stokoe
Date: 20 Sept 93

B. Resonant Column Test Results: High-Amplitude Test($\gamma > 0.001\%$)

Test results used for confirming the computations performed by the computer program, RCTEST, are presented below. They were determined with a different specimen than those used in Section A (pp 61-68).

Depth : 25.5 ft (7.8 m)
Boring Number : CATAZ-1
Sample Number : 22
Test Number : UT43C
Confining Pressure : 62 psi
Type of Test Performed : High-Amplitude Resonant Column Test
Time : 1445 minutes

Test results (at a time of 1445 minutes after applying a confining pressure of 62 psi) performed by computer program "RCTEST" are as follows:

Measured by Computer Program:

a) Accelerometer Output = 6305.1 mv
b) Resonant Frequency, f_r = 65.016 Hz
c) LVDT Output = 2.460 volts

Measured by Hand:

a) Accelerometer Output = 6300 mv
b) Resonant Frequency, f_r = 65.0 Hz
c) LVDT Output = 2.460 volts

Calculated by Computer Program:

d) Void Ratio, e = 1.199
e) Shearing Strain, $\gamma = 7.025 \times 10^{-2}$ %
f) Shear Modulus, G = 1.891×10^3 ksf
g) Shear Wave Velocity, V_s = 739 fps
h) Damping Ratio from Free-Vibration Decay Curve = 3.92 %

1. Known Constants of Sample(Before Applying Isotropic Confining Pressure):

a) D_{outo} : Initial Outer Diameter of Sample
= 5.00 cm = 5.00(cm) / 2.54(cm/in.) / 12(in/ft) = 0.1640 ft

b) D_{into} : Initial Inner Diameter of Sample
= 0.0 cm = 0.0(cm) / 2.54(cm/in.) / 12(in/ft) = 0.0 ft

c) H_{tsamo} : Initial Height of Sample
= 9.61 cm = 9.61(cm) / 2.54(cm/in.) / 12(in/ft) = 0.3153 ft

d) W_{tsamo} : Initial Weight of Sample
= 318.5 gm = 318.5 (gm) / 453.6(gm/lbs) = 0.7022 lbs

e) W_{csamo} : Initial Water Content of Sample
= 55.2 %

f) G_s : Specific Gravity of Sample(Assumed)
= 2.72

g) V_{lvdto} : Initial LVDT Reading
= 5.4758 volts

QA:QA

2. Calibration Factors of Testing Device:

a) D_p : Mass Polar Moment of Inertia of Drive Plate No. 5
= 0.0021729 ft-lbs-sec^2**

b) T_c : Mass Polar Moment of Inertia of Top Cap No. 2 (Dia. = 2 in.)
= 0.0000506 ft-lbs-sec^2**

c) F_{ac} : Calibration Factor of Accelerometer No. 3879
= 2.5450 volts/g (for a Setting of 73.3 pcmb/g on Charge Amplifier No. 4102M)**

d) F_{lvdt} : Calibration Factor of LVDT No. 4
= 0.0043598 ft/volt **

3. Unknowns:

a) Dry Unit Weight, γ_d
b) Void Ratio, e_o and e
c) Initial Degree of Saturation, S_r
d) Shear Wave Velocity, V_s
e) Shear Modulus, G
f) Shearing Strain, γ
g) Damping Ratio from Free-Vibration Decay Curve, D_{fv}

4. Hand Calculations for Initial Conditions (Before any Confinement):

a) Dry Unit Weight, γ_d, pcf:

$$\gamma_d = \frac{\text{Dry Weight of Sample}}{\text{Volume of Sample}}$$

$$= \frac{\frac{W_{tsamo}}{(1+W_{csamo})}}{\text{Volume of Sample}}$$

$$= \frac{0.7022/(1+0.552)}{\pi \times 0.1640^2 \times 0.3153/4}$$

$$= 67.93 \text{ pcf } (67.95 \text{ pcf})^*$$

** RC Test Version 2.1 and TS Test Version 3.1 have new calibration factors.

D_p =	2.0630E-03 ft lb sec^2	
T_c =	5.09296E-05 ft lb sec^2	
F_{ac} =	SAME	(Accelerometer No. 3879 is not used.)
F_{lvdt} =	SAME	(LVDT No.4 is not used.)

b) Void Ratio, e_o:

$$e_o = \frac{G_s \times \gamma_w}{\gamma_d} - 1 = \frac{2.72 \times 62.4}{67.93} - 1 = 1.499 \ (1.499)^*$$

c) Degree of Saturation, S_{rsamo}, %:

$$S_{rsamo} = \frac{W_{csamo} \times G_s}{e_o} = \frac{55.2 \times 2.72}{1.499} = 100.2\ \% \ (100\ \%)^*$$

* Numbers printed out in computer program.

d) Volume of Sample(V_{olo}):

$$V_{olo} = D_{outo}^2 \times \pi / 4 \times H_{tsamo}$$
$$= 0.1640^2 \text{ ft} \times \pi / 4 \times 0.3153 \text{ ft}$$
$$= 0.00666 \text{ ft}^3 \ (0.00666 \text{ ft}^3)^*$$

e) Dry Weight of Sample(W_{tdry}):

$$W_{tdry} = W_{tsamo} / (1 + W_{csamo})$$
$$= 0.7022 \text{ lbs} / (1 + 0.552)$$
$$= 0.4524 \text{ lbs}$$

f) Volume of Solid(V_{solid}):

$$V_{solid} = W_{tdry} / (G_s \times \gamma_w)$$
$$= 0.4524 \text{ lbs} / (2.72 \times 62.4 \text{ lbs/ft}^3)$$
$$= 0.00267 \text{ ft}^3$$

4. Hand Calculations at a Confinement Time = 1445 minutes:

a) Length of Sample(H_t):

$$H_t = H_{tsamo} - (V_{lvdt} - V_{lvdto}) \times F_{lvdt}$$
$$= 0.3153 \text{ ft} - (5.4758 - 2.460) \text{ volts} \times 0.0043598 \text{ ft/volt}$$
$$= 0.3022 \text{ ft}$$

b) Outer Diameter of Sample(D_{out}) (Assuming Isotropic Strain for Isotropic Confinement):

$$D_{out} = D_{outo} \times (H_t / H_{tsamo})$$
$$= 0.1640 \text{ ft} \times (0.3022 \text{ ft} / 0.3153 \text{ ft})$$
$$= 0.1572 \text{ ft}$$

c) Volume of Sample(V_{olume}):

$$V_{olume} = D_{out}^2 \times H_t \times \pi / 4$$
$$= 0.1572^2 \text{ ft} \times 0.3022 \text{ ft} \times \pi / 4$$
$$= 0.00587 \text{ ft}^3$$

d) Total Weight of Sample(W_{eight}) (Assuming S_r Remains Constant):

$$W_{eight} = W_{tsamo} - ((V_{olo} - V_{olume}) \times S_{rsamo} \times \gamma_w)$$
$$= 0.7022 \text{ lbs} - ((0.00666 \text{ ft}^3 - 0.00587 \text{ ft}^3) \times 1.0 \times 62.4 \text{ lbs/ft}^3)$$
$$= 0.6529 \text{ lbs}$$

e) Void Ratio(e):

$$e = (V_{olume} - V_{solid}) / V_{solid}$$
$$= (0.00587 \text{ ft}^3 - 0.00267 \text{ ft}^3) / 0.00267 \text{ ft}^3$$
$$= 1.199 \ (1.199)^*$$

f) Shear Wave Velocity(V_s):

Mass Polar Moment of Inertia of Sample(I):

$$I = W_{eight} \times D_{out}^2 / (8 \times g)$$
$$I = 0.6529 \text{ lbs} \times 0.1572^2 \text{ ft}^2 / (8 \times 32.2 \text{ ft/sec}^2)$$
$$I = 0.0000626 \text{ ft-lbs-sec}^2$$

* Numbers printed out in computer program.

QA:QA

P.O.# A17376YS0A

Mass Polar Moment of Inertia of Drive Plate and Top Cap(I_O):

$I_O = Dp + Tc = 0.0021729$ ft-lbs-sec^2 + 0.0000506 ft-lbs-sec^2

$I_O = 0.0022235$ ft-lbs-sec^2

$I / I_O = 0.0000626 / 0.0022235$

$I / I_O = 0.0281538$

Solving for β from equation $I / I_O = \beta \times \tan \beta$

$\beta \approx 0.1670408$

β(rad)	β ×tanβ
0.170	0.0291817
0.1675	0.0283216
0.1673	0.0282534
0.1672	0.0282193
0.1671	0.0281852
0.16705	0.0281682
0.16704	0.0281648
0.16700	0.0281512
0.167005	0.0281529
0.167008	0.0281539

Since $\beta = \omega_n \times H_t / V_s$ and for Small Damping Ratios, $f_n \approx f_r$

$V_s = (2 \times \pi \times f_r) \times H_t / \beta$

$= (2 \times \pi \times 65.016 \text{ Hz}) \times 0.3022 \text{ ft} / 0.1670408$

$= 739.2$ fps (739 fps)*

g) Shear Modulus(G):

$G = \rho \times V_s^2$

$= (\text{Weight} / \text{Volume} \times g) \times V_s^2$

$= (0.6529 \text{ lbs} / (0.00587 \text{ ft}^3 \times 32.2 \text{ ft/sec}^2)) \times (739 \text{ fps})^2$

$= 1887$ ksf (1891 ksf)*

h) Shearing Strain, γ, %:

$$\gamma = \frac{2}{3} \times \frac{1}{H_t} \times \frac{D_{out}/2}{2/12} \times \frac{\sqrt{2} \times 32.2 \times V_a}{2.5450} \times \frac{1}{4 \times \pi^2 \times f_r^2} \times 10^{-1}\ \% \ ^+$$

$$= \frac{2}{3} \times \frac{1}{0.3022} \times 3 \times 0.1572 \times \frac{\sqrt{2} \times 32.2 \times 6305.1}{2.5450} \times \frac{1}{4 \times \pi^2 \times 65.016^2} \times 10^{-1}\ \%$$

$= 0.07033$ % (0.07025 %)*

* Numbers printed out in computer program.

+ RC Test Version 2.1 and TS Test Version 3.1 use C = 0.82 to 0.79, depending upon the strain amplitude.

QA:QA
P.O.# A1737EYS-A

j) Damping Ratio from Free-Vibration Decay Curve, D_{fv} (See Fig. A.14):

$$\delta = \ln\left(\frac{Z_1}{Z_2}\right)$$

$$D_{fv} = \sqrt{\frac{\delta^2}{4\pi^2 + \delta^2}}$$

where,

δ : Logarithmic Decrement

Z_1; Z_2 : Two Successive Peaks from Free-Vibration Decay Curve

D : Damping Ratio

No. of Cycle	Peak, Zi	Logarithmic Decrement	Damping Ratio, %
1	82	-	-
2	67	0.2020	3.21
3	52	0.2534	4.03
4	40	0.2624	4.17
5	34	0.1625	2.59
6	30	0.1252	1.99
7	24	0.2231	3.55
8	19	0.2336	3.72

Average Damping Ratio of First Three Cycles = 3.80 %(3.92 %)*

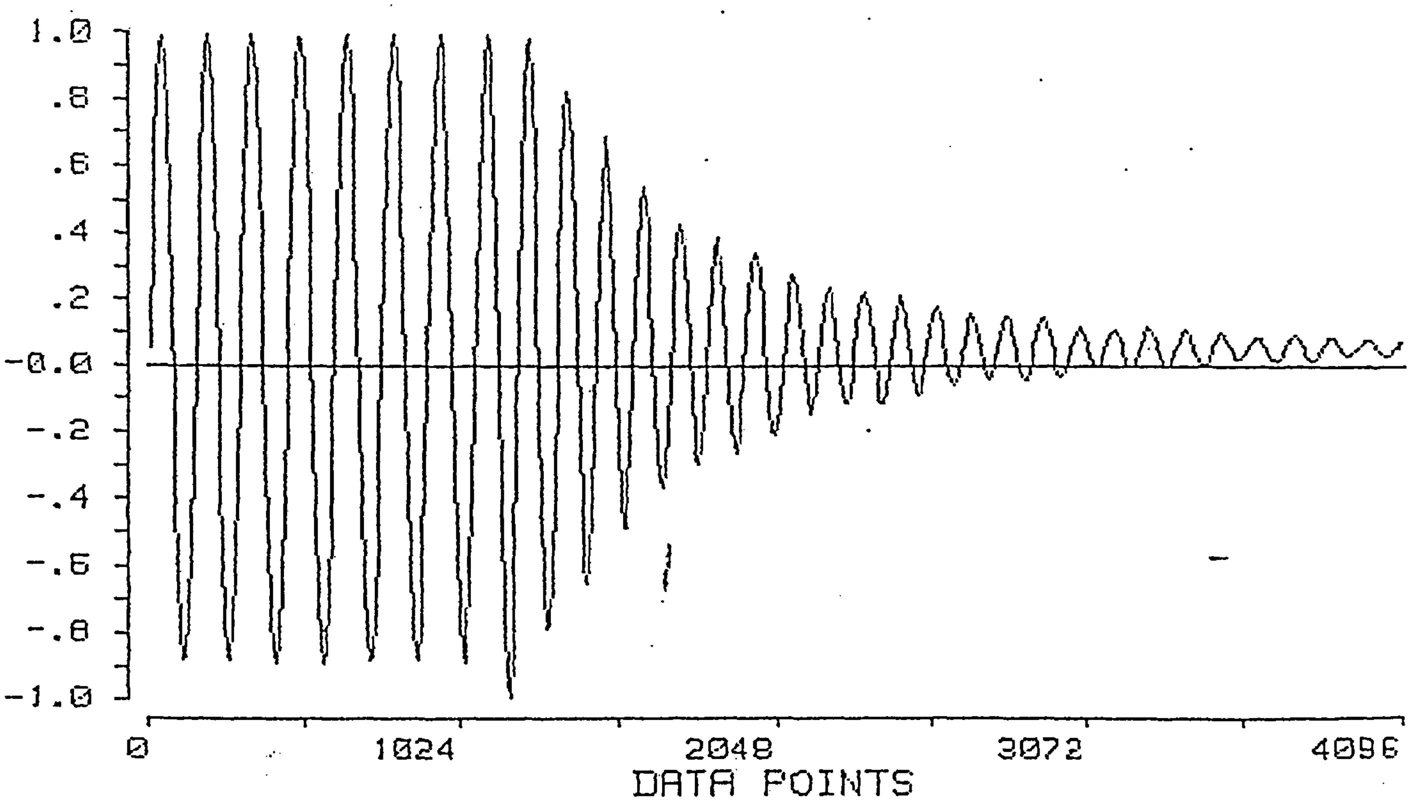

Fig. A. 14 Free-Vibration Decay Curve

* Numbers printed out in computer program.

Performed by: [signature]
Checked by: [signature]
Date: 20 Sept. 93

C. Torsional Shear Test Results

Test results used for confirming the computations performed by the computer program, TSTEST, are presented below.

Depth : 25.5 ft (7.8 m)
Boring Number : CATAZ-1
Sample Number : 22
Test Number : UT43C71
Confining Pressure : 20.8 psi
Type of Test Performed : Torsional Shear Test
Time : 1520 minutes

1. Calculated by Computer Program:
   a) Shear Strain, $\gamma = 4.47 \times 10^{-2}$ %
   b) Shear Modulus, $G = 1.333 \times 10^3$ ksf
   c) Damping Ratio from Hysteretic Loop = 4.20 %

2. Known Constants of Sample(Before Applying Isotropic Confining Pressure):

   a) D_{outo} : Initial Outer Diameter of Sample
   = 4.998 cm = 4.998(cm) / 2.54(cm/in.) / 12(in/ft) = 0.1640 ft

   b) D_{into} : Initial Inner Diameter of Sample
   = 0.0 cm = 0.0(cm) / 2.54(cm/in.) / 12(in/ft) = 0.0 ft

   c) H_{tsamo} : Initial Height of Sample
   = 9.610 cm = 9.610(cm) / 2.54(cm/in.) / 12(in/ft) = 0.3153 ft

   d) W_{tsamo} : Initial Weight of Sample
   = 318.5 gm = 318.5 (gm) / 453.6(gm/lbs) = 0.7022 lbs

   e) W_{csamo} : Initial Water Content of Sample
   = 55.2 %

   f) G_s : Specific Gravity of Sample(Assumed)
   = 2.72

   g) V_{lvdto} : Initial LVDT Reading
   = 5.4758 volts

   h) Settings on the Nicolet Oscilloscope = 20 msec
   Time per Point = 20 msec
   Voltage Range for Proximitor Signal, V_a = ± 4 volts
   Voltage Range for Input Signal, V_b = ± 40 volts

* RC Test Version 2.1 and TS Test Version 3.1 have new calibration factors.
K_p = 6.0143E-04 rad/V
K_t = 6.9802E-03 ft lb/V
F_{lvdt} = SAME (LVDT No.4 is not used.)

3. Calibration Factors of Testing Device:

   a) Proximitor Calibration Factor, K_p = 1.33909E-03 rad/volt *
   b) Torque Calibration Factor, K_t = 1.48830E-02 ft-lbs/volt *
   c) Calibration Factor of LVDT No. 4, F_{lvdt} = 0.0043598 ft/volt *

4. Unknowns:
   a) Shear Modulus, G
   b) Shearing Strain, γ
   c) Damping Ratio from Hysteretic Loop, D

5. Hand Calculations for Initial Conditions:

   a) Dry Unit Weight, γ_d, pcf:

$$\gamma_d = \frac{\text{Dry Weight of Sample}}{\text{Volume of Sample}}$$

$$= \frac{\dfrac{W_{tsamo}}{(1+W_{csamo})}}{\text{Volume of Sample}}$$

$$= \frac{0.7022/(1+0.552)}{\pi \times 0.1640^2 \times 0.3153/4}$$

$$= 67.93 \text{ pcf } (67.95 \text{ pcf})^*$$

   b) Void Ratio, e_o:

$$e_o = \frac{G_s \times \gamma_w}{\gamma_d} - 1 = \frac{2.72 \times 62.4}{867.93} - 1 = 1.499\ (1.499)^*$$

   c) Degree of Saturation, S_{rsamo}, %:

$$S_{rsamo} = \frac{W_{csamo} \times G_s}{e_o} = \frac{55.2 \times 2.72}{1.499} = 100.2\%\ (100\ \%)^*$$

   d) Volume of Sample(V_{olo}):

$$V_{olo} = D_{outo}^2 \times \pi / 4 \times H_{tsamo}$$
$$= 0.1640^2 \text{ ft} \times \pi / 4 \times 0.3153 \text{ ft}$$
$$= 0.00666 \text{ ft}^3\ (0.00666 \text{ ft}^3)^*$$

   e) Dry Weight of Sample(W_{tdry}):

$$W_{tdry} = W_{tsamo} / (1 + W_{csamo})$$
$$= 0.7022 \text{ lbs} / (1 + 0.552)$$
$$= 0.4520 \text{ lbs}$$

   f) Volume of Solid(V_{solid}):

$$V_{solid} = W_{tdry} / (G_s \times \gamma_w)$$
$$= 0.4520 \text{ lbs} / (2.72 \times 62.4 \text{ lbs/ft}^3)$$
$$= 0.00266 \text{ ft}^3$$

* Numbers printed out in computer program.

QA:QA

6. Hand Calculations at Confinement Time = 1520 minutes:

a) Length of Sample(H_t):

$$H_t = H_{tsamo} - (V_{lvdt} - V_{lvdto}) \times F_{lvdt}$$
$$= 0.3153 \text{ ft} - (5.4758 - 4.0292) \text{ volts} \times 0.0043598 \text{ ft/volt}$$
$$= 0.3090 \text{ ft}$$

b) Outer Diameter of Sample(D_{out}) (Assuming Isotropic Strain for Isotropic Confinement):

$$D_{out} = D_{outo} \times (H_t / H_{tsamo})$$
$$= 0.1640 \text{ ft} \times (0.3090 \text{ ft} / 0.3153 \text{ ft})$$
$$= 0.1607 \text{ ft}$$

c) Volume of Sample(V_{olume}):

$$V_{olume} = D_{out}^2 \times H_t \times \pi/4$$
$$= 0.1607^2 \text{ ft}^2 \times 0.3090 \text{ ft} \times \pi/4$$
$$= 0.00627 \text{ ft}^3$$

d) Total Weight of Sample(W_{eight}) (Assuming S_r Remains Constant):

$$W_{eight} = W_{tsamo} - ((V_{olo} - V_{olume}) \times S_{rsamo} \times \gamma_w)$$
$$= 0.7022 \text{ lbs} - ((0.00666 \text{ ft}^3 - 0.00627 \text{ ft}^3) \times 1.0 \times 62.4 \text{ lbs/ft}^3)$$
$$= 0.6779 \text{ lbs}$$

e) Void Ratio(e):

$$e = (V_{olume} - V_{solid}) / V_{solid}$$
$$= (0.00627 \text{ ft}^3 - 0.00266 \text{ ft}^3) / 0.00266 \text{ ft}^3$$
$$= 1.357$$

f) Area Polar Moment of Inertia, J_p

$$J_p = \pi \times D_{out}^4 / 32$$
$$= \pi \times 0.1607^4 \text{ ft}^4 / 32$$
$$= 6.5473 \times 10^{-5} \text{ ft}^4$$

g) Shear Modulus, G:

From Fig. A. 15,

Max. Output Applied to the Coils,	A_{cmax} = 1991 units*
Min. Output Applied to the Coils,	A_{cmin} = -2003 units
Max. Output from the Proximitors,	A_{pmax} = 793 units
Min. Output from the Proximitors,	A_{pmin} = -772 units

Actual Voltage Readings are:

$$V_{cmax} = A_{cmax} / 2000 \times V_b = 1991/2000 \times 40 = 39.82 \text{ volts}$$
$$V_{cmin} = A_{cmin} / 2000 \times V_b = -2003/2000 \times 40 = -40.06 \text{ volts}$$
$$V_{pmax} = A_{pmax} / 2000 \times V_a = 793/2000 \times 4 = 1.586 \text{ volts}$$
$$V_{pmin} = A_{pmin} / 2000 \times V_a = -772/2000 \times 4 = 1.544 \text{ volts}$$

* The output from the Nicolet Oscilloscope is represented by 12 bits over the complete voltage range (± X volts). For the voltage to the coils, the voltage range setting was ± 40 volts. The Nicolet uses 2000 units for 0 to + 40 volts and 2000 points for 0 to -40 volts.

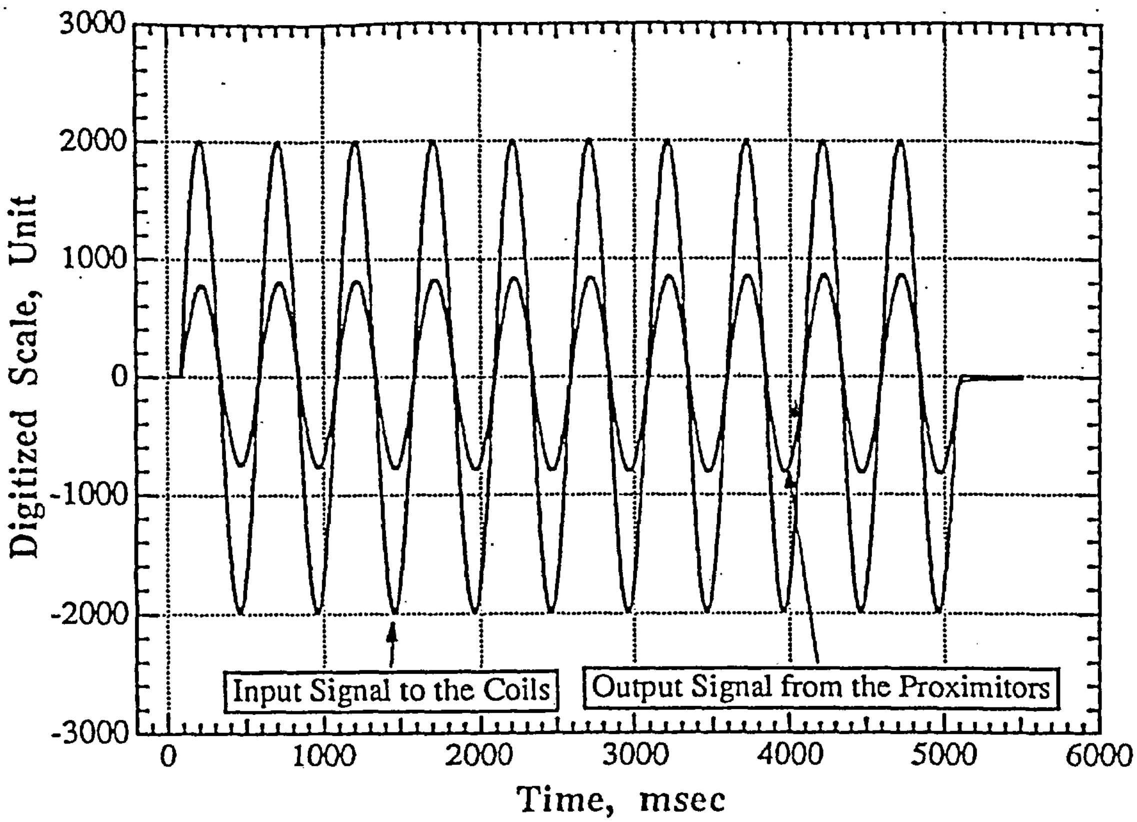

Fig. A. 15 Digitized Output Signals from Proximitors and Coils in Time Domain

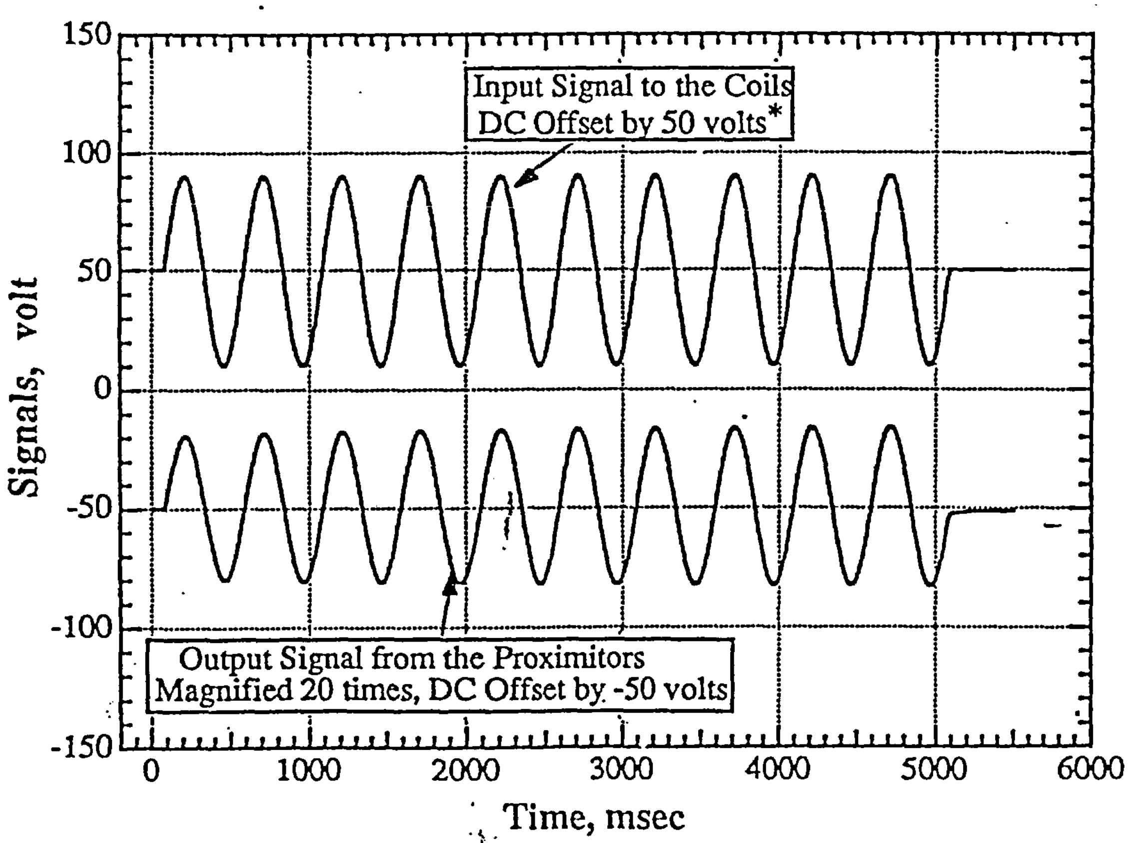

Fig. A. 16 Signals in Time Domain Obtained from TSTEST

* See Note at the Bottom of Page 78

Applied Torque and Resulting Twist:

$$Torque_{max} = V_{cmax} \times K_t$$
$$= 39.82 \text{ volts} \times 0.014883 \text{ ft-lbs/volt}$$
$$= 0.59264 \text{ ft-lbs}$$

$$Torque_{min} = V_{cmin} \times K_t$$
$$= -40.06 \text{ volts} \times 0.014883 \text{ ft-lbs/volt}$$
$$= -0.59621 \text{ ft-lbs}$$

$$Twist_{max} = V_{pmax} \times K_p$$
$$= 1.586 \text{ volts} \times 0.0013391 \text{ rad/volt}$$
$$= 0.0021238 \text{ rad}$$

$$Twist_{min} = V_{pmin} \times K_p$$
$$= -1.544 \text{ volts} \times 0.0013391 \text{ rad/volt}$$
$$= -0.0020676 \text{ rad}$$

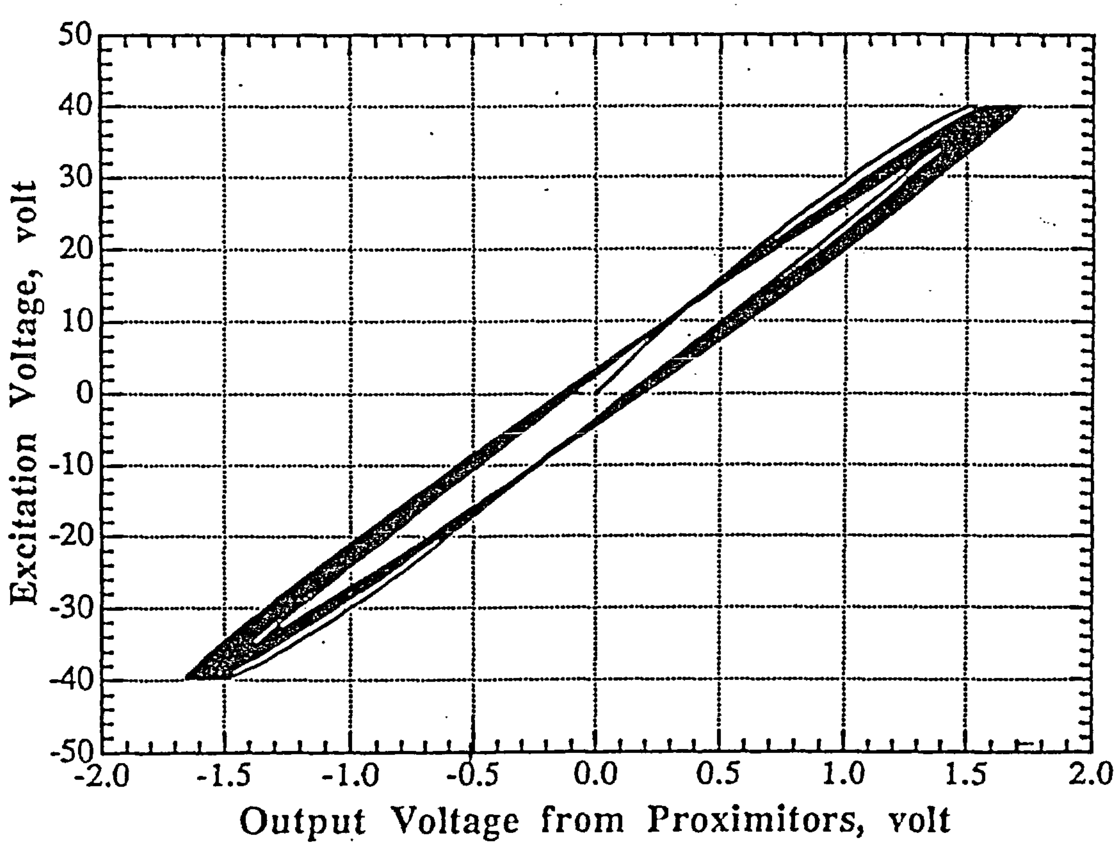

Fig. A. 17 Hysteretic Loops of Ten Cycles of TSTEST

* The DC offset was simply added in the computer program used to display the records for ease in viewing the two traces.

QA:QA

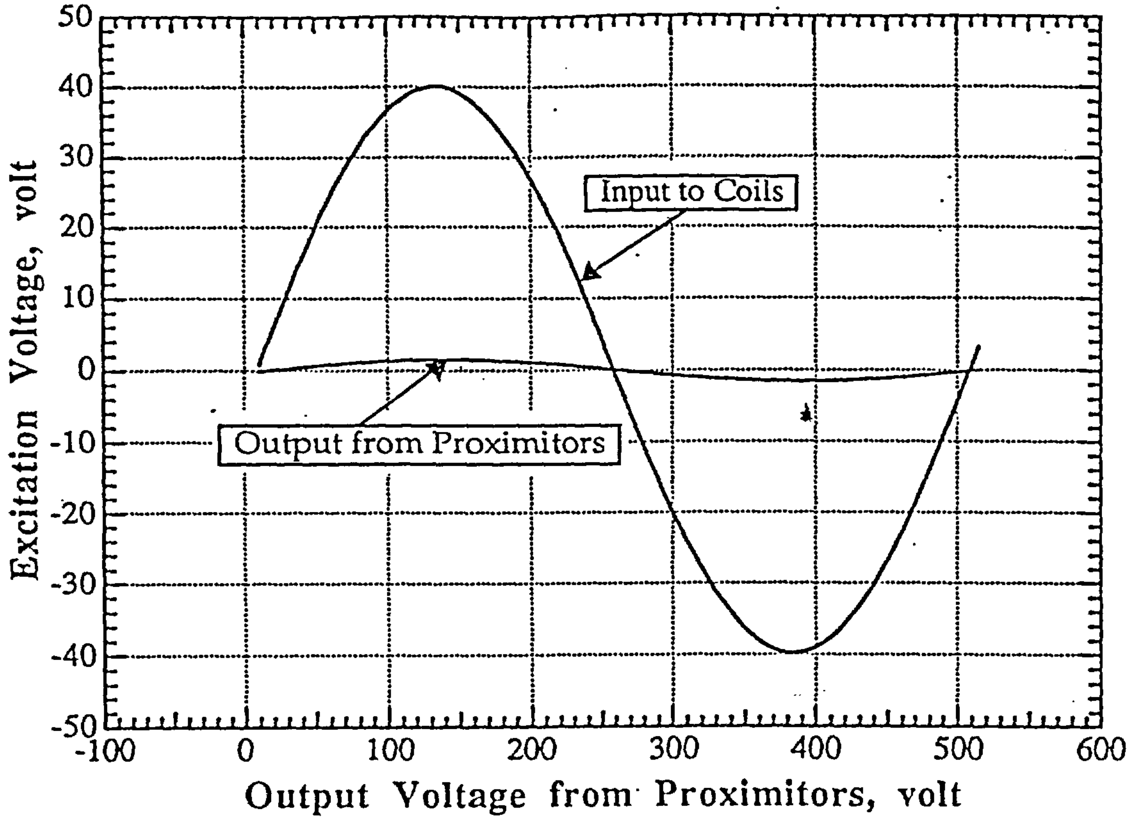

Fig. A. 18 Second Cycle Output Signals from Proximitors and Coils in Time Domain

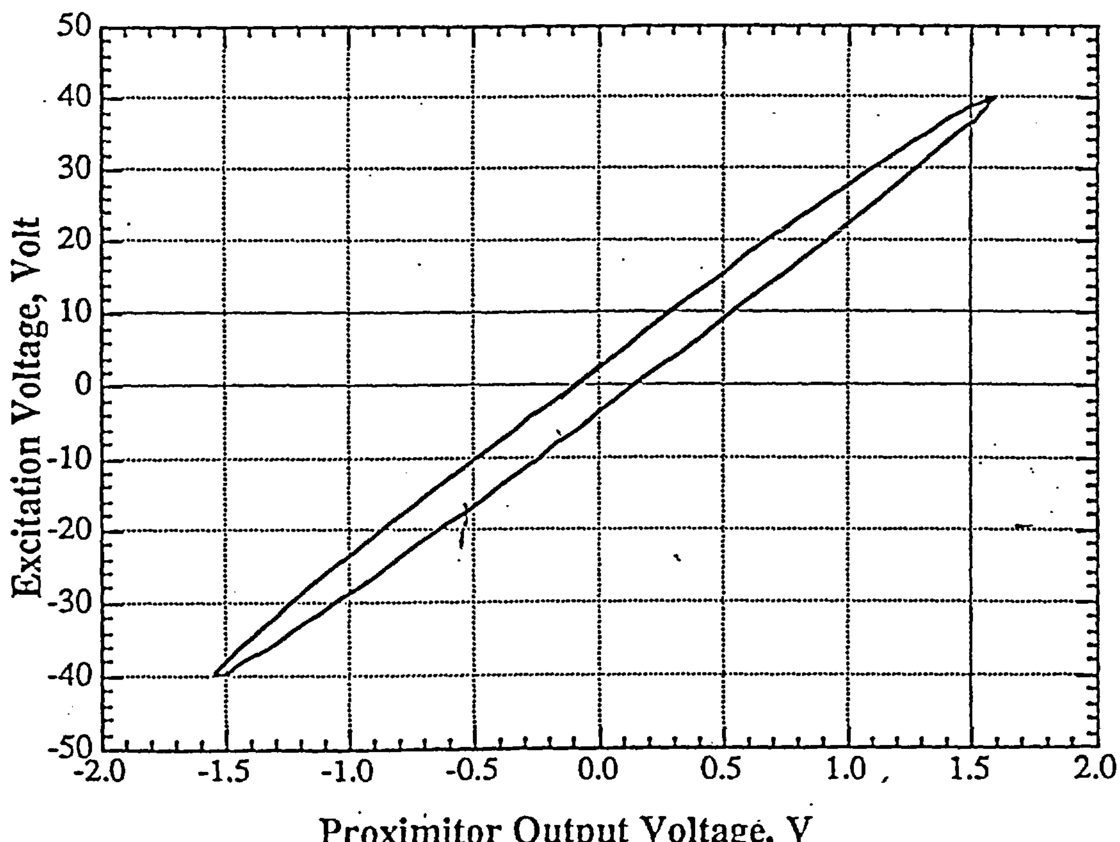

Fig. A. 19 Hysteretic Loop of Second Cycle from Torsional Shear Test

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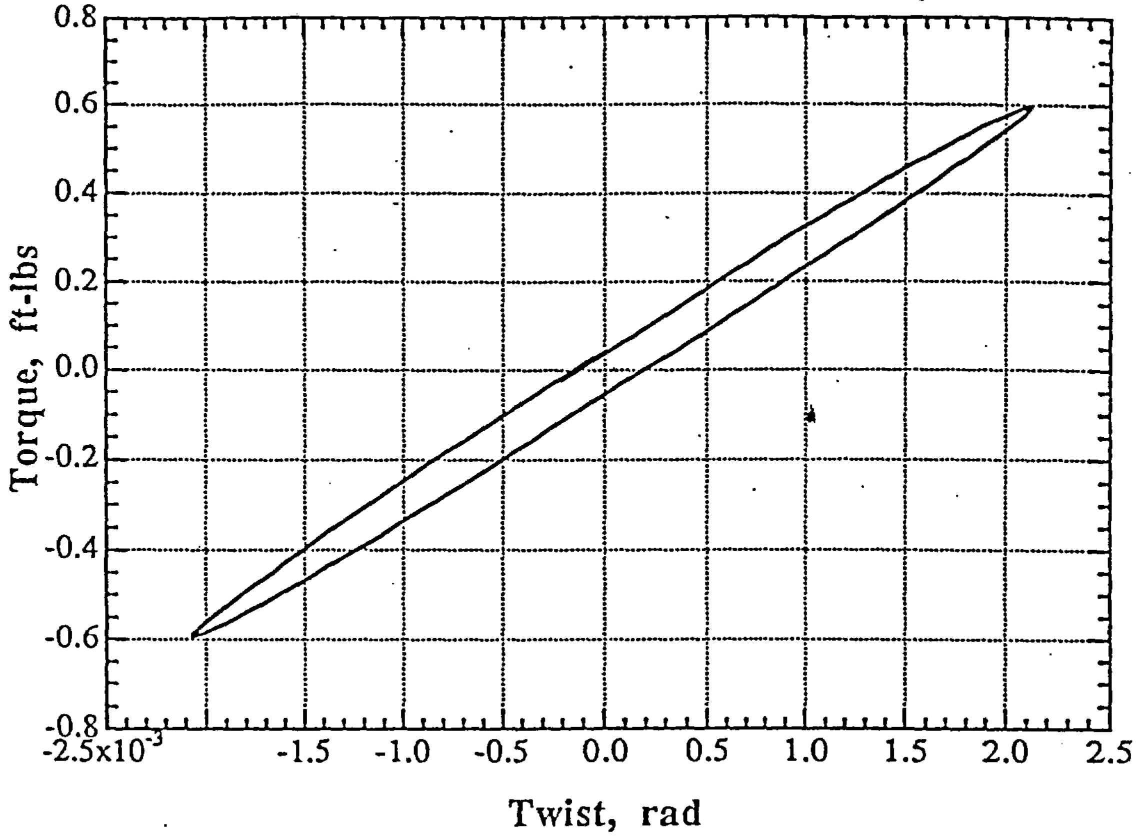

Fig. A. 20 Torque versus Twist of Second Cycle from Torsional Shear Test

Since Equivalent Radius, $r_{eq} = 0.82^{*} \times r_{out}$ where, $r_{out} = D_{out} / 2$

$$\tau_{max} = Torque_{max} \times 0.82 \times (D_{out} / 2) / J_p$$
$$= 0.59264 \text{ ft-lbs} \times 0.82 \times (0.1607 \text{ ft} / 2) / (6.5473 \times 10^{-5} \text{ ft}^4)$$
$$= 596.39 \text{ psf}$$

$$\tau_{min} = Torque_{min} \times 0.82 \times (D_{out} / 2) / J_p$$
$$= -0.59621 \text{ ft-lbs} \times 0.82 \times (0.1607 \text{ ft} / 2) / (6.5473 \times 10^{-5} \text{ ft}^4)$$
$$= -599.98 \text{ psf}$$

$$\gamma_{max} = Twist_{max} \times 0.82 \times (D_{out} / 2) / H_t$$
$$= 0.0021238 \text{ rad} \times 0.82 \times (0.1607 \text{ ft} / 2) / 0.3090 \text{ ft}$$
$$= 0.0004529$$

$$\gamma_{min} = Twist_{min} \times 0.82 \times (D_{out} / 2) / H_t$$
$$= -0.0020676 \text{ rad} \times 0.82 \times (0.1607 \text{ ft} / 2) / 0.3090 \text{ ft}$$
$$= -0.0004409$$

* Chen, A. T. F. and Stokoe, K. H., II (1979), "Interpretation of Strain-Dependent Modulus and Damping from Torsional Soil Tests," Report No. USGS-GD-79-002, NTIS No. PB-298479, U.S. Geological Survey, pp 46.

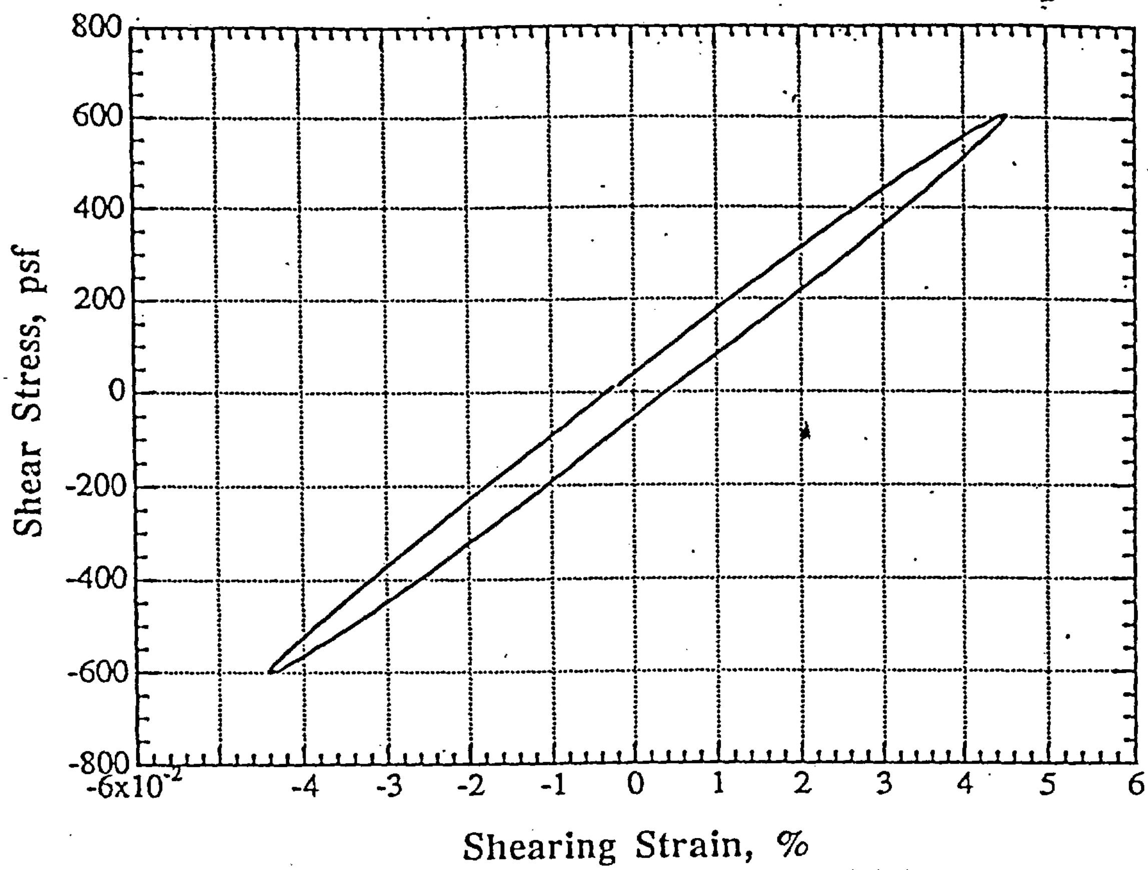

Fig. A. 21 Stress versus Strain of Second Cycle from Torsional Shear Test

Therefore, Shear Modulus, G and Shearing Strain, γ:

$$G = \tau_{max} / \gamma_{max}$$
$$= (596.39 + 599.98) \text{ psf} / (0.0004529 + 0.0004409)$$
$$= 1339 \text{ ksf } (1333 \text{ ksf})^*$$

$$\gamma = (0.0004529 + 0.0004409) / 2$$
$$= 0.0004469 \times 100 \%$$
$$= 0.0447 \% \ (0.0447\%)^*$$

b) Damping Ratio from Hysteretic Loop, D:

$$D = \frac{W_d}{(4 \times \pi \times W_s)}$$

where, W_d = Energy Dissipated in One Cycle of Loading

W_s = Peak Strain Energy Stored in the Specimen

From the Hysteretic Loop Shown in Fig. A. 22 ← correction Feb. 2, 99

W_d = ~~113~~ 226 units area

W_s = 426 units area

$$D = \frac{226}{(4 \times \pi \times 426)} = 4.22 \% (4.20 \%)^*$$

* Numbers printed out in computer program.

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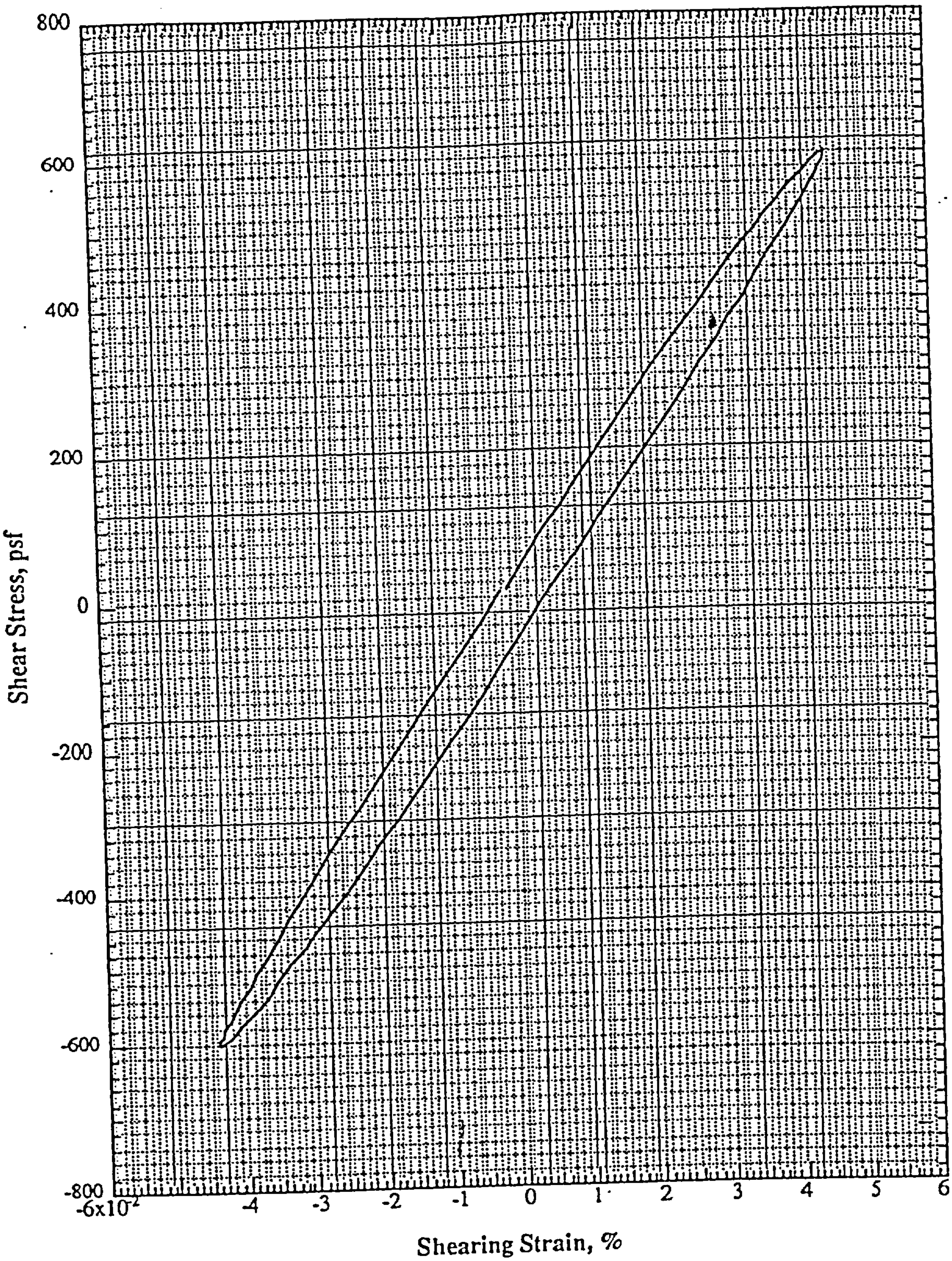

Fig. A. 22 Expanded Hysteretic Loop (Shown in Fig. A. 21) for Damping Ratio Calculation

ATTACHMENT 4

TYPICAL OUTPUT FROM RCTEST *

RESONANT COLUMN TEST - SOIL DYNAMICS LABORATORY - UNIVERSITY OF TEXAS AT AUSTIN

------------- PROGRAM RCTEST Version 1.0 -------------

DATE: 21 MAY 1993 TIME: 0:40: 1
Title: UT390--SAVANNAH RIVER(T-5B)--861FT--GRAY SHALE/CLAYEY SILT
Pressure level no. = 9 Confining Pressure Pc = 215.1 psi
Pressure Gage No. : 2
LVDT: Input = 4.7695 Volts Output = 4.9074 Volts

Frequency Sweep to Determine Resonant Frequency and Damping:
Input Voltage: RMS = 128.000 mV PEAK-TO-PEAK = 181.019 mV
Rough max accel output = 190.2 mV, Freq. = 309.780 Hz, Period = 3.228 mSec
Fine max. accel. output = 192.150 mV, Freq. = 306.053Hz, Period = 3.267 mSec
Damping Ratio (by Half Power Method) = 1.261 %

Damping Ratio From The Free Vibration Decay Curve At Resonance (306.053 Hz):

Peak No.= 17, , No of peak points for cal. Dr = 8
989 881 784 705 644 594 557 521
496
Correlation = -.9910 Damping Ratio = 1.2982 %
Peak No.= 16, , No of peak points for cal. Dr = 7
988 875 782 705 641 599 554 524
Correlation = -.9935 Damping Ratio = 1.3597 %
Peak No.= 16, , No of peak points for cal. Dr = 7
982 879 783 706 641 593 554 522
Correlation = -.9931 Damping Ratio = 1.3809 %
The avg. Damping Ratio is 1.346 %

Time min.	Cell Pres. psi	LVDT Output V	Max Ac Output mV	Reson. Frequency Hz	Void Ratio	Shear Strain %	Shear Modulus psf	Damping FV %	Damping HP %	Vs fps
102	215.1	4.9074	192	306.053	.349	9.908E-05	3.003E+07	1.35	1.26	2722

* New version (Version 2.1) of RC Test with updated calibration factors is used. Calculations and output format with this version are identical as previous version.

Q4:QA
PO# A17870

ATTACHMENT 5

TYPICAL OUTPUT FROM TSTEST*

```
oximity Calibration Factor =  1.33909E-03 rad/volt
rque Calibration Factor =  1.48830E-02 ft-lb/volt
DT Calibration Factor =      .0043598 inch/volt
equency is     .50  Hz     The number of cycles =   2.00

oothing 0 Times
x. Strain =2.743227E-04      Max. Stress =9.81003E+00 psf
00032918
1.7720311796
.47652454752E-5    -.297761248049
equency is          .5            Hz
Max. Strain =       .000274322718565 %
IEAR MODULUS =      3.570222E+6 psf
MPING RATIO =       .809 %
```

```
               ********************************
                SUMMARY OF TORSIONAL SHEAR TEST
               ********************************

 @ Austin -- Geotech. Eng. -- Soil Dynamics Lab. ** 20 MAR 1993,  15:48:39
39G--SAVANNAH RIVER(PS13)--283.5FT--GRAY SAND WITH SILT
essure Level No. 5 : (Pa,Pb,Pc) = (93,93,93)psi.

LE NAME IS :        UT39G3_A
```

Fr	Cyc	Str(%)	G(psf)	Dr(%)	Str(%)	G(psf)	.Dr(%)	Str(%)	G(psf)	Dr(%)
.50	1	2.76E-04	3.556E+06	0.00	2.76E-04	3.563E+06	0.00	2.76E-04	3.569E+06	0.00
.50	2	2.74E-04	3.570E+06	.81	2.74E-04	3.579E+06	.81	2.73E-04	3.588E+06	.81
.50	3	2.74E-04	3.577E+06	1.19	2.74E-04	3.582E+06	1.19	2.73E-04	3.590E+06	1.18
.50	4	2.77E-04	3.534E+06	.39	2.76E-04	3.547E+06	.39	2.75E-04	3.556E+06	.39
.50	5	2.74E-04	3.591E+06	.86	2.73E-04	3.588E+06	.86	2.73E-04	3.593E+06	.86
.50	6	2.77E-04	3.534E+06	.68	2.75E-04	3.548E+06	.67	2.74E-04	3.558E+06	.67
.50	7	2.77E-04	3.549E+06	.31	2.75E-04	3.561E+06	.30	2.74E-04	3.571E+06	.30
.50	8	2.76E-04	3.573E+06	.72	2.76E-04	3.565E+06	.72	2.75E-04	3.570E+06	.72
.50	9	2.77E-04	3.537E+06	.85	2.77E-04	3.541E+06	.85	2.76E-04	3.546E+06	.85
.50	10	2.76E-04	3.557E+06	.82	2.75E-04	3.570E+06	.83	2.74E-04	3.577E+06	.84

* New version (Version 3.1) of TS Test with updated calibration factors is used. Calculations and output format with this version are identical as previous version. This new version also prints the version number in the output.

ATTACHMENT 6

The University of Texas at Austin - Soil Dynamics Laboratory
Resonant Column and Torsional Shear Test

Project No. ________________ Test No. __________ Sample No. __________
Performed by________________________ Date ________________
Checked by ________________________ Date ________________

Site Location : ______________________ Date Started : ______________
Sample Depth : ______________________ Boring Number : ______________
Cell No. : __________ Visual Sample Classification : ______________
Drive Plate No.: ____ LVDT No. : ___ Top Cap No. : ______ Accel. No. : _____
Proximitor No. : ____ Pressure Gage No. : ______________________

Water Content Determination Proximitor Reading(Y/R)

	Top	Sides	Bottom
Tare Number			
Weight of Tare (g)			
Weight of Tare + Wet Soil(g)			
Weight of Tare + Dry Soil(g)			
Weight of Water (g)			
Weight of Dry Soil (g)			
Water Content, %			
Average Water Content, %			

$$\overline{\sigma}_m = \frac{(1+2K_o)}{3}\{h_w \gamma_t + (h_t - h_w)(\gamma_t - \gamma_w)\}$$

Weight of Sample + Mold (g) = ____________________
Weight Mold (g) = ____________________________
Weight of Sample before testing (g) = ______________

Dimension of Sample before Testing

	Height (cm)	Outside Dia. (cm)	Isotropic Confining Pressure, σ_0, psi								
0° or Top											
120° or Middle			RC-LAT								
240° or Bottom			TS								
Average			RC-HAT								

Specific Gravity : ________ Density : ________ Initial LVDT Reading (V) : __________
Seating Pressure Applied (Vacuum) : _________psi

Description of Specimen and Comments

QA:QA

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UTACED

ATTACHMENT 7

The University of Texas at Austin - Soil Dynamics Laboratory
Torsional Shear Test

Project No. ______________ Test No. __________ Sample No. __________
Performed by______________________ Date ______________
Checked by ______________________ Date ______________

Site Location : ______________________ Boring Number : ______________
Sample Depth : ______________________ Proximitor No. : ______________
Confining Pressure = ____________ psi Cell No. : __ Drive Plate No.: __
LVDT No. : __ Top Cap No. : __ Proximitor No. : __ Pressure Gage No. : ______

File Name	Fr (Hz)	Input Volt. (V)	No. of Cycles	Cut-off Fr. (Hz)		Amplification Set.		Voltage Range Set.		Time per point	Shear Strain 10^{-3} %	Shear Mod. (ksf)	Damp. Ratio (%)
				CH1	CH2	CH1	CH2	CH1	CH2				

P.O.# A17376YS0A

ATTACHMENT 8

List of Equipment Used in RC and TS Tests

Item	Manufacturer and Model No.	Serial No.
Computer	HP Vectra 4865/33M	UT634243
Oscilloscope	Nicolet Model 201	UT337671
Operational Amplifier	Tektronix AM 501	UT309931
Digital Signal Filter	Wavetek System 716	UT416434
Function Generator	HP 3314A	UT389812
Universal Counter	HP 5334A	UT388338
Digital Multimeter	HP 3458A	UT507070
Power Supply Amplifier	HP 6824A	UT337824
Printer	HP 82906A	UT386400
Multimeter	HP 3478A	UT405096
Switch/control Unit	HP 3488A	UT390474
Regulated Power Supply	Lambda Model LL-902-OV	UT408705
Proximitor	Bently Nevada 20929-01	UT328827
Proximitor	Bently Nevada 20929-01	UT328828
DC-Shifter	Univ. of Texas	-
Pressure Gage (No. 1)	Heise CM-34677 (0-150psi)	-
Pressure Gage (No. 2)	Ashcroft (0-100psi)	UT279327
Pressure Gage (No. 4)	Ashcroft (0-600psi)	UT289551
Vacuum Gage (No. 5)	Heise CM-60750 (0- -14psi)	UT409547
Vacuum Pump	J/B Industries, Inc.	UT004252
Pressure Regulators	Fairchild	-
Pressure Regulators	Tescom Model 44-2200	-
LVDTs	Columbia Model SH-200-S3R	-
Accelerometer (No. 1)	Columbia Model 302-6	3878
Accelerometer (No. 2)	Columbia Model 302-6	2919
Accelerometer (No. 3)	Columbia Model 302-6	2963
Accelerometer (No. 4)	Columbia Model 302-6	3877
Accelerometer (No. 5)	Columbia Model 302-6	3879
Accelerometer (No. 6)	Columbia Model 302-6	3873
Charge Amplifier	Columbia Model 4102M	-

COMMENTS ON REVISIONS

Revision 0 – Contained a total of 70 pages and was dated 30 March 93.

Revision 1 – Contains a total of 88 pages and is dated 20 September 98.

a. page 1 – new set of signatures for Revision 1.
b. pages 2 to 32 – no changes.
c. pages 33 to 60 – Attachments 1 and 2 replaced pages 32 to 66 of Revision 0. These pages are the new write-up for the user's guide to programs RCTEST and TSTEST and eliminate any reference to the "mainframe" computer, update the interactive messages, and eliminate the hand calculations (verification) part.
d. pages 60 to 82 – Attachment 3, "Hand Calculations." Replaces pages 53 to 56 of Revision 0.
e. page 83 – Attachment 4 replaces page 67 of Revision 0. Shows Version 1 of computer program on the print-out and also lists the gage number used in each test.
f. page 84 – Attachment 5 replaces page 68 of Revision 0 Same as page 68 of Revision 0 except for attachment number.
g. page 85 – Attachment 6 replaces page 69 of Revision 0. Updated version of original page 69.
h. page 86 – Attachment 7 replaces page 70 of Revision 0. Updates version of original page 70.
i. page 87 – Attachment 8 is a new list of equipment with UT serial numbers.
j. page 88 – Comments on revisions.

Revision 2 – Contains a total of 88 pages and is dated 20 January 99.

a. page 1 – in the title replace "Testing of Intact Soil Samples" with "Testing of Soil and Rock Samples."
b. page 2 - in the title replace "Testing of Intact Soil Samples" with "Testing of Soil and Rock Samples."
c. page 2 – line 3, replace "intact soil specimens" with "soil and rock specimens."
d. page 2 – Fig. 1, replace "Soil Specimen, I" with "Specimen, I."
e. page 8 – Fig. 6, replace "Soil" with "Specimen."
f. page 8 – line 2, replace "soil" with "specimen."
g. page 9 – Section 2.4 line 1, delete the word "soil."
h. page 10 – Section 2.5, line 1, delete the word "soil."
i. page 10 – last paragraph, line 1, replace "soils" with "soil and rock specimens."
j. page 12 - after Eq. 1., replace "I_s = ... soil" with "I_s = ...specimen."
k. page 13 – line below Eq. 3, replace "soil" with "specimen."
l. page 13 – Section 3.3, line 4, replace "soil" with "specimen."
m. page 13 – last paragraph, line 1, replace "soils" with "soil and rock specimens."
n. page 14 – Fig. 11, replace "Soil Specimen" with "Specimen."
o. page 14 - title of Fig. 11, replace "Soil" with "RCTS Specimen."
p. page 17 – Section 4.0, line 2, replace "soil" with "soil or rock specimens."
q. page 20 – line 1, replace "soils, material" with "soil or rock materials."
r. page 22 – paragraph 3, line 2, replace "soil" with "soil or rock."
s. page 22 – last paragraph, line 5, "soil" with "soil or rock."

QA:QA

P.O.# A17376YS0A

APPENDIX A

Additional Material Accompanying

Procedure PBRCTS-1

QA:QA

Checklist for Setting Up A Reconstituted Soil Specimen for RCTS Testing

Project No.____________ Test No.________ Sample No.________

Performed by____________________ Date__________________

Checked by_____________________ Date__________________

Preparing Specimen

_____ 1. Clean base pedestal, porous stone (if required), and base plate.

_____ 2. Place base pedestal on base plate and secure using screws. Ensure that drainage holes on pedestal and plate are correctly aligned.

_____ 3. Saturate all water lines to the base of the sample (if required).

_____ 4. Coat the sides of the top cap and base pedestal with vacuum grease.

_____ 5. Place membrane on base pedestal and carefully place O-ring seal.

_____ 6. Place compaction mold around base pedestal while holding membrane vertically. Secure compaction mold to the base pedestal.

_____ 7. Carefully roll membrane over top of compaction mold.

_____ 8. Apply vacuum to expand the membrane against the compaction mold.

_____ 9. Prepare water content cans, and fill out initial data sheet (Attachment 5).

_____ 10. Remove desired soil sample.

_____ 11. Compact a specimen in three to five lifts on the base pedestal following the undercompaction method (Reference Ladd (1978)). Record the weight of sample used to construct the specimen.

_____ 12. Place top cap and roll membrane up the sides of the top cap.

_____ 13. Apply a small seating vacuum pressure of about 1 to 2 psi to the sample and detach the compaction mold.

_____ 14. Using the O-ring expander, place O-rings around the top cap and base pedestal to seal the membrane.

_____ 15. Add an additional membrane and O-rings to the sample (if necessary).

_____ 16. Visually inspect to ensure that the reconstituted specimen is intact.

_____ 17 Weigh some soil sample for water content measurement and return unused portion of the soil sample to control area (return water content sample to control area after getting the water content).

_____ 18. Measure the height of the sample using a cathometer in three different places. Measure the diameter of the sample in three places using a pi-tape.

QA:QA

Checklist – Reconstituted Soil Specimen Set-Up

Assembling the Cell

_____ 19. Clean and apply vacuum grease the bottom of the inside of the fluid chamber and install (if required). Apply vacuum grease to the base of the chamber on the outside.

_____ 20. Pour silicon fluid around the sample (if required).

_____ 21. Affix the RCTS ring stand to the base plate with appropriate screws.

_____ 22. Align the screw holes of the drive plate with those of the top cap and gently tighten the four securing screws.

_____ 23. Carefully and accurately center the magnets in the drive coils and secure the coil plate by tightening the two securing screw plate screws.

_____ 24. Attach proximitor target to drive plate and proximitors to the fixed post. Adjust proximitors to correct distance from target (voltage = 7.0 v ±0.1 v).

_____ 25. Attach LVDT to the fixed post, properly align, and adjust the height of the core to an output voltage of 4.0 v ±0.1 v.

_____ 26. Clean and grease the confining chamber sealing O-ring in the base plate. Place the confining chamber onto the base plate.

_____ 27. Attach all electrical connections through the confining chamber and obtain an initial LVDT reading. Run small strain RC test to ensure equipment is in working order. Visually inspect the resonance and vibration decay curves.

_____ 28. Clean and grease the confining chamber O-ring and attach the top plate to the confining chamber. Screw in the four (or eight) locking rods to the base plate and tighten the bolts to secure the confining cell.

_____ 29. Apply required confinement and begin RCTS testing, as described on the RCTS Test Procedures Checklist.

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Checklist for Setting Up An Intact Rock Specimen for RCTS Testing

Project No.__________ Test No._______ Sample No.______
Performed by_______________ Date______________
Checked by_______________ Date______________

Preparing Specimen

_____ 1. Clean base pedestal and base plate.

_____ 2. Place base pedestal on base plate and secure using screws. Ensure that drainage holes on the side of the pedestal are unobstructed.

_____ 3. Saturate all water lines to the base of the sample (if required).

_____ 4. Coat the sides of the top cap and base pedestal with vacuum grease.

_____ 5. Place membrane in the membrane spreader, prepare water content cans, (if required) prepare carrying mold (if required) and fill out initial data sheet (Attachment 5).

_____ 6. Remove desired rock sample.

_____ 7. Select an intact portion of the sample via visual inspection.

_____ 8. Core a specimen with appropriate core bit if a smaller diameter specimen is desired. Use air as the lubricant.

_____ 9. Re-label subdivided sample parts and return unused portion of the rock sample to control area.

_____ 10. Visually inspect to ensure that specimen is undisturbed and intact.

_____ 11. Place specimen in appropriate rock saw and trim excess material from ends. Use air as the lubricant.

_____ 12. Again, visually inspect sample to ensure that it is undisturbed and intact.

_____ 13 Weigh shavings from the side, top, and bottom of the trimmed specimen for water content measurements (if required) and return unused portion of the rock sample to control area (return water content sample to control area after getting the water content).

_____ 14. Measure the height of the sample in three different places using a micrometer. Measure the diameter of the sample in three places using a pi-tape.

_____ 15. Weigh sample before placing sample on base pedestal.

_____ 16. Place epoxy on the ends of the base pedestal and top cap and immediately place specimen.

_____ 17. Secure a strip of filter paper around the base of the sample and the base pedestal to prevent membrane puncture. Repeat this procedure at the junction of the top of the specimen and the top cap.

Checklist – Rock Specimen Set-Up

_____ 18. Apply a vacuum to the membrane expander and place membrane over the specimen. Gently detach the membrane from the expander.

_____ 19. Apply a small seating vacuum pressure of about 1 to 2 psi to the sample.

_____ 20. Using the O-ring expander, place O-rings around the top cap and base pedestal to seal the membrane.

_____ 21. Add an additional membrane and O-rings to the sample (if necessary).

_____ 22. Allow epoxy to dry for about 30 minutes before commencing further setup or dynamic testing

Assembling the Cell

_____ 23. Clean and apply vacuum grease the bottom of the inside of the fluid chamber and install (if required). Apply vacuum grease to the base of the chamber on the outside.

_____ 24. Pour silicon fluid around the sample (if required).

_____ 25. Affix the RCTS ring stand to the base plate with appropriate screws.

_____ 26. Align the screw holes of the drive plate with those of the top cap and gently tighten the four securing screws.

_____ 27. Carefully and accurately center the magnets in the drive coils and secure the coil plate by tightening the two securing screw plate screws.

_____ 28. Attach proximitor target to drive plate and proximitors to the fixed post. Adjust proximitors to correct distance from target (voltage = 7.0 v $\pm$0.1 v).

_____ 29. Attach LVDT to the fixed post, properly align, and adjust the height of the core to an output voltage of 4.0 v $\pm$0.1 v.

_____ 30. Clean and grease the confining chamber sealing O-ring in the base plate. Place the confining chamber onto the base plate.

_____ 31. Attach all electrical connections through the confining chamber and obtain an initial LVDT reading. Run small strain RC test to ensure equipment is in working order. Visually inspect the resonance and vibration decay curves.

_____ 32. Clean and grease the confining chamber O-ring and attach the top plate to the confining chamber. Screw in the four (or eight) locking rods to the base plate and tighten the bolts to secure the confining cell.

_____ 33. Apply required confinement and begin RCTS testing, as described on the RCTS Test Procedures Checklist.

QA:QA

Equipment List for Resonant Column and Torsional Shear Testing

Item	Manufacturer and Model No.	Serial No.
Computer	HP Vectra 486s/33M	3325S02509
Oscilloscope	Nicolet Model 201	UT337671
Operational Amplifier	Tektronix AM 501	UT309931
Digital Signal Filter	Wavetek System 716	UT416434
Function Generator	HP 3314A	2141A02471
Universal Counter	HP 5334A	2350A00797
Digital Multimeter	HP 3458A	2823A12370
Power Supply Amplifier	HP 6824A	UT337824
Printer	HP 82906A	UT386400
Multimeter	HP 3478A	UT405096
Multimeter	HP 3478A	UT405098
Switch/control Unit	HP 3488A	UT390474
Regulated Power Supply	Lambda Model LL-902-OV	UT408705
Proximitor	Bently Nevada 20929-01	50525
Proximitor	Bently Nevada 20929-01	92111
DC-Shifter	Univ. of Texas	-
Pressure Gage (No. 1)	Heise CM-34677 (0-150psi)	-
Pressure Gage (No. 2)	Ashcroft (0-100psi)	UT279327
Pressure Gage (No. 3)	Ashcroft (0-100psi)	UT315924
Pressure Gage (No. 4)	Ashcroft (0-600psi)	UT289551
Vacuum Gage (No. 5)	Heise CM-60750 (0- -14psi)	UT409547
Vacuum Pump	J/B Industries, Inc.	UT004252
Pressure Regulators	Fairchild	-
Pressure Regulators	Tescom Model 44-2200	-
LVDT	Columbia Model SH-200-S3R	7907
LVDT	Columbia Model SH-200-S3R	77002
Accelerometer (No. 1)	Columbia Model 302-6	3878
Accelerometer (No. 2)	Columbia Model 302-6	2919
Charge Amplifier	Columbia Model 4102M	480
Weight Balance	Sauter RC 4021hp	UT617925

* Current equipment list is presented in Appendix B on page B-3.

QA:QA

Equipment List for Resonant Column and Torsional Shear Calibration

Item	Manufacturer and Model No.	Calibration No
Universal Counter	HP 5334A	006518
Digital Multimeter	HP 3458A	006626
Dynamic Signal Analyzer	HP 3562A	006642
Accelerometer	Columbia Model 3021	998953
Charge Amplifier	Columbia Model 4102M	998954
Differential Pressure Transducer	Validyne DP 15-48	998955
Mulichannel Carrier Demodulator	Validyne CD 280-2	998955
Gage Blocks	Webber	991194
Calibration Weight Set	Troemner (1g - 100g)	991195
Calibration Weight	Ohaus (200 g)	991196
Calibration Weight	Ohaus (500 g)	991198
Calibration Weight	Ohaus (1 kg)	991199
Calibration Weight	Ohaus (2 kg)	993464

* Current calibration equipment list is presented in Appendix B on page B-4.

List of Calibration Factors Used in Resonant Column and Torsional Shear Testing

Item (Serial No.)	New Calibration Factor
LVDT (7907)	3.799E-03 ft/V
LVDT (77002)	4.389E-03 ft/V
Accelerometer (3878)	2.518 pkV/g
Accelerometer (2919)	2.894 pkV/g
I of Drive Plate No. 4	2.09673E-03 ft Ib sec^2
I of Drive Plate No. 5	2.05714E-03 ft Ib sec^2
I of 1.5 in. Stainless Steel Top Cap	4.62155E-05 ft Ib sec^2
I of 1.5 in. Aluminum Top Cap	1.61770E-05 ft Ib sec^2
I of 2.0 in. Stainless Steel Top Cap	7.28132E-05 ft Ib sec^2
I of 2.0 in. Aluminum Top Cap	5.09296E-05 ft Ib sec^2
I of 2.5 in. Stainless Steel Top Cap	1.778732E-04 ft Ib sec^2
Proximitor of Drive Plate (No. 4)	9.4604E-04 rad/V
Proximitor of Drive Plate (No. 5)	1.01354E-03 rad/V
Torque of Drive Plate (No. 4)	7.62695E-03 ft Ib/V
Torque of Drive Plate (No. 5)	7.09663E-03 ft Ib/V

* Current calibration factors is presented in Appendix B on page B-5.

QA:QA

COMMENTS ON REVISIONS

Revision 3 – Contains a total of 88 pages plus Appendix A (A-1 through A-9) and is dated 8 March 99.

a. page 1 – Added "Plus Appendix A (A-1 through A-9)" in footer.
b. page 62 – item 2; a, b, c, and d, added "**" for footnote to indicate the new calibration factors in RC Test Version 2.0 and TS Test Version 3.0.
c. page 65 – line 6, added "+" for footnote to indicate the change in calculation of equivalent shearing strength in RC Test Version 2.0 and TS Test Version 3.0.
d. page 70 - item 2; a, b, c, and d, added "**" for footnote to indicate the new calibration factors in RC Test Version 2.0 and TS Test Version 3.0.
e. page 72 - line 18, added "+" for footnote to indicate the change in calculation of equivalent shearing strength in RC Test Version 2.0 and TS Test Version 3.0.
f. page 74 - item 3; a, b, and c, added "*" for footnote to indicate the new calibration factors in RC Test Version 2.0 and TS Test Version 3.0.
g. page 81 – line 3 from bottom of page; typing error corrected by Dr. K.H. Stokoe on 2 February 1999.
h. page 83 – line 2, "*" added for footnote to indicate change in printout showing the new version number of RC Test (Version 2.0).
i. page 84 - line 2, "*" added for footnote to indicate change in printout showing the version number of TS Test (Version 3.0).
j. pages A-1 to A-9 – Appendix A added.

APPENDIX B

Additional Material Accompanying

Procedure PBRCTS-1

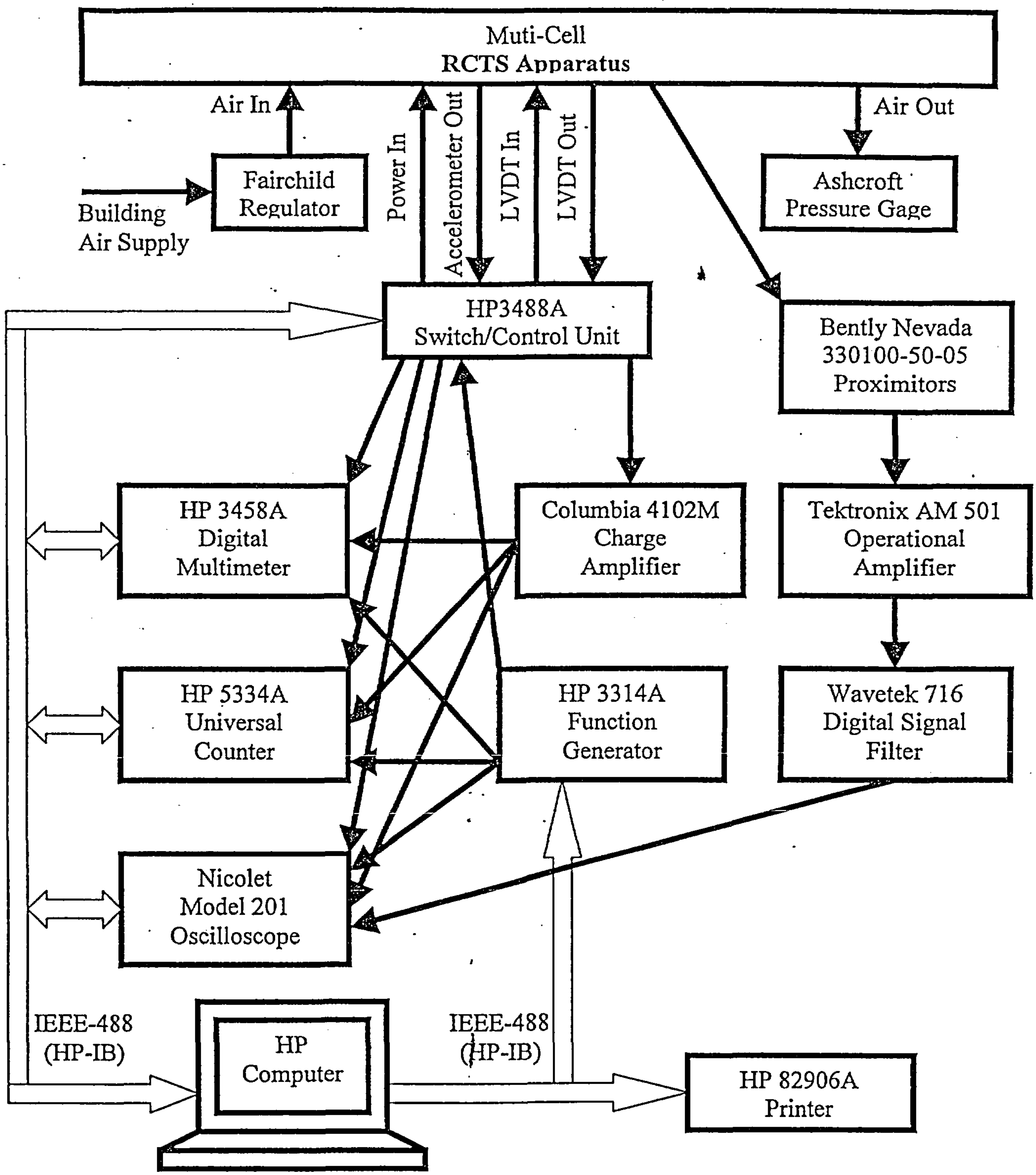

Figure B.1 – Configuration of Computerized RCTS Test Equipment

QA:QA

EQUIPMENT LIST FOR RESONANT COLUMN AND TORSIONAL SHEAR TESTING

Item	Manufacturer and Model No.	Serial No.
Computer	HP Vectra 486s/33M	3325S02509
Oscilloscope	Nicolet Model 201	UT337671
Operational Amplifier	Tektronix AM 501	UT309931
Digital Signal Filter	Wavetek System 716	UT416434
Function Generator	HP 3314A	2141A02471
Universal Counter	HP 5334A	2350A00797
Digital Multimeter	HP 3458A	2823A12370
Power Supply Amplifier	HP 6824A	UT337824
Printer	HP 82906A	UT386400
Multimeter	HP 3478A	UT405096
Multimeter	HP 3478A	UT405098
Switch/control Unit	HP 3488A	UT390474
Regulated Power Supply	Lambda Model LL-903	UT238462
Proximitor	Bently Nevada 330100-50-05	FEB G106073
Proximitor	Bently Nevada 330100-50-05	FEB G106076
DC-Shifter	Univ. of Texas	-
Pressure Gage (No. 1)	Ashcroft (0-100psi)	UT279327
Pressure Gage (No. 2)	Ashcroft (0-600psi)	UT289551
Vacuum Gage (No. 3)	Heise CM-60750 (0- -14psi)	UT409547
Vacuum Pump	J/B Industries, Inc.	UT004252
Pressure Regulators	Fairchild	-
Pressure Regulators	Tescom Model 44-2200	-
LVDT	Columbia Model SH-200-S3R	7907
LVDT	Columbia Model SH-200-S3R	77002
Accelerometer (No. 1)	Columbia Model 302-6	3878
Accelerometer (No. 2)	Columbia Model 302-6	2919
Charge Amplifier	Columbia Model 4102M	480
Weight Balance	Sauter RC 4021hp	UT617925

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P.O.# A17376YS0A

EQUIPMENT LIST FOR RESONANT COLUMN AND TORSIONAL SHEAR CALIBRATION

Item	Manufacturer and Model No.	Calibration No.
Universal Counter	HP 53131A	006847
Digital Multimeter	Agilent 34401A	006846
Dynamic Signal Analyzer	HP 3562A	006872
Accelerometer	Columbia Model 3021	998953
Charge Amplifier	Columbia Model 4102M	998954
Differential Pressure Transducer	Validyne DP 15-48	998955
Multichannel Carrier Demodulator	Validyne CD 280-2	998955
Pressure Transducer	Sensotec Z/0761-29ZG	993872
Readout Unit	Sensotec 060-3147-01	993872
Micrometer	L.S. Starrett 465M	993873
LVDT	Columbia Model SH-200-S3R	993871
Gage Blocks	Webber	991194
Calibration Weight Set	Troemner (1g - 100g)	991195
Calibration Weight	Ohaus (200 g)	991196
Calibration Weight	Ohaus (500 g)	991198
Calibration Weight	Ohaus (1 kg)	991199
Calibration Weight	Ohaus (2 kg)	993464

P.O.# A17376Y

LIST OF CALIBRATION FACTORS USED IN RESONANT COLUMN AND TORSIONAL SHEAR TESTING

Item (Serial No.)	Calibration Factor
LVDT (7907)	3.768E-03 ft/V
LVDT (77002)	4.463E-03 ft/V
Accelerometer (3878)	2.741 pkV/g
Accelerometer (2919)	2.382 pkV/g
I of Drive Plate No. 4	2.1527E-03 ft Ib sec^2
I of Drive Plate No. 5	2.0630E-03 ft Ib sec^2
I of 1.5 in. Stainless Steel Top Cap	4.62155E-05 ft Ib sec^2
I of 1.5 in. Aluminum Top Cap	1.61770E-05 ft Ib sec^2
I of 2.0 in. Stainless Steel Top Cap	7.28132E-05 ft Ib sec^2
I of 2.0 in. Aluminum Top Cap	5.09296E-05 ft Ib sec^2
I of 2.5 in. Stainless Steel Top Cap	1.778732E-04 ft Ib sec^2
Proximitor of Drive Plate (No. 4)	5.9938E-04 rad/V
Proximitor of Drive Plate (No. 5)	6.0143E-04 rad/V
Torque of Drive Plate (No. 4)	7.2315E-03 ft Ib/V
Torque of Drive Plate (No. 5)	6.9802E-03 ft Ib/V

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CONTROL OF ELECTRONIC DATA

RCTS TESTING OF SOIL AND ROCK SPECIMENS

P.O.# A17376YSOA
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1. The computer used in RCTS testing at The University of Texas at Austin is password protected. Thus, both the data acquisition software and data itself can not be modified by unauthorized users.
2. Initial properties of specimens and setup information are recorded on a data sheet prior to computer entry. Contents of this data sheet are checked by a second individual.
3. During RCTS testing, a hard copy of all data is automatically printed as part of the test procedure.
4. At the end of testing each specimen, the data required for evaluation of linear and nonlinear dynamic soil and rock properties are transferred on to a floppy disk. This disk is set to write-protection and is affixed with a seal for prevention of data modification.
5. The contents of this disk are printed and compared with the initial specimen properties on the data sheet and with the continuous printout gathered during testing.
6. All data required for evaluation of linear and nonlinear dynamic soil and rock properties are duplicated. Two digital copies and two hard copies of data are created.
7. All data sheets, computer printouts, one digital copy and one hard copy of the data are placed in a fire-resistant filing cabinet in ECJ 9.227, near Prof. Stokoe's office.
8. The second set of digital and hard copies of the data is placed in a locked cabinet in the soil dynamics laboratory in ECJ 6.408, where the RCTS testing is performed.

QA:QA

COMMENTS ON REVISIONS

Revision 4 – Contains a total of 88 pages plus Appendices A (A-1 through A-9) and B (B-1 through B-7). This revision is dated 10 October 2000.

a. page 1 – Changed project information to indicate current work, replaced "K Reactor Area, Pen Branch Fault; Savannah River Site; Aiken, South Carolina; Project No. AA891070" with "Waste Handling Building Area; Yucca Mountain Project; TRW Environmental Safety Systems, Inc.; Las Vegas, Nevada; Project No. A17376YSOA; Geotechnical Engineering Center", and added "and Appendix B (B-1 through B-7)" in footer.
b. page 7 – Added "*" for footnote to indicate change in configuration of computerized RCTS test equipment.
c. page 56 – items 4 and 5, Added "*" for footnote to indicate subroutines that are not used.
d. page 62 – Changed footnote to indicate current version of subroutines and calibration factors.
    - Replaced "RC Test Version 2.0" with "RC Test Version 2.1".
    - Replaced "TS Test Version 3.0" with "TS Test Version 3.1".
    - Replaced "D_p = 2.05714E-03 ft Ib sec^2" with "D_p = 2.0630E-03 ft Ib sec^2".
    - Replaced "F_{ac} = 2.518 pkV/g" with "F_{ac} = 2.741 pkV/g".
    - Replaced "F_{lvdt} = 3.799E-03 ft/V" with "F_{lvdt} = 3.768E-03 ft/V"
e. page 65 – Changed footnote to indicate current version of subroutines.
    - Replaced "RC Test Version 2.0" with "RC Test Version 2.1".
    - Replaced "TS Test Version 3.0" with "TS Test Version 3.1".
f. page 70 – Changed footnote to indicate current version of subroutines and calibration factors.
    - Replaced "RC Test Version 2.0" with "RC Test Version 2.1".
    - Replaced "TS Test Version 3.0" with "TS Test Version 3.1".
    - Replaced "D_p = 2.05714E-03 ft Ib sec^2" with "D_p = 2.0630E-03 ft Ib sec^2".
g. page 72 – Changed footnote to indicate current version of subroutines.
    - Replaced "RC Test Version 2.0" with "RC Test Version 2.1".
    - Replaced "TS Test Version 3.0" with "TS Test Version 3.1".
h. page 74 – Changed footnote to indicate current version of subroutines and current calibration factors.
    - Replaced "RC Test Version 2.0" with "RC Test Version 2.1".
    - Replaced "TS Test Version 3.0" with "TS Test Version 3.1".
    - Replaced "K_p = 1.01354E-03 rad/V" with "K_p = 6.0143E-04 rad/V".
    - Replaced "K_t = 7.09663E-03 ft Ib/V" with "K_t = 6.9802E-03 ft Ib/V".
i. page 83 – Changed footnote to indicate current version of RC Test, replaced "Version 2.0" with "Version 2.1".
j. page 84 – Changed footnote to indicate current version of TS Test, replaced "Version 3.0" with "Version 3.1".
k. page A-6 – Added "*" for footnote to indicate change in equipment list
l. page A-7 – Added "*" for footnote to indicate change in calibration equipment list
m. page A-8 – Added "*" for footnote to indicate change in calibration factors
n. page A-9 – first line, Replaced "Appendix A (A-1 through A-8)" with "Appendix A (A-1 through A-9)" to indicate correct number of pages.
o. pages B-1 through B-7 – Added Appendix B.

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P.O.# A17376YS0A

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13.6. Photo Log (1 page)

Photograph Log			
			Page No._____ of _____ pages
Camera	Roll #	Project No.:	Project Name:
			Geologist__________________________________
Frame	**Date**	**Location**	**Description**