APPENDIX A

CHECKLIST FOR PLANNING STEPS

Systematic planning of a monitoring program should proceed through the steps described in Chapter 4. The steps are summarized in this appendix in checklist form.

1. **Define the Project Conditions**
   (a) Project type
   (b) Project layout
   (c) Subsurface stratigraphy and engineering properties
   (d) Groundwater conditions
   (e) Status of nearby structures or other facilities
   (f) Environmental conditions
   (g) Planned construction method
   (h) Knowledge of crisis situation
2. **Predict Mechanisms that Control Behavior**
3. **Define the Geotechnical Questions that Need to Be Answered**
4. **Define the Purpose of the Instrumentation**
   (a) Benefits during design
      • definition of initial site conditions
      • proof testing
      • fact-finding in crisis situations
   (b) Benefits during construction
      • safety
      • observational method
      • construction control
      • providing legal protection
      • measurement of fill quantities
      • enhancing public relations
      • advancing the state of the art
   (c) Verifying satisfactory performance after construction is complete
5. **Select the Parameters to Be Monitored**
   (a) Pore water pressure or joint water pressure
   (b) Total stress within soil mass
   (c) Total stress at contact with structure or rock
   (d) Stress within rock mass
   (e) Vertical deformation
   (f) Horizontal deformation
   (g) Tilt
   (h) Strain in soil or rock
   (i) Load or strain in structural members
   (j) Temperature
6. **Predict Magnitudes of Change**
   (a) Predict maximum value, thus instrument range
   (b) Predict minimum value, thus instrument sensitivity or accuracy
   (c) Determine hazard warning levels
7. **Devise Remedial Action**
   (a) Devise action for each hazard warning level, ensuring that labor and materials will be available
   (b) Determine who will have contractual authority for initiating remedial action

(c) Ensure that communication channel is open between design and construction personnel

(d) Determine how all parties will be forewarned of planned remedial actions

8. Assign Tasks for Design, Construction, and Operation Phases

(a) Complete Table 4.2

(b) Assign supervisory responsibility for tasks by instrumentation specialist

(c) Plan liaison and reporting channels

(d) Plan who has overall responsibility and contractual authority for implementation

9. Select Instruments

(a) Plan for high **reliability:**

- study suggested recipe for reliability in Chapter 15
- maximum simplicity
- don't allow lowest cost to dominate selection
- maximum durability in installed environment
- minimum sensitivity to climatic conditions
- good past performance record
- consider transducer, readout unit, and communication system separately
- is reading necessarily correct?
- can calibration be verified after installation?

(b) Discuss application with manufacturer

(c) Recognize any limitations in skill or quantity of available personnel

(d) Consider both construction and long-term needs and conditions

(e) Ensure good conformance

(f) Ensure minimum interference to construction and minimum access difficulties

(g) Determine need for automatic data acquisition system

(h) Plan readout type and arrangements, consistent with required reading frequency

(i) Plan need for spare parts and standby readout units

(j) Evaluate adequacy of lead time

(k) Evaluate adequacy of time available for installation

(l) Question whether the selected instrument will achieve the objective

10. Select Instrument Locations

(a) Identify zones of primary concern

(b) Select primary instrumented sections

(c) Select secondary instrumented sections

(d) Plan quantities to account for less than 100% survival

(e) Arrange locations to provide early data

(f) Arrange locations to provide cross-checks

(g) Avoid nonconformance or weakness at clusters

11. Plan Recording of Factors that May Influence Measured Data

(a) Construction details

(b) Construction progress

(c) Visual observations of expected and unusual behavior

(d) Geology and other subsurface conditions

(e) Environmental factors

12. Establish Procedures for Ensuring Reading Correctness

(a) Visual observations

(b) Duplicate instruments

(c) Backup system

(d) Study of consistency

(e) Study of repeatability

(f) Regular in-place checks

13. List the Specific Purpose of Each Instrument

14. Prepare Budget

Include costs, being particularly careful to make a realistic estimate of project duration, for

(a) Planning monitoring program

(b) Making detailed instrument designs

(c) Procuring instruments

(d) Making factory calibrations

(e) Installing instruments

(f) Maintaining and calibrating instruments on a regular schedule

(g) Establishing and updating data collection schedule

(h) Collecting data

(i) Processing and presenting data
(j) Interpreting and reporting data
(k) Deciding on implementation of results

15. Write Instrument Procurement Specifications

(a) Assign responsibility for procurement
- construction contractor
- owner
- design consultant
- instrument suppliers acting as assigned subcontractors

(b) Select specifying method
- descriptive specification, with brand name and model number
- descriptive specification, without brand name and model number
- performance specification

(c) Select basis for determining price
- negotiation
- bid

(d) Write specifications
(e) Plan factory calibrations
(f) Plan acceptance tests when instruments are first received by user, and determine responsibility

16. Plan Installation

(a) Prepare step-by-step installation procedure well in advance of scheduled installation dates, including list of required materials and tools
(b) Prepare installation record sheets
(c) Plan staff training
(d) Coordinate plans with contractor
(e) Plan access needs
(f) Plan protection from damage and vandalism
(g) Plan installation schedule

17. Plan Regular Calibration and Maintenance

(a) Plan calibrations during service life
- readout units
- embedded components

(b) Plan maintenance
- readout units
- field terminals
- embedded components

18. Plan Data Collection, Processing, Presentation, Interpretation, Reporting, and Implementation

(a) Plan data collection
- prepare preliminary detailed procedures for collection of initial and subsequent data
- prepare field data sheets
- plan staff training
- plan data collection schedule
- plan access needs

(b) Plan data processing and presentation
- determine need for automatic data processing
- prepare preliminary detailed procedures for data processing and presentation
- prepare calculation sheets
- plan data plot format
- plan staff training

(c) Plan data interpretation
- prepare preliminary detailed procedures for data interpretation

(d) Plan reporting of conclusions
- define reporting requirements, contents, frequency

(e) Plan implementation
- verify that all Step 7 items are in place

19. Write Contractual Arrangements for Field Instrumentation Services

(a) Select field service contract method (complete Table A.1)
(b) Write detailed specifications

20. Update Budget

Include costs for all tasks listed in Step 14

Table A.1. Allocation of Responsibilities for Field Instrumentation Services

Services Provided by	Installation	Regular Calibration and Maintenance	Data Collection, Processing and Presentation	Data Interpretation and Reporting
Owner's personnel				
Construction contractor, using bid items in construction contract, without prequalification	Only very simple instrumentation	Only very simple instrumentation	Only very simple instrumentation	Not suitable
Construction contractor, using bid items in construction contract, with prequalification				Not suitable
Instrumentation specialist selected by and contracting with owner				
Instrumentation specialist selected by owner and contractor, and contracting with contractor as an assigned subcontractor				

APPENDIX B

CHECKLIST FOR CONTENT OF SPECIFICATIONS FOR PROCUREMENT OF INSTRUMENTS

Specifications for procurement of instrumentation are discussed in Chapter 5, and recommended content is given in Section 5.4. The content is summarized in this appendix in checklist form. As indicated in Section 5.4, it is not intended that all specifications should address all items in the checklist. Greatest detail is required when the low-bid procedure with an *or equal* provision is used.

The headings in this checklist correspond to the subheadings in Section 5.4.

Part 1. General (Wording Applicable to All Instruments)

5.4.1. Division of Responsibilities
- Procurement
- Factory calibration and quality assurance
- Review of proposed instruments
- Acceptance tests
- Summary statement of work included

5.4.2. Submittals
- Experience lists
- Requests for review of proposed instruments
- Calibration certificates
- Quality assurance checklists
- Warranties
- Instruction manuals
- Shipping documents
- Instrument samples
- Schedules for all submittals

5.4.3. Operating Environment
- Definition of environment
- Ground deformation

5.4.4. Experience
- Projects
- Users

5.4.5. General Material Requirements
- Factors in Table 5.4
- Longevity

5.4.6. Review of Proposed Instruments
- Requirements for review
- *Or equal* specification
- Submittals

5.4.7. Factory Calibration and Quality Assurance
- Factory calibrations
- Calibration certificates
- Unique identification
- Preshipment inspections
- Quality assurance checklists

5.4.8. Warranty

5.4.9. Instruction Manual

5.4.10. Shipment and Delivery
- Delivery dates
- Partial shipment schedule
- Method of shipment
- Prepayment of freight charges
- Insurance in transit
- Submittal of shipping and insurance documents

Part 2. Instrument Details (Separate Subheading for Each Instrument)

5.4.11. Instrument Operating Principles

5.4.12. Component Specifications
- Descriptive or performance specification
- Range
- Acceptable uncertainty
- Conformance requirements
- Method of verifying reading correctness
- Detail design of nonstandard components
- Verification that all required components have been included

5.4.13. Compatibility with Other Instruments

5.4.14. Physical Size Limitations

5.4.15. Submittal of Samples
- Requirements
- Characteristics to be tested

5.4.16. Installation Tools and Materials

5.4.17. Spare Parts
- Damage during installation
- Malfunction during operation
- Readout units
- Accessible terminals

Part 3. Measurement and Payment (Section 5.4.18)
- Measurement method
- Payment method
- Adequate definition of quantity and dimensions for payment purposes
- Pay item for every specified requirement
- Assigned subcontracts:
  Definition of procedure
  Markup
  Adjustment of allowance

Reviews of Specification (Section 5.4)
- By experienced specification writer
- By instrumentation specialist
- By personnel familiar with other sections of the specifications

APPENDIX C

CHECKLIST FOR CONTENT OF SPECIFICATIONS FOR FIELD INSTRUMENTATION SERVICES

Specifications for field instrumentation services are discussed in Chapter 6, and recommended content is given in Section 6.6. The content is summarized in this appendix in checklist form. As indicated in Section 6.6, it is not intended that all specifications should address all the items in the checklist but, if the low-bid procedure has been selected for any task, extra care must be taken to write a comprehensive specification and all relevant requirements should be specified.

The headings in this checklist correspond to the subheadings in Section 6.6.

Part 1. General

6.6.1. Purpose of Instrumentation Program
- Overall purpose
- Parameters monitored by each instrument
- Use of data (brief statement)

6.6.2. Division of Responsibilities
- Procurement
- Factory calibration
- Acceptance tests
- Installation
- Regular maintenance
- Regular calibration
- Establishing and updating reading schedule
- Data collection
- Data processing and presentation
- Data interpretation
- Reporting of results
- Deciding on implementation of results
- Summary statement of contractor responsibilities: work included

6.6.3. Specification Method
- Definition and listing of support work
- Definition and listing of specialist work
- Description of specification method for:
  - Installation
  - Regular calibration and maintenance
  - Data collection, processing, and presentation
  - Data interpretation and reporting
- Definition and use of contingency allowance or assigned subcontract (brief statement)

6.6.4. Related Work Specified Elsewhere
- Listing
- Section numbers

6.6.5. Qualifications of Specialist Field Instrumentation Personnel
- General requirements
- Requirements for firm
- Requirements for individuals
- Schedule for qualification statements

6.6.6. Submittals During Construction
- Detailed requirements
- Schedule

6.6.7. Cooperation Between Construction Contractor and Owner's Specialist Field Instrumentation Personnel

Part 2. Products

6.6.8. Procurement of Instruments
- If procured by others:
  - Listing
  - Operating principles
  - Sizes
  - Factory calibration and quality assurance
  - Acceptance tests by owner
  - Warranties
  - Shipment and delivery
  - Schedules
  - Insurances
  - Handing over
  - Checking
  - Responsibility
- If procured by construction contractor:
  - Chapter 5 and Appendix B
  - Tabular listing of quantities
- Storage space

6.6.9. Support Work (Relating to Products)
- Detailed specification for each biddable and incidental work item (unless specified later)
- Description of each nonbiddable work item, paid for under a contingency allowance (unless specified later)
- Schedule requirements

Part 3. Execution

6.6.9. Support Work (Relating to Execution)
- Detailed specification for each biddable and incidental work item (unless specified later)
- Description of each nonbiddable work item, paid for under a contingency allowance (unless specified later)
- Schedule requirements

6.6.10. Locations of Instruments
- Approximate locations on drawings
- Owner's representative will finalize
- Record survey, with required accuracy

6.6.11. Installation of Instruments
- Details on drawings
- Step-by-step procedures
- General and instrument-specific drilling requirements
- Submission for review
- Log of installation activities
- Schedules
- Work restrictions
- Drilling specification
- Grouting specification
- Acceptance tests

6.6.12. Regular Maintenance and Calibration
- Procedures
- Schedules

6.6.13. Data Collection, Processing, and Presentation
- Procedures
- Format and schedule for data submission
- Frequency
- Start and termination schedule
- Joint initial readings

6.6.14. Availability of Data
- Availability of raw or interpreted data
- Schedule
- Contractor's responsibility for safety

6.6.15. Implementation of Data
- Use of data
- Action to be taken:
  - Predetermined remedial actions
  - Hazard warning levels
  - Contractual responsibility
  - Method of forewarning
- Consistency with non-instrumentation sections verified

6.6.16. Delay to Construction
- Delay time estimates
- Payment

6.6.17. Damage to Instrumentation
- Protection requirements
- Responsibility of contractor
- Timeliness for repair or replacement
- Work stoppage
- Financial penalty

6.6.18. Disposition of Instruments
- Ownership of portable instruments
- Salvage and ownership of recoverable components
- Restoration of surface and subsurface
- Overhaul of long-term instruments

Part 4. Measurement and Payment (Section 6.6.19)

- Every work item:
  - Measurement method
  - Payment method
  - Work included and excluded
- Furnish and install work items:
  - Definition of major component prices
- Data-set work items:
  - Definition of unit
- Contingency allowance item for nonbiddable support work:
  - Applicable work items
  - Payment rates for labor
  - Payment rates for plant and equipment
  - Payment rates for materials
  - Markup
- Assigned subcontract for specialist work:
  - Applicable work items
  - Definition of procedure
  - Markup
  - Adjustment of allowance

Reviews of Specification (Section 6.6)

- By experienced specification writer
- By instrumentation specialist
- By personnel familiar with other sections of the specifications

APPENDIX D

COMMERCIALLY AVAILABLE GEOTECHNICAL INSTRUMENTS

Instruments are grouped in the categories that have been defined in Part 3. The numbers alongside each category refer to the alphabetical listing of manufacturers given at the end of this appendix.

Certain manuacturers' names may not be listed alongside certain instrument categories. Any such omissions result solely from the author's lack of knowledge and do not imply any inadequacy in those omitted instruments.

Table D.1. Instruments for Measuring Groundwater Pressure

Instruments	Manufacturers
Observation wells	1, 2
Open standpipe piezometers	20, 36, 48, 49, 53, 54, 73, 95, 100, 102, 107, 108, 109, 110, 112
Twin-tube hydraulic piezometers	48, 53, 62, 73, 91, 95, 107, 109
Pneumatic piezometers	10, 49, 53, 55, 57, 107, 108, 109, 121, 124
Vibrating wire piezometers	46, 48, 51, 67, 82, 96, 109, 116, 120
Bonded electrical resistance piezometers	15, 53, 54, 68, 72, 91, 102, 107, 108, 121, 122
Unbonded electrical resistance piezometers	24, 62, 108
Multipoint piezometers	111, 112, 120, 124, 129

Table D.2. Instruments for Measuring Total Stress in Soil

Instruments	Manufacturers
Diaphragm earth pressure cells with vibrating wire transducer	41, 48, 116, 120
Diaphragm earth pressure cells with bonded electrical resistance strain gage transducer	22, 23, 62, 72
Hydraulic earth pressure cells with pneumatic transducer	49, 55, 57, 107, 108, 109, 124
Hydraulic earth pressure cells with vibrating wire transducer	46, 67, 82, 96, 109, 120
Hydraulic earth pressure cells with bonded electrical resistance strain gage transducer	54, 72, 91, 121
Hydraulic earth pressure cells with unbonded electrical resistance strain gage transducer	24, 62, 108

Table D.3. Instruments for Measuring Stress Change in Rock

Instruments	Manufacturers
Borehole pressure cells	46, 55, 104, 108
USBM borehole deformation gages	46, 67, 100, 101
Yoke borehole deformation gage	29
Biaxial strain cells	25, 100
Triaxial strain cells	25, 77, 80, 86
Vibrating wire stressmeters	46, 67, 82
Photoelastic stressmeters	117

Table D.4. Instruments for Measuring Deformation

Instruments	Manufacturers
Surveying instruments	70, 76, 132, 133
Electronic distance measuring instruments	4, 26, 70, 76, 87, 127, 132, 133
Photogrammetric instruments	70, 132, 133
Mechanical crack gages	1 (see also under *Surface-mounted mechanical strain gages,* in Table D.5)
Electrical crack gages	57, 100, 102, 107 (see also under *Surface-mounted vibrating wire* and *electrical resistance strain gages,* in Table D.5)
Convergence gages	46, 53, 66, 67, 70, 82, 100, 102, 108, 109, 110, 120
Mechanical tiltmeters	96, 109
Tiltmeters with accelerometer transducer	107, 108, 109, 111, 118, 121, 122
Tiltmeters with vibrating wire transducer	82, 96, 120
Tiltmeters with electrolytic level transducer and geodetic sensitivity	11, 40, 114, 126
Probe extensometers: mechanical heave gage	1
Probe extensometers: crossarm gage	1, 72, 96, 108, 109
Probe extensometers: mechanical probe within inclinometer casing	53, 66, 108
Probe extensometers: sliding micrometer	111
Probe extensometers: gages with induction coil transducer	62, 65, 66, 82, 96, 107, 108, 109, 120
Probe extensometers: magnet/reed switch gage	53, 109
Probe extensometers: magnetostrictive gage	46, 67
Settlement platforms	1
Fixed embankment extensometers: mechanical gage with tensioned wires	1 (also most manufacturers of fixed borehole extensometers)
Fixed embankment extensometers: gage with electrical linear displacement transducers	Most manufacturers of fixed borehole extensometers
Soil strain gages	18
Fixed borehole extensometers	1, 6, 46, 48, 49, 53, 55, 62, 66, 67, 72, 82, 99, 100, 102, 107, 108, 109, 110, 111, 118, 120, 122
Borros anchors	20, 48, 108
Spiral-foot gages	1, 100
Inclinometers	29, 48, 49, 53, 55, 66, 68, 72, 82, 102, 107, 108, 109, 110, 111, 120, 121, 122
Shear plane indicators	1, 17, 50, 53, 66, 108, 109
Plumb lines and inverted pendulums	62, 66, 72, 96, 109, 120
Remote monitoring system for plumb lines	62, 96, 113
In-place inclinometers and multiple deflectometers	66, 107, 108, 120, 121, 122
Portable borehole deflectometers	66, 108, 111
Liquid level gages	1, 20, 46, 49, 53, 54, 55, 57, 65, 66, 67, 88, 96, 107, 108, 109, 120, 124
Telltales	1
Convergence gages for slurry trenches	1
Time domain reflectometry	58, 120
Acoustic emission monitoring	3, 32, 66, 88, 94, 108, 131

Table D.5. Instruments for Measuring Load and Strain in Structural Members

Instruments	Manufacturers
Mechanical load cells	66, 97
Hydraulic load cells	55, 66, 102, 109, 118, 124
Electrical resistance load cells	19, 22, 29, 31, 45, 46, 60, 61, 62, 67, 72, 84, 102, 108, 109, 115, 118, 128
Vibrating wire load cells	41, 46, 48, 67, 82, 109, 116, 120
Photoelastic load cells	93, 117
Calibrated hydraulic jacks	31
Cable tension meters	22, 39, 100, 115
Surface-mounted mechanical strain gages	13, 33, 62, 66, 75, 84, 96, 100, 102, 103, 108, 110, 118
Surface-mounted vibrating wire strain gages	41, 46, 48, 67, 82, 108, 116, 120
Surface-mounted electrical resistance strain gages	19, 22, 23, 35, 59, 60, 72, 85, 123
Embedment strain gages: mechanical type	1
Embedment strain gages: vibrating wire types	41, 46, 48, 67, 82, 96, 116, 120
Embedment strain gages: electrical resistance types	19, 22, 24, 35, 62, 72, 107, 108, 118, 123
Concrete stress cells	24, 46, 55, 62, 66, 67, 72, 82, 96, 102, 109

Table D.6. Instruments for Measuring Temperature

Instruments	Manufacturers
Mercury thermometers	2
Bimetal thermometers	2
Thermistors	12, 27, 37, 89, 105
Thermocouples	12, 27, 37, 85, 89
Resistance temperature devices	12, 24, 27, 66, 89, 120
Vibrating wire transducers	46, 48, 67, 82, 120
Frost gages	1

Table D.7. Miscellaneous

Instruments	Manufacturers
Electrical cable	5, 16, 21, 38, 42, 130
Splices for electrical cable	9, 30, 42, 125
Automatic data acquisition systems for geotechnical instrumentation	22, 46, 47, 48, 52, 53, 55, 67, 72, 82, 108, 109, 120, 122, 124
Lightning protection devices	43, 44, 74, 81, 98
Borehole directional survey instruments	34, 56, 63, 90, 92
Ultrasonic monitoring instrument for measuring verticality of slurry trenches	71
Additives to water for hydraulic instruments	8, 79
Bentonite pellets	7, 46, 53, 67, 95, 100, 102, 108, 109, 124
Bentonite gravel	78
Additives to grout	28, 83, 106
Biodegradable drilling mud	69
Inflatable packers	14, 64, 102

NAMES AND ADDRESSES OF MANUFACTURERS AND NORTH AMERICAN SUPPLIERS*

1. Instrument can be fabricated by the user from locally available parts.
2. Instrument is available from numerous manufacturers.
   Listings may be found in:
   - Various trade journals
   - Local industrial buyers' guides
   - *Electronic Buyers' Guide* (McGraw-Hill Book Co., New York)
   - *Instruments and Control Systems Buyers' Guide* (Chilton Co., Radnor, PA)
   - *Directory of Instrument Society of America* (ISA, Research Triangle Park, NC)
   - *Thomas Register* (Thomas Publishing Co., New York)
3. Acoustic Emission Technology Corporation, 1812 J Tribute Road, Sacramento, CA 95815, U.S.A.
4. AGA Geotronics AB, Box 64, S-182 11 Danderyd, Sweden
5. Alpha Wire Corporation, 711 Lidgerwood Avenue, Elizabeth, NJ 07207, U.S.A.
6. Amberg Measuring Technique Ltd., Ausstellungsstrasse 88, P.O. Box 3141, CH-8031 Zürich, Switzerland (NAS: Roctest Ltd.)
7. American Colloid Company, Drilling Fluid Products Division, 5100 Suffield Court, Skokie, IL 60077, U.S.A.
8. American Cyanamid Company, 1 Cyanamid Plaza, Wayne, NJ 07470, U.S.A.
9. AMP, Inc., 449 Eisenhower Blvd., Harrisburg, PA 17105, U.S.A.
10. Apparatus Specialties Company, Box 122, Saddle River, NJ 07458, U.S.A.
11. Applied Geomechanics, Inc., 1336 Brommer Street, Santa Cruz, CA 95062, U.S.A.
12. Atkins Technical, Inc., 3401 S.W. 40th Blvd., Archer Interchange (I75), Industrial Area, Gainesville, FL 32608, U.S.A.
13. Avongard Products, U.S.A. Ltd., 2836 Osage, Waukegan, IL 60087, U.S.A.
14. Baski Water Instruments, Inc., 1586 South Robb Way, Denver, CO 80226, U.S.A.
15. BAT Envitech AB, P.O. Box 27194, S-102 52, Stockholm, Sweden (NAS: BAT Envitech, Inc., P.O. Box 7826, Long Beach, CA 90807, U.S.A.; Soiltest, Inc.)
16. Belden Corporation, P.O. Box 1980, Richmond, IN 47374, U.S.A.
17. Bemek, Box 11063, S-95111 Luleå, Sweden
18. Bison Instruments, Inc., 5708 West 36th Street, Minneapolis, MN 55416, U.S.A.
19. BLH Electronics, 75 Shawmut Road, Canton, MA 02021, U.S.A.
20. Borros AB, Box 3063, S-17103, Solna, Sweden (NAS: Roctest Ltd.; Wykeham Farrance, Inc., 8000 Glenwood Ave., P.O. Drawer 30967, Raleigh, NC 27612, U.S.A.)
21. Brand-Rex Corporation, Electronic and Industrial Cable Division, Willimantic, CT 06226, U.S.A.
22. Brewer Engineering Laboratories, Teledyne Engineering Services, P.O. Box 288, Marion, MA 02738, U.S.A.
23. Cambridge Insitu, Little Eversden, Cambridge CB3 7HE, England
24. Carlson Instruments, 1190-C Dell Avenue, Campbell, CA 95008, U.S.A.
25. Chamber of Mines of South Africa, P.O. Box 91230, Auckland Park, 2006, Republic of South Africa
26. Com-Rad Electronic Equipment Ltd., 256 Ipswich Road, Trading Estate, Slough, Berkshire, England
27. Conax Buffalo Corporation, 2300 Walden Avenue, Buffalo, NY 14225, U.S.A.
28. Concrete Chemicals Company, 1705 Superior Building, Cleveland, OH 44114, U.S.A.
29. CSIRO, Division of Geomechanics, P.O. Box 54, Mount Waverley, 3149, Australia
30. Dow Corning Corporation, Midland, MI 48640, U.S.A.
31. Richard Dudgeon, Inc., 7A Market Street, Stamford, CT 06902, U.S.A.
32. Dunegan/Endevco, Rancho Viejo Road, San Juan Capistrano, CA 92675, U.S.A.
33. Eastlex Machine Corporation, 2170 Christian Road, Lexington, KY 40505, U.S.A.

*NAS = North American Supplier.

34. Eastman Christensen Company, P.O. Box 14609, Houston, TX 77021, U.S.A.
35. Eaton Corporation, 5340 Alla Road, Los Angeles, CA 90066, U.S.A.
36. ELE International Ltd., Eastman Way, Hemel Hempstead, Hertfordshire, HP2 7HB, England (NAS: Engineering Laboratory Equipment, Inc., 2205 Lee Street, Evanston, IL 60202, U.S.A.)
37. Fenwal, Inc., Ashland, MA 01721, U.S.A.
38. Fluorocarbon Company, Samuel Moore Group, Dekoron Division, 1199 South Chillicothe Road, Aurora, OH 44202, U.S.A.
39. Fulmer Components Ltd., 231 Berwick Avenue, Slough, Berks, SL1 4QT, England
40. G + G Technics AG, Leimenweg 4, CH-4419 Lupsingen/BL, Switzerland
41. Gage Technique Ltd., P.O. Box 30, Trowbridge, Wilts BA14 8YD, England
42. General Electric Company, Wire and Cable Division, 1285 Boston Avenue, Bridgeport, CT 06486, U.S.A.
43. General Electric Company, Electronics Park, Syracuse, NY, 13201, U.S.A.
44. General Semiconductor Industries, Inc., 2001 West Tenth Place, Tempe, AZ 85281, U.S.A.
45. Geodesy, 832 High Street, East Kew, 3102, Australia
46. Geokon, Inc., 48 Spencer Street, Lebanon, NH 03766, U.S.A.
47. Geomation, Inc., 15000 W. 6th Avenue, Golden, CO 80401, U.S.A.
48. Geonor A/S, Grini Molle, P.O. Box 99 Roa, Oslo 7, Norway (NAS: Geonor USA, 1425 Broad Street, Clifton, NY 07013; Roctest Ltd.; Slope Indicator Company)
49. Geosistemas, S.A. de C.V., Aniceto Ortega No. 1306, 03100 Mexico, D.F., Mexico
50. Geosystems (AUST) Pty. Ltd., 3 Hocking Street, Coburg, 3058, Australia
51. Geotech AB, Klangfärgsg 10, 421-52 Västra Frolunda, Sweden (NAS: Roctest Ltd.)
52. Geotechnical Engineering and Mining Services (U.S.A.), Inc., A Subsidiary of Synergetics International, Inc., 6565 Odell Place, P.O. Box E, Boulder, CO 80306, U.S.A.
53. Geotechnical Instruments (U.K.) Ltd., Station House, Old Warwick Road, Leamington Spa, Warwickshire CV31 3NR, England
54. Geotechniques International, Inc., P.O. Box E, Middleton, MA 01949, U.S.A.
55. Glötzl GmbH, D-7512 Rheinstetten, 4-Fo, Karlsruhe, West Germany (NAS: Geo Group, Inc., 2209 Georgian Way, #12, Wheaton, MD 20902, U.S.A.)
56. Gyrodata, Inc., 1682 West Belt North, Houston, TX 77043, U.S.A.
57. Earl B. Hall, Inc., 1050 Northgate Drive, Suite 400, San Rafael, CA 94903, U.S.A.
58. Hewlett-Packard, 1820 Embarcadero Road, Palo Alto, CA 94303, U.S.A.
59. HITEC Products, Inc., P.O. Box 790, 87 Fitchburg Road, Ayer, MA 01432, U.S.A.
60. Hottinger Baldwin Measurements, Inc., 139 Newbury Street, Framingham, MA 01701, U.S.A.
61. Houston Scientific International, Inc., 4202 Directors Row, Houston, TX 77092, U.S.A.
62. Huggenberger AG, Tödistrasse 68, Postfach CH-8812 Horgen, Switzerland (NAS: Slope Indicator Company)
63. Humphrey, Inc., 9212 Balboa Avenue, San Diego, CA 92123, U.S.A.
64. Hydrophilic Industries, Inc., 5815 Meridian Avenue North, Puyallup, WA 98371, U.S.A.
65. Dr. Ing. Heinz Idel, Potthoffs Borde 15, 43 Essen, West Germany (NAS: Slope Indicator Company)
66. Interfels GmbH, Postfach 75, D-4444, Bad Bentheim 1, West Germany (NAS: Roctest Ltd.)
67. Irad Gage, Klein Drive, Salem, NH 03079, U.S.A.
68. ISMES S.p.A., Viale G. Cesare 29, 24100 Bergamo, Italy
69. Johnson Division of UOP, Inc., P.O. Box 43118, St. Paul, MN 55164, U.S.A.
70. Kern & Co. Ltd., CH-5001, Aarau, Switzerland (NAS: Kern Instruments, Inc., Geneva Road, Brewster, NY 10509, U.S.A.)
71. Koden Electronics Company Ltd., 2-10-45, Kami-Osaki, Shinagawa-ku, Tokyo, Japan

72. Kyowa Electronic Instruments Company Ltd., 5-1 Chofugaoka 3-chome, Chofu-shi, Tokyo, Japan (NAS: Kyowa Dengyo Corporation, 10 Reuten Drive, Closter, NJ 07624, U.S.A.)
73. Landtest Ltd., 43 Baywood Road, Rexdale, Ontario, M9V 3Y8, Canada
74. LEA, Inc., 12516 Lakeland Road, Santa Fe Springs, CA 90670, U.S.A.
75. Leigh Instruments Ltd., Engineering and Aerospace Division, 2680 Queensview Drive, Ottawa, Ontario, K2B 8J9, Canada
76. The Lietz Company, 9111 Barton, Box 2934, Overland Park, KS 66201, U.S.A.
77. LNEC, Laboratório Nacional de Engenharia Civil, 101, Av. do Brasil, P-1799, Lisbon, Portugal
78. L. V. Lomas Chemical Company Ltd./Ltée, 6365 Northwest Drive, Mississauga, Ontario L4V 1J8, Canada (NAS: L. V. Lomas Chemical Company Ltd./Ltée, 5500 Main Street, Suite 3-C, Williamsville, NY 14221, U.S.A.).
79. Lonza AG, 3930 Visp, Switzerland (NAS: Lonza, Inc., 22-10 Route 208, Fair Lawn, NJ 07410, U.S.A.)
80. Luleå University of Technology, Division of Rock Mechanics, S-951 87 Luleå, Sweden
81. Lumex Corporation, 540 North Court, Palatine, IL 60067, U.S.A.
82. Maihak AG, Semperstrasse 38, P.O. 60 17 09, D-2000 Hamburg 60, West Germany (NAS: Ampower Corporation, 1 Marine Plaza, North Bergen, NJ 07047, U.S.A.)
83. Master Builders, Division of Martin Marietta Corporation, 23700 Chagrin Blvd., Beachwood, OH 44122, U.S.A.
84. W. H. Mayes & Son (Windsor) Ltd., Vansittart Estate, Arthur Road, Windsor, Berkshire, SL4 1SD, England
85. Measurements Group, Inc., Micro-Measurements Division, P.O. Box 27777, Raleigh, NC 27611, U.S.A.
86. Mindata, 91A Orrong Crescent, Caulfield North, 3161, Australia (NAS: Geokon, Inc.)
87. Nippon Kogaku K. K., Fuji Bldg., 2-3, Marunouchi 3-chome, Chiyoda-ku, Tokyo 100, Japan
88. Walter Nold Company, Inc., 24 Birch Road, Natick, MA 01760, U.S.A.
89. Omega Engineering, Inc., One Omega Drive, Box 4047, Stamford, CT 06907, U.S.A.
90. Owl Technical Associates, Inc., 1111 Delaware Avenue, Longmont, CO 80501, U.S.A.
91. Oyo Corporation, 2-19 Daitakubo 2-chome, Urawa, Saitama 336, Japan (NAS: Oyo Corporation U.S.A., 7334 N. Gessner Road, Houston, TX 77040, U.S.A.)
92. Pajari Instruments Ltd., P.O. Box 820, Orillia, Ontario L3V 6K8, Canada
93. Perard Torque Tension Ltd., Claylands Avenue, Worksop, Nottinghamshire S81 7BQ, England (NAS: P. T. T. Mining Equipment, Inc., 3924 Youngfield Street, Wheat Ridge, CO 80033, U.S.A.)
94. Physical Acoustics Corporation, P.O. Box 3135, 743 Alexander Road, Princeton, NJ 08540, U.S.A.
95. Piezometer Research & Development, 939 Barnum Avenue, B341, Bridgeport, CT 06608, U.S.A.
96. Ing. Franco Pizzi, Via Ripoli 207E, 50126 Firenze, Italy (Successor to Officine Galileo, Firenze, Italy)
97. Proceq, SA, Riesbachstrasse 57, CH-8034, Zürich 8, Switzerland
98. RKS Industries, 208 Mount Herman Road, Suite 2, Scotts Valley, CA 95066, U.S.A.
99. Rock Instruments Ltd., Bell Lane, Uckfield, East Sussex, TN22 1QL, England (NAS: Irad Gage; Solinst Canada Ltd.)
100. Roctest Ltd., 665 Pine, St. Lambert (Montreal), Quebec J4P 2P4, Canada. Also Roctest, Inc., 7 Pond Street, Plattsburgh, NY 12901, U.S.A.
101. Rogers Arms & Machine Company, P.O. Box 2344, 1426 Ute Avenue, Grand Junction, CO 81501, U.S.A.
102. RS Technical Instruments Ltd., 18-1780 McLean Avenue, Port Coquitlam, British Columbia, V3C 4K9, Canada
103. Satec Systems, Inc., Grove City, PA 16127, U.S.A.
104. Serata Geomechanics, Inc., 1229 Eighth Street, Berkeley, CA 94710, U.S.A.

105. Sierracin/Western Thermistor, 354 Via Del Monte, Oceanside, CA 92504, U.S.A.

106. Sika Corporation, P.O. Box 297, Lyndhurst, NJ 07071, U.S.A.

107. SIS Geotecnica s.r.l., Via Del Santuario 39, 20096 Seggiano Di Pioltello, Milano, Italy

108. Slope Indicator Company, P.O. Box C-30316, Seattle, WA 98103, U.S.A. (also successor to Terrametrics, Golden, CO, U.S.A.)

109. Soil Instruments Ltd., Bell Lane, Uckfield, East Sussex, TN22 1QL, England (NAS: Irad Gage; Solinst Canada Ltd.)

110. Soiltest, Inc., 2205 Lee Street, Evanston, IL 60202, U.S.A.

111. Solexperts AG, P.O. Box 230, CH-8603, Schwerzenbach, Zürich, Switzerland

112. Solinst Canada Ltd., 2240 Industrial Street, Burlington, Ontario, L7P 1A5, Canada

113. Spectron Engineering, Inc., 800 West 9th Avenue, Denver, CO 80204, U.S.A.

114. Sperry Corporation, Sensing Systems, Aerospace & Marine Group, P.O. Box 21111, Phoenix, AZ 85036, U.S.A.

115. Strainsert Company, Union Hill Industrial Park, West Conshohocken, PA 19428, U.S.A.

116. Strainstall Ltd., Denmark Road, Cowes, Isle of Wight, PO31 7TB, England

117. Stress Engineering Services, Charlton Lane, Midsomer Norton, Bath, Avon, BA3 4BE, England

118. Structural Behavior Engineering Laboratories, Inc., P.O. Box 23167, Phoenix, AZ 85063, U.S.A.

119. Tektronix, Inc., P.O. Box 500, Beaverton, OR 97077, U.S.A.

120. Telemac, 2 Rue August Thomas, 92600 Asnières, France (NAS: Roctest Ltd.)

121. Terra Technology Corporation, 3860 148th Avenue, N.E., Redmond, WA 98052, U.S.A.

122. Terrascience Systems Ltd., 1574 West 2nd Avenue, Vancouver, British Columbia V6J 1H2, Canada

123. Texas Measurements, Inc., P.O. Box 2618, College Station, TX 77840, U.S.A.

124. Thor International, Inc., 13751 Lake City Way N.E., Seattle, WA 98125, U.S.A.

125. 3M Company, 3M Center 225-4N-05, St. Paul, MN 55144, U.S.A.

126. Tilt Measurement Ltd., Works Road, Letchworth, Herts SG6 1JU, England

127. Tokyo Optical Co. Ltd., 75-1 Hasunuma-cho, Itabashi-ku, Tokyo 174, Japan (NAS: Topcon Instrument Corporation of America, 65 West Century Road, Paramus, NJ 07652, U.S.A.)

128. Transducers, Inc., 14030 Bolsa Lane, Cerritos, CA 90701, U.S.A.

129. Westbay Instruments Ltd., 507 East Third Street, North Vancouver, British Columbia V7L 1G4, Canada

130. Westinghouse Electric Corporation, 25 Bridle Lane, Westborough, MA 01581, U.S.A.

131. Weston Geophysical Corporation, P.O. Box 550, Westborough, MA 01581, U.S.A.

132. Wild Heerbrugg Ltd., CH-9435 Heerbrugg, Switzerland (NAS: Wild Heerbrugg Instruments, Inc., 465 Smith Street, Farmingdale, NY 11735, U.S.A.)

133. Carl Zeiss, D-7082, Oberkochen, West Germany (NAS: Carl Zeiss, Inc., One Zeiss Drive, Thornwood, NY 10594, U.S.A.)

APPENDIX E

DETAILS OF TWIN-TUBE HYDRAULIC PIEZOMETER SYSTEM

The operating principle of the twin-tube hydraulic piezometer is described in Chapter 9, and advantages and limitations are given. The application for twin-tube hydraulic piezometers is almost exclusively limited to long-term monitoring of pore water pressures in embankment dams, and therefore longevity is a primary need. Systems have been developed in the United States and England, and each has been widely used in embankment dams throughout the world with very variable success. The system developed in England appears to have a better success record than the system developed in the United States, and is readily available from instrument manufacturers in England. Successful long-term use of twin-tube hydraulic piezometers entails close adherence to many proven details. Details are given in this appendix.

E.1. COMPONENTS

E.1.1. Piezometers

Piezometers are of two types, depending on whether they are to be installed in saturated or unsaturated soil. They are referred to here as *cylindrical piezometers* and *Bishop piezometers*, respectively. Cylindrical piezometers are typically installed below the groundwater table in boreholes, and Bishop piezometers are typically installed in compacted fill.

A Bishop piezometer is shown in Figures 9.12 and 9.13 and consists of a tapered ceramic filter retained with neoprene washers between two end caps. Two compression fittings are attached to the larger end cap. The filter should be a *high air entry filter* (Section 9.11) with a pore diameter of approximately 4×10^{-5} in. (1 micron), a permeability to water of about 3×10^{-6} cm/sec, and an air entry value of at least 15 lb/in.^{2} (100 kPa). A typical size of the filter is 4 in. (100 mm) long, with outside diameter tapering from 2 to 1.5 in. (50 to 38 mm). As indicated in Section E.1.3, the compression fittings connected to the top end cap should be of type 316 stainless steel. It is important that the diameter of the waterway through the compression fitting and top cap should not be less than the inside diameter of the tubing: a reduction of diameter at this point is thought to be the cause of blockage in some piezometers in Australia (Mitchell, 1985).

Available options for end cap material are brass, PVC, and stainless steel. Brass is incompatible with the stainless steel compression fittings, since galvanic corrosion may occur; therefore, it should not be used. Available options for the connecting rod material are also brass, PVC, and stainless steel. However, a connecting rod of PVC is too weak to

give sufficient grip at the end caps for sealing on the ends of the filter, and a brass connecting rod is subject to corrosion. In summary, recommended materials are:

Compression fittings—type 316 stainless steel
End caps—PVC or type 316 stainless steel
Connecting rod—type 316 stainless steel
Washers—neoprene

Because the polyethylene sheath must be pared back (Section E.1.3) before attaching tubing to the compression fittings, the short lengths of bared nylon tubing above the compression fittings are a potential weakness if they are allowed to bend during installation. A worthwhile improvement to the standard procedure would be the addition of thick-wall heat shrink tubing over the compression fittings and the first few inches of tubing, shrunk in place after making the connections.

A cylindrical piezometer consists of a cylindrical ceramic filter between two circular plastic end caps, with two compression fittings attached to one end cap. The filter should be a *low air entry filter* (Section 9.11) with a pore diameter of approximately 0.002 in. (60 microns), a permeability to water of about 3×10^{-2} cm/sec, and an air entry value of about 0.7 lb/in.^{2} (5 kPa). The type of compression fittings and the size of the waterway through the fittings should be as described above for Bishop piezometers.

E.1.2. Tubing

Recommendations for tubing material and diameter are given in Section 8.2.3.

Unplasticized nylon 11 with a polyethylene (polythene) sheath is generally accepted as the tubing of choice. The absence of a plasticizer is very important, because this additive tends to form a layer of crystals inside the tubing and may ultimately cause blockage. Mitchell (1985) analyzed crystals that formed in plasticized tubing and found them to be N-butyl-benzene-sulfanamide.

The nylon should be of natural coloring and should not contain more than 0.15% of water-soluble material. The maximum water absorption by the nylon 11 should not be greater than 1.8% at a relative humidity of 100% (a lower-quality nylon 11 is available, with a water absorption of more than 10%) and the tubing should withstand a short-term bursting pressure of not less than 1200 ft head (350 m) of water. The tubing should be suitable for operation within the temperature range 0–50°C and should be capable of being bent at 0°C through 360 degrees around a 4 in. (100 mm) diameter rod without collapse or rupture. The tensile strength of the tubing should not be less than 7000 lb/in.^{2} (50 MPa) at 20°C and should be able to withstand 10% tensile strain at 20°C without rupture.

When the length of single tubing between piezometer and terminal enclosure is less than 600 ft (200 m), a nylon tubing with a 0.11 in. (2.8 mm) inside diameter and a 0.19 in. (4.8 mm) outside diameter is suitable. For longer lengths, these diameters should be either 0.15 in. (3.8 mm) and 0.25 in. (6.4 mm) or 0.2 in. (5.0 mm) and 0.3 in. (8.0 mm), respectively: both sizes have been used with success. The tolerance on the outside diameter should be +0.002 in. (+0.05 mm) and −0.008 in. (−0.2 mm), and the tolerance on the wall thickness should be ±0.003 in. (±0.08 mm). The radial thickness of the polyethylene sheath should be 0.04 ± 0.003 in. (1 ± 0.08 mm).

Unless absolutely impracticable, tubing should be in a continuous length from the piezometer tip to the terminal enclosure: any connections are potential sources of weakness and leakage. Tubing is available in continuous lengths of up to 2000 ft (600 m). It should be tested, before installation, at a pressure well in excess of the anticipated pressure in the field, and an appropriately sized ball bearing should be blown through to ensure that there are no constrictions: these have been found on several occasions. Prior to installation, tubing should be stored away from direct sunlight and the ends should be capped to prevent the entry of dust and insects.

In some cases, pairs of nylon 11 tubes have been sheathed within a coating of polyethylene. However, the polyethylene often does not completely fill between the two tubes, and to avoid seepage along this space, any connections should be encased in an epoxy resin to close off the ends of the passage. The electrical cable splice kits described in Section 8.4.17 are suitable.

E.1.3. Compression Fittings

Recommendations for compression fitting material and type are given in Section 8.2.3: type 316 stainless steel fittings with positive alignment of the compression sleeve. Brass compression fittings are

often used on twin-tube hydraulic piezometers, and the author has no specific evidence that excessive corrosion has occurred. However, the author believes in recognizing that brass is subject to corrosion by dissolved gases in the liquid within the tubing and in water surrounding the fittings and thus in adopting a conservative approach.

Compression fittings should seal on the nylon tubing, **not** the polyethylene sheath. The sheath must therefore be pared back, using a cutting tool made for the purpose, and the protruding nylon tube inspected carefully to ensure that it has not been damaged.

E.1.4. Liquid in Tubing

Recommendations for liquid are given in Section 8.2.3: filtered distilled water, produced by steam distillation and de-aired to reduce the dissolved gas content to less than 1 ppm DO. QAC should be added as a wetting agent and bacterial inhibitor.

E.1.5. De-Airing Equipment

The correct functioning of a twin-tube hydraulic piezometer system depends on the absence of gas in the system. If liquid is not de-aired, gas will soon collect to create discontinuities in the liquid, and pressure readings will be incorrect. When this happens, fresh liquid can be flushed into the system to remove the gas, but new discontinuities will soon form. It is therefore necessary to de-air the liquid, and the greater the efficiency of de-airing, the less will be the required flushing frequency. The tubing and piezometer filters described earlier have been selected to minimize the entry of gas, either from unsaturated soil or from the atmosphere.

Some agencies responsible for embankment dams attempt to minimize the dissolved gas content in the liquid by using a simple air trap, consisting of a transparent cylinder in which air floats out of the water and is bled off periodically. Houlsby (1982) describes such a system. Houlsby (1983) reports that, with this system, flushing is needed at 3–6 month intervals, with additional attention to those piezometers showing marked differences in inlet and outlet gage readings. As indicated in Section 8.2.3, dissolved gas content should preferably be reduced to less than 1 part per million dissolved oxygen, either by using a water boiler made for the purpose or by using the patented Nold De-Aerator™. Both methods are described in Section 8.2.3.

E.1.6. Flushing Equipment

Various flushing systems are available from the manufacturers of twin-tube hydraulic piezometers, consisting of liquid containers, pumps, pressure gages, and associated pipework and valves. Examples, excluding the pumps, are shown in Figure E.1. Alternatively, the *Pressurized De-Aired Water Containment System,* manufactured by Walter Nold Company, Inc., can be used. The system consists of a portable tank that is filled, in a field laboratory or other on- or off-site facility, with de-aired liquid under pressure as shown in Figure E.2. The tank is then carried to the terminal enclosure, together with a regulator assembly, and used for flushing under controlled pressure. The arrangements in the terminal enclosure when this system is used are shown in Figure E.3.

As described in Section E.3, a vacuum is applied to the output line of each piezometer during flushing. Depending on site conditions, the vacuum may be created by a venturi-type ejector (e.g., Houlsby, 1982), driven by high pressure water or air, a hand pump, or an electric vacuum pump powered by mains supply or a portable generator. A trap is inserted at the output connection to contain returning liquid and is graduated for use in determining when the required volume of liquid has been replaced.

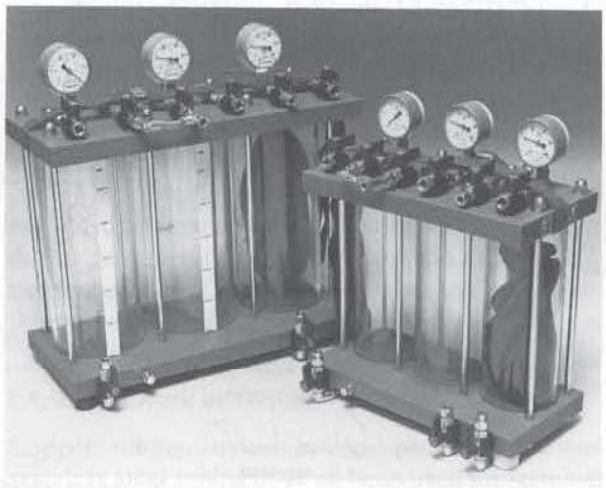

Figure E.1. Flushing equipment (courtesy of Geotechnical Instruments (U.K.) Ltd., Leamington Spa, England).

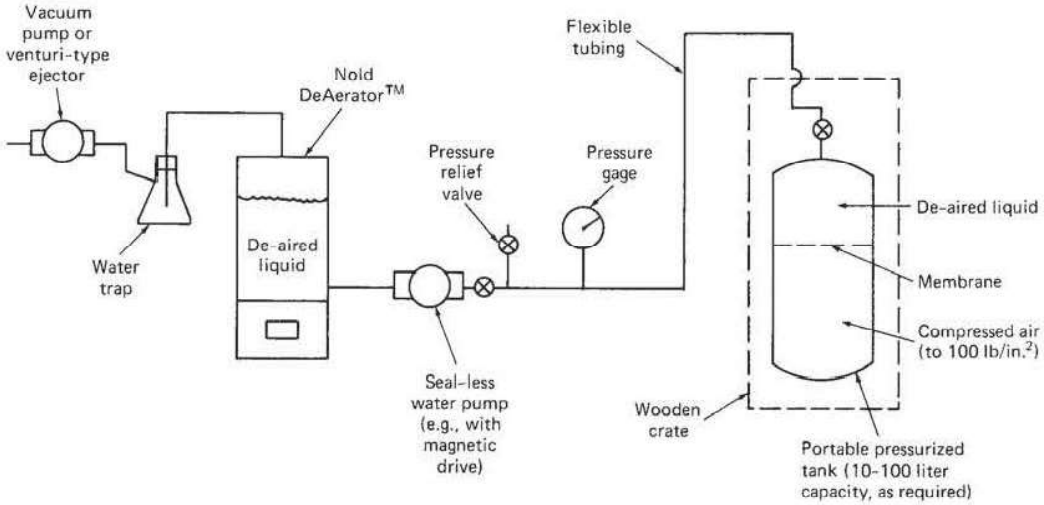

Figure E.2. Schematic of *Pressurized De-Aired Water Containment System* (courtesy of Walter Nold Company, Inc., Natick, MA).

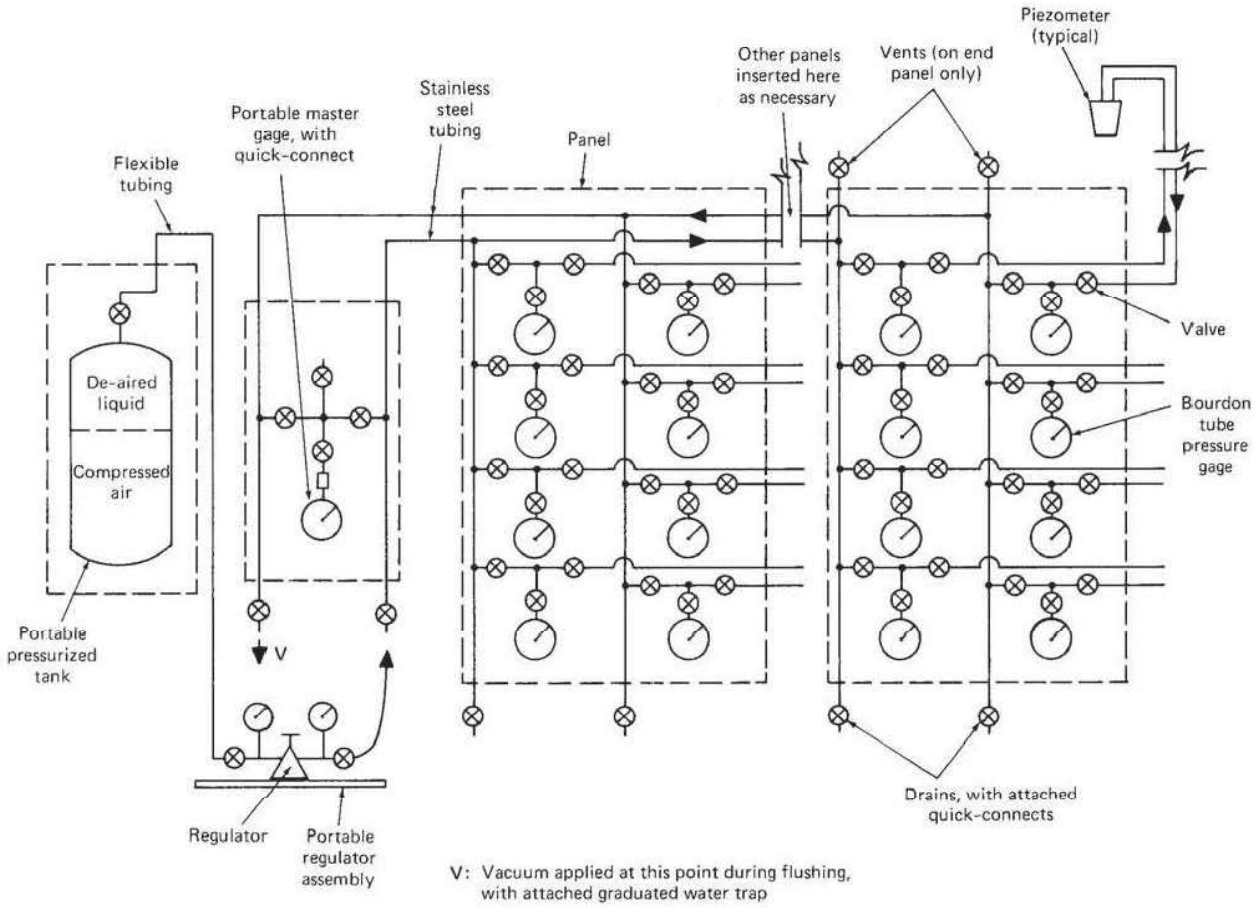

Figure E.3. Schematic of arrangements in terminal enclosure.

E.1.7. Pressure Measuring Equipment

Pressure measuring equipment can be Bourdon tube pressure gages, mercury manometers, or electrical transducers.

When opting for Bourdon tube pressure gages, the user must make a choice between inexpensive gages that will corrode and require replacement and gages that have a good chance of longevity. All readily available standard commercial gages in an affordable price range (less than about $500 U.S.) appear to have some aluminum components and are subject to corrosion. Some users in Australia favor a gage with a glass-filled nylon case, acetal copolymer movement, polycarbonate dial, nylon pointer, beryllium–copper Bourdon tube, and brass top connection, and Houlsby (1982) reports that these gages have virtually trouble-free internal workings. However, in the general case, any gage that allows air in contact with the internal parts may be subject to corrosion, and gages made from plastic and stainless steel and filled with transformer grade silicone oil are the most satisfactory choice when longevity is required. These gages are not standard items but are custom made by Walter Nold Company, Inc.* at a reasonable cost. Gages filled with glycerin are subject to excessive corrosion, because the glycerin contains water. A full-scale accuracy of $\pm 1\%$ is suitable.

Mercury manometers are sometimes the preferred choice, because of their durability and reliability, but mercury is a hazardous material and its use raises environmental concerns. Mercury manometers require greater reading skill than Bourdon tube pressure gages, and this skill may not always be available during the operating life of a dam. In fact, inexperienced personnel have on occasion blown mercury out of manometers while flushing the system, and it is not uncommon to find that mercury has entered the piezometer tubing. Electrical transducers with a digital display are available as an alternative to Bourdon tube pressure gages and manometers.

Figure E.3 shows the preferred layout of Bourdon tube gages, valves, and pipework in the terminal enclosure. Two gages are provided for each piezometer, so that no valve manipulation is needed when readings are taken, and relatively untrained personnel can therefore be used to take readings. A valve on the piezometer side of each gage allows isolation of the gage from the piezometer when checking and adjusting the gage against a *master* gage. This valve is normally left open at other times, and thus the pressure gages register direct hydraulic pressure from the tip and the reading operation consists merely of recording these pressures. The top connections to the gages minimize entrapment of gas, and the valve arrangement allows any malfunctioning gage to be removed and replaced easily.

The *master* gage is used for periodic checking of all active gages. Sometimes a gage with $\pm 0.25\%$ full-scale accuracy is permanently installed in the terminal enclosure, but such a gage is subject to deterioration. A better arrangement is to install a valve and quick-connect fitting for the gage and to store it in an indoor environment, attaching it to the terminal system only when periodic checks are to be made. There are two other available methods for checking active gages. First, a mercury/water manometer can be installed permanently in the terminal closure for this purpose, providing an inexpensive absolute standard that can be used both in the negative and positive range. However, use of mercury involves hazards and environmental concerns. Second, a dead weight tester can be used, but this is expensive and somewhat cumbersome and cannot be used to measure over the negative range.

E.1.8. Valves and Fittings in Terminal Enclosure

Terminal panel valves should be *no-volume change* ball valves.

Two options are available for selection of valves and fittings: stainless steel and brass. Type 316 stainless steel creates a *minimum maintenance* system, but at slightly greater procurement cost than brass. Brass is subject to corrosion by dissolved gases in the internal liquid and by a humid atmosphere, the maintenance obligation must be accepted, and vigilance on the part of reading personnel must be assumed. The assumption of vigilance during the operating life of a dam will often be unwarranted, and stainless steel valves and fittings are the preferred choice.

E.1.9. Pipework in Terminal Enclosure

Copper tubing, nylon tubing, plastic pipe, and stainless steel tubing have all been used for terminal enclosure pipework. Copper tubing is subject to corrosion, and plastic pipe creates difficulties in

*See Appendix D.

connecting to valves and fittings. Nylon tubing can be used, but it is probably worthwhile to include a polyethylene sheath, to minimize the permeability to water (Section 8.2.3). However, the flexibility of plastic tubing creates a need for a large number of attachment points between the pipework and panel. The preferred material is ⅜ in. (10 mm) stainless steel tubing.

E.1.10. Equipment for Automatic Operation

When electrical transducers are used for pressure measurement, automatic reading is possible, thereby reducing reading effort and cost. The terminal panel is provided with no-volume change electric solenoid valves that are used to link with each piezometer in turn, and a scanner and printer are connected. Scanning can be manual, continuous, or on a programmed cycle, and data can be recorded on paper, punch, or magnetic tape. Data can also be logged and interfaced with a microcomputer so that, by using appropriate software, a rapid assessment of embankment dam performance can be made. Use of an automatic reading system overcomes the sluggishness that otherwise arises when using twin-tube hydraulic piezometers with tubes longer than about 2000 ft (600 m), because the system can be programmed to connect to a piezometer and wait for a prescribed time before recording pressure and linking with the next piezometer.

When electrical transducers are used, their zero readings and calibration must be checked at least once a year against known pressures, and they must be protected from severe temperature changes.

Semi-automatic flushing equipment is manufactured for circulating a predetermined volume of de-aired liquid through each piezometer at a selected pressure and vacuum. An automatic version of the Nold DeAerator™ is available for continuous preparation of de-aired liquid.

E.1.11. Terminal Enclosure

As discussed in Chapter 21, vertical runs of tubing should be avoided wherever possible. Figure 21.8 shows acceptable and unacceptable arrangements for terminal enclosures.

The terminal enclosures should be buried in the fill, and it is often convenient to provide access from a berm. They should have an external waterproof coating, a good drain under the floor, and should be protected from freezing, if necessary either by heating or by constructing below the frost line. Guidelines on terminal enclosure design are given by USBR (1974). However, in the author's experience a *walk-in* terminal enclosure is preferable to a pit, because a person who descends into a pit is likely to have an adverse psychological reaction, and care over reading and maintenance is likely to be reduced.

All components should be wall-mounted, because components placed on the floor are subject to damage by water, dirt, and personnel. If the inside walls of terminal enclosures are painted, the paint should be selected carefully because certain paint solvents dissolve plastic tubing.

E.2. INSTALLATION

E.2.1. Installation of Cylindrical Piezometers in Boreholes

Various installation methods are described in Sections 9.17 and 9.18.

E.2.2. Installation of Bishop Piezometers in Fill

General guidelines on the installation of piezometers in compacted clay fill are given in Sections 9.15 and 17.6. The following installation sequence is recommended for Bishop piezometers:

- Perform all necessary tests on components.
- Complete construction of the terminal enclosure, and fill all appropriate components in the enclosure with de-aired liquid.
- Prepare the fill as described in Sections 9.15 and 17.6.
- Install tubing from terminal enclosure to piezometer location.
- Saturate the piezometer, as described in Section 9.14.
- Fill tubing with de-aired liquid, by pumping from the terminal enclosure.
- Cut tubing to length and attach to piezometer under water in a container.
- Measure the elevation of the water in the container, using surveying methods, and verify that the measurement agrees with the pressure indicated in the terminal enclosure.
- Form a tapered hole in the fill and press the saturated filter into place.

- Place backfill material as described in Sections 9.15 and 17.6.
- Take sufficient readings to indicate the minimum pore water pressure (maximum suction) achieved, for use as the initial reading for that piezometer.

The exact sequence for filling appropriate components in the terminal enclosure with de-aired liquid depends on the layout of tubing, valves, and gages, and a sequence should be developed that ensures complete filling. A detailed procedure for use with their system is included in the hydraulic piezometer users' manual by Soil Instruments Ltd. (Soil Instruments Ltd., 1983). Usually, the first step is filling the lengths of terminal panel tubing that serve more than one piezometer (often referred to as the *busbars*), by applying suction at one point and de-aired liquid under a low pressure at another point. The system unique to each piezometer is then filled, following the flushing procedure described in Section E.3: calculation of required pressures and volumes, and circulation of de-aired liquid.

Procedures for installation of tubing from the terminal enclosure to the piezometer location are described in Section 17.6, including trenching, filling, splicing, labeling, and a method devised by Clements (1982) for the installation of tubing on the surface of previously compacted fill. Guidelines on routing are given in Chapter 21. De-aired liquid can withstand significant subatmospheric pressure without the formation of gas bubbles. When the dissolved gas content has been reduced to below 1 ppm dissolved oxygen, a practical limit of subatmospheric pressure appears to be about 20 ft (6 m), and tubes should be routed so that no part is above the internal pressure head level by more than this amount. Even within this limit there is a tendency for gas bubbles to form with time, and if possible tubes should be routed so that a positive pressure exists at all times. Tubing should be installed below the frost line.

The Bishop piezometer is installed in relatively stone-free material by pushing a special mandrel into the soil to form a hole 12 in. (300 mm) deep. This leaves an impression into which the piezometer should fit exactly, making close contact with the surrounding material. The piezometer is pressed into place with the aid of an extension handle that is later removed, and above the piezometer the hole is backfilled with the excavated material after removal of any large stones. This material should carefully be compacted by tamping. If the fill is too hard for pushing or driving the mandrel, an auger or chisel can be used to create a hole slightly smaller than the mandrel, and this hole can finally be shaped with the mandrel.

E.3. MAINTENANCE

Maintenance entails regular checking of all components in the terminal enclosure and occasional flushing of the system with de-aired liquid.

Bourdon tube pressure gages (and electrical transducers if used) should be checked on a regular schedule against the master gage, mercury/water manometer, or dead weight tester. Valves are closed to isolate the master gage and each gage in turn from the rest of the system, and pressure is applied to pressurize the gages throughout their range. A piston device is available from some manufacturers of geotechnical instruments for this purpose. Equipment for automatic operation of course requires regular skilled maintenance.

If the system is properly designed, by using the components described in Section E.1, flushing is seldom necessary unless subatmospheric pore water pressures are being read. Flushing frequency should be determined on a site-specific basis, dependent on reading changes caused by flushing, and with a properly designed system may be as infrequent as once every 5 years.

The flushing procedure is described by Little and Vail (1960). Refer to Figure E.4:

u = pore water pressure in the fill at the piezometer,

p = pressure on the pressure side of the flushing equipment,

v = pressure on the vacuum side of the flushing equipment,

h = difference in head between the piezometer and the pressure and vacuum gages of the flushing equipment,

f_{AB} and f_{BC} = friction losses in the piezometer tubing.

All pressures are measured with respect to atmospheric pressure. For equilibrium,

$$p = h + u + f_{AB}$$

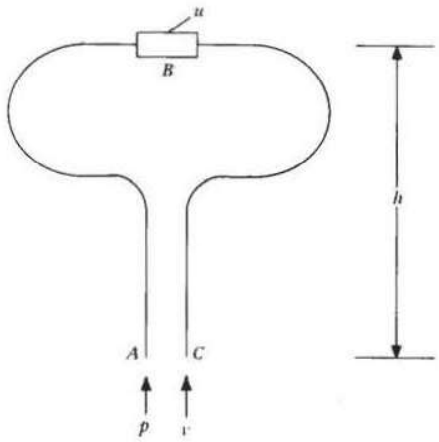

Figure E.4. Pressures during flushing (after Little and Vail, 1960).

and

$$v = h + u - f_{BC}.$$

Since $AB = BC$, and if no liquid flows in or out of the piezometer, the velocity will be the same throughout the system and

$$f_{AB} = f_{BC}.$$

Then

$$p = 2(h + u) - v.$$

In a piezometer installation h is known, v can be maintained at a known value, and u for each piezometer can be estimated using previous readings of pore water pressure. In this way, p can be calculated for each piezometer and de-airing carried out at the appropriate pressure. Examples of the calculation are given by Soil Instruments Ltd. (1983). Little and Vail (1960) advise that when a piezometer has accumulated a large amount of air, care should be taken to apply sufficient pressure to drive liquid at least as far as the piezometer before applying a vacuum to the other tube. If this is not done, air will be drawn in through the piezometer from the fill, because friction loss in the return tube carrying air is much less than in the one carrying liquid.

Vaughan (1974b) advises that it is desirable to maintain a small excess pressure at the piezometer tip for three reasons: first, to prevent air-saturated water being drawn from the soil; second, to avoid applying pressures that may rupture the soil; and third, to avoid a major drop in pressure in the return tube, which may cause air bubbles to come out of solution and create discontinuities in the liquid, and in some installations also cause cavitation. Figure E.5 shows the heads in the tubing during flushing. Vaughan comments that, to fulfill these requirements, it is often necessary to use a small differential pressure with a backpressure on the return tube. In these circumstances, the time for complete circulation may be long and automatic operation is helpful.

Prior to flushing, the volume of liquid required to fill the two tubes to each piezometer is calculated, and flushing is continued until at least this volume has emerged from the return tube. A check for leaks can be made by using tapered orifice flowmeters in the flushing panel system, one connected to the inlet and the other to the outlet tube. After flushing has been completed, appropriate valves closed or opened, and equilibrium has been established in the system, both pressure gages connected to each piezometer should show the same pressure. If the readings do not agree closely, it is probable that some air is present in the system, and further flushing is required.

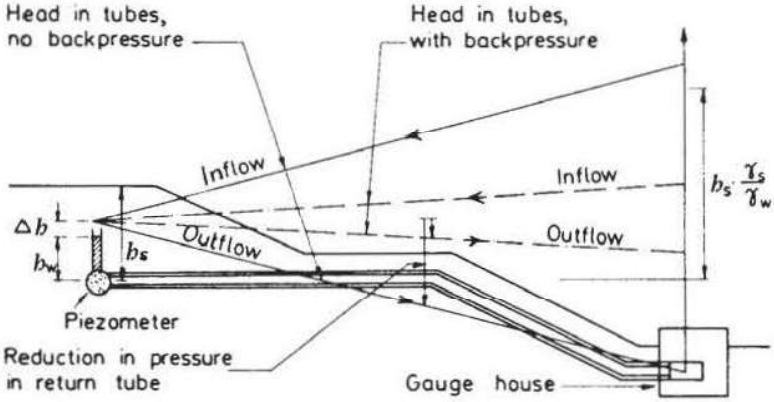

Figure E.5. Head in piezometer tubing during flushing (after Vaughan, 1974b).

APPENDIX F

DIMENSIONS OF DRILL RODS, FLUSH-JOINT CASING, DIAMOND CORING BITS, HOLLOW-STEM AUGERS, AND U.S. PIPE*

*Written with the assistance of Charles O. Riggs, Manager of Research and Marketing, Central Mine Equipment Company, St. Lous, MO.

Table F.1. Dimensions of Drill Rods

	Outside Diameter of Rod		Inside Diameter of Rod		Inside Diameter of Coupling[b]	
Size[a]	(in.)	(mm)	(in.)	(mm)	(in.)	(mm)
EX	1.312	33.3	0.844	21.4	0.437	11.1
AX	1.625	41.3	1.125	28.6	0.562	14.3
BX	1.906	48.4	1.406	35.7	0.625	15.9
NX	2.375	60.3	2.000	50.8	1.000	25.4
RW	1.094	27.8	0.719	18.3	0.406	10.3
EW	1.375	34.9	0.875	22.2	0.500	12.7
AW	1.750	44.4	1.219	31.0	0.625	15.9
BW	2.125	54.0	1.750	44.5	0.750	19.0
NW	2.625	66.7	2.250	57.2	1.375	34.9
HW	3.500	88.9	3.062	77.8	2.375	60.3
(L) AQWL	1.750	44.5	1.375	34.9	—	—
(C) AXWL	1.812	46.0	1.500	38.1	—	—
(L) BQWL	2.187	55.6	1.812	46.0	—	—
(C) BXWL	2.250	57.2	1.906	48.4	—	—
(L) NQWL	2.750	69.9	2.375	60.3	—	—
(C) NXWL	2.875	73.0	2.391	60.7	—	—
(L) HQWL	3.500	88.9	3.062	77.8	—	—
(C) HCWL	3.500	88.9	3.000	76.2	—	—
(L) PQWL	4.625[c]	117.5[c]	4.062	103.2	4.062	103.2
(C) CPWL	4.625	117.5	4.000	101.6	—	—

[a]X and W sizes are available from most manufacturers of drill rod. (L) indicates Longyear Company system. (C) indicates Christensen Dia-Min Tools, Inc. system.

[b]X and W series have a separate coupling. WL wireline series, except PQWL, are flush-joint, internally and externally, without a separate coupling.

[c]PQWL has a separate coupling, protruding outside the rod o.d., but internally flush. The outside diameter in table is o.d. of coupling. The outside diameter of rod is 4.500 in. (114.3 mm).

Source: Longyear Company and Christensen Dia-Min Tools, Inc.

Table F.2. Dimensions of Flush-Joint Casing

	Outside Diameter of Casing[a]		Inside Diameter of Casing[a]	
Size	(in.)	(mm)	(in.)	(mm)
RW	1.437	36.5	1.187	30.1
EW	1.812	46.0	1.500	38.1
AW	2.250	57.1	1.906	48.4
BW	2.875	73.0	2.375	60.3
NW	3.500	88.9	3.000	76.2
HW	4.500	114.3	4.000	101.6
PW	5.500	139.7	5.000	127.0
SW	6.625	168.3	6.000	152.4
UW	7.625	193.7	7.000	177.8
ZW	8.625	219.1	8.000	203.2

[a]No separate couplings. Connections are flush, internally and externally.

Source: Longyear Company and Christensen Dia-Min Tools, Inc.

Table F.3. Dimensions of Diamond Coring Bits

	Diameter of Core		Diameter of Borehole	
Size	(in.)	(mm)	(in.)	(mm)
EX, EXM	0.845	21.5	1.485	37.7
EWD3	0.835	21.2	1.485	37.7
AX	1.185	30.1	1.890	48.0
AWD4, AWD3	1.136	28.9	1.890	48.0
AWM	1.185	30.1	1.890	48.0
AQ Wireline, AV	1.065	27.1	1.890	48.0
BX	1.655	42.0	2.360	59.9
BWD4, BWD3	1.615	41.0	2.360	59.9
BXB Wireline, BWC3	1.432	36.4	2.360	59.9
BQ Wireline, BV	1.432	36.4	2.360	59.9
NX	2.155	54.7	2.980	75.7
NWD4, NWD3	2.060	52.3	2.980	75.7
NXB Wireline, NWC3	1.875	47.6	2.980	75.7
NQ Wireline, NV	1.875	47.6	2.980	75.7
HWD4	2.400	61.1	3.650	92.7
HXB Wireline, HWD3	2.400	61.1	3.650	92.7
HQ Wireline	2.500	63.5	3.790	96.3
CP, PQ Wireline	3.345	85.0	4.827	122.6

Source: Christensen Dia-Min Tools, Inc.

Table F.4. Dimensions of Typical Hollow-Stem Augers

Inside Diameter of Hollow-Stem		Outside Diameter of Flighting		Cutting Diameter of Auger Head	
(in.)	(mm)	(in.)	(mm)	(in.)	(mm)
2.25	57	5.625	143	6.25	159
2.75	70	6.125	156	6.75	171
3.25	83	6.625	168	7.25	184
3.75	95	7.125	181	7.75	197
4.25	108	7.625	194	8.25	210
6.25	159	9.625	244	10.25	260
8.25	210	11.625	295	12.5	318

Source: Central Mine Equipment Company.

Table F.5. Dimensions of U.S. Standard Weight Steel and PVC Pipe[a]

Nominal Diameter (in.)	Outside Diameter of Pipe (in.)	Outside Diameter of Pipe (mm)	Inside Diameter of Pipe (in.)	Inside Diameter of Pipe (mm)	Typical Outside Diameter of Steel Coupling[b] (in.)	Typical Outside Diameter of Steel Coupling[b] (mm)	Typical Outside Diameter of PVC Socket Coupling[b] (in.)	Typical Outside Diameter of PVC Socket Coupling[b] (mm)
⅛[c]	0.405	10.3	0.269	6.8	0.563	14.3	—	—
¼[c]	0.540	13.7	0.364	9.2	0.719	18.3	—	—
⅜[c]	0.675	17.1	0.493	12.5	0.875	22.2	—	—
½	0.840	21.3	0.622	15.8	1.063	27.0	1.125	28.6
¾	1.050	26.7	0.824	20.9	1.313	33.4	1.312	33.3
1	1.315	33.4	1.049	26.6	1.576	40.0	1.625	41.3
1¼	1.660	42.2	1.380	35.1	1.900	48.3	2.000	50.8
1½	1.900	48.3	1.610	40.9	2.200	55.9	2.250	57.2
2	2.375	60.3	2.067	52.5	2.750	69.9	2.750	69.9
2½	2.875	73.0	2.469	62.7	3.250	82.6	3.500	88.9
3	3.500	88.9	3.068	77.9	4.000	101.6	4.000	101.6
3½[c]	4.000	101.6	3.548	90.1	4.625	117.5	—	—
4	4.500	114.3	4.026	102.3	5.000	127.0	5.000	127.0
5[c]	5.563	141.3	5.047	128.2	6.296	159.9	—	—
6	6.625	168.3	6.065	154.1	7.390	187.7	7.687	195.2
8	8.625	219.1	7.981	202.7	9.625	244.5	9.937	252.4

[a] Standard weight pipe is also referred to as *Schedule 40* pipe. Steel pipe has threaded couplings. PVC pipe has cemented socket couplings (wall is generally too thin for threaded couplings).
[b] Outside diameters of couplings are not standard. Users should contact local pipe suppliers for diameters of couplings available from local sources.
[c] Not available in PVC.

Source: American Institute of Steel Construction, Nibco Inc., and Wheeling Machine Products Company.

Table F.6. Dimensions of U.S. Extra Strong Steel and PVC Pipe[a]

Nominal Diameter (in.)	Outside Diameter of Pipe (in.)	Outside Diameter of Pipe (mm)	Inside Diameter of Pipe (in.)	Inside Diameter of Pipe (mm)	Typical Outside Diameter of Steel Coupling[b] (in.)	Typical Outside Diameter of Steel Coupling[b] (mm)	Typical Outside Diameter of PVC Socket Coupling[b] (in.)	Typical Outside Diameter of PVC Socket Coupling[b] (mm)
⅛[c]	0.405	10.3	0.215	5.5	0.563	14.3	—	—
¼	0.540	13.7	0.302	7.7	0.719	18.3	1.000	25.4
⅜[c]	0.675	17.1	0.423	10.7	0.875	22.2	—	—
½	0.840	21.3	0.546	13.9	1.063	27.0	1.312	33.3
¾	1.050	26.7	0.742	18.8	1.313	33.4	1.562	39.7
1	1.315	33.4	0.957	24.3	1.576	40.0	1.875	47.6
1¼	1.660	42.2	1.278	32.5	2.054	52.2	2.250	57.2
1½	1.900	48.3	1.500	38.1	2.200	55.9	2.562	65.1
2	2.375	60.3	1.939	49.3	2.875	73.0	3.062	77.8
2½	2.875	73.0	2.323	59.0	3.375	85.7	3.625	92.1
3	3.500	88.9	2.900	73.7	4.000	101.6	4.312	109.5
3½[c]	4.000	101.6	3.364	85.4	4.625	117.5	—	—
4	4.500	114.3	3.826	97.2	5.200	132.1	5.500	139.7
5[c]	5.563	141.3	4.813	122.3	6.296	159.9	—	—
6	6.625	168.3	5.761	146.3	7.390	187.7	7.750	196.9
8	8.625	219.1	7.625	193.7	9.625	244.5	9.937	252.4

[a] Extra strong pipe is also referred to as *extra heavy* pipe and *Schedule 80* pipe. Steel pipe has threaded couplings. PVC pipe has either threaded or cemented socket couplings. PVC pipe can also be machined with threaded or cemented ends to form a connection that is flush on the inside and outside.
[b] Outside diameters of couplings are not standard. Users should contact local pipe suppliers for diameters of couplings available from local sources.
[c] Not available in PVC.

Source: American Institute of Steel Construction, Nibco Inc., and Wheeling Machine Products Company.

Table F.7. Dimensions of U.S. SDR 21, Class 200 PVC Belled End Pipe

Nominal Diameter (in.)	Outside Diameter of Pipe (in.)	Outside Diameter of Pipe (mm)	Inside Diameter of Pipe (in.)	Inside Diameter of Pipe (mm)	Typical Outside Diameter of Belled End[a] (in.)	Typical Outside Diameter of Belled End[a] (mm)
½[b,c]	0.840	21.3	0.696	17.7	0.99	25
¾[c]	1.050	26.7	0.910	23.1	1.19	30
1[c]	1.315	33.4	1.169	29.7	1.46	37
1¼[c]	1.660	42.2	1.482	37.6	1.84	47
1½[c]	1.900	48.3	1.700	43.2	2.10	53
2	2.375	60.3	2.129	54.1	2.62	67
2½	2.875	73.0	2.581	65.6	3.17	81
3	3.500	88.9	3.146	79.9	3.86	98
4	4.500	114.3	4.046	102.8	4.96	126
5[c]	5.563	141.3	5.001	127.0	6.13	156
6	6.625	168.3	5.955	151.3	7.29	185
8	8.625	219.1	7.755	197.0	9.49	241

[a]Type and outside diameters of belled ends are not standard. Users should contact local pipe suppliers for types and diameters available from local sources.
[b]Not available in SDR 21. Sizes given are SDR 13.5, Class 315.
[c]May not be readily available with belled ends.
Source: Harvel Plastics, Inc.

Table F.8. Dimensions of U.S. SDR 26, Class 160 PVC Belled End Pipe

Nominal Diameter (in.)	Outside Diameter of Pipe (in.)	Outside Diameter of Pipe (mm)	Inside Diameter of Pipe (in.)	Inside Diameter of Pipe (mm)	Typical Outside Diameter of Belled End[a] (in.)	Typical Outside Diameter of Belled End[a] (mm)
1[b]	1.315	33.4	1.175	29.8	1.46	37
1¼[b]	1.660	42.2	1.512	38.4	1.81	46
1½[b]	1.900	48.3	1.734	44.0	2.07	53
2	2.375	60.3	2.173	55.2	2.58	65
2½	2.875	73.0	2.635	66.9	3.12	79
3	3.500	88.9	3.210	81.5	3.79	96
4	4.500	114.3	4.134	105.0	4.87	124
5[b]	5.563	141.3	5.109	129.8	6.02	153
6	6.625	168.3	6.085	154.6	7.17	182
8	8.625	219.1	7.921	201.2	9.33	237

[a]Type and outside diameters of belled ends are not standard. Users should contact local pipe suppliers for types and diameters available from local sources.
[b]May not be readily available with belled ends.
Source: Harvel Plastics, Inc.

APPENDIX G

EXAMPLE OF INSTALLATION PROCEDURE, WITH MATERIALS AND EQUIPMENT LIST

The following example illustrates the level of detail required when preparing written installation procedures as described in Chapter 17.

The chosen example is installation of inclinometer casing in a vertical borehole through soft clay and into clayey sand, a few feet beyond the toe of a future embankment. Substantial vertical compression is predicted at the casing location; therefore, telescoping couplings have been selected. Because some lateral deformation may occur before vertical compression, couplings must allow for extension as well as compression. Previous borings in the clay have shown that borehole walls cannot be supported adequately by drilling mud, and drill casing will be required. The stratigraphy will not allow grout to bleed into the soil; thus, grout backfill can be used. The borehole is less than 100 ft (30 m) deep; therefore, buoyancy of the casing during grouting can be overcome by using a bottom weight, rather than by using the weight of the grout pipe. The "double-shutoff" arrangement (Figure 12.74) can therefore be used on the grout pipe.

It has been assumed that installations will be made by an instrumentation specialist working with a drilling contractor; therefore, no general contractor is involved. Plastic inclinometer casing will be used.

Some readers may argue that the level of detail in this example is not needed if *instrumentation specialists* are involved, and this of course is true if their experience includes previous identical installations. However, the author normally finds it worthwhile to write procedures in this detail, thereby ensuring that they are tailored to site-specific requirements and that all required materials and equipment are on hand.

Explanatory notes are in square brackets. In an actual installation procedure, these would be replaced by site specific requirements.

1. Complete appropriate parts of installation record sheet (Figures G.1 and G.2), including planned coordinates, ground surface elevation, two bottom cap dimensions as shown (F and length of perforated section), planned inclinometer casing groove orientation and top and bottom elevations, planned total length of inclinometer casing. Complete remainder of record as installation proceeds, and keep a time log.
2. Verify that all materials and equipment are readily available, as per Table G.1.
3. Prepare bottom casing section, with male quick-connect coupling. [Details depend on

Project Name _____

Inclinometer Casing No. _____

Planned Coordinates N _____ E _____

As-built Coordinates N _____ E _____

Start Date _____ Time _____ Finish Date _____ Time _____

Contractor _____ Contractor's Engineer _____

Driller _____ Owner's Representative _____

Type of Drill Rig _____ Size of Drill Casing _____

Ground Elevation _____ ft Borehole Diameter _____

Planned Groove Orientation _____

Planned Inclinometer Casing Bottom Elev. (A) _____ ft

Planned Inclinometer Casing Top Elev. (B) _____ ft

Planned Total Length of Inclinometer Casing (B − A) _____ ft

Length of Bottom Casing Section (C) _____ ft

Number of Standard Casing Sections = (B − A − C)/(section length + gap at coupling) = _____ (round up to integer)

Actual Total Length of Inclinometer Casing (C + D) _____ ft

Planned Depth to Bottom of Borehole _____ ft

Depth to Top of Clay _____ ft Depth to Bottom of Clay _____ ft

Actual Depth to Bottom of Borehole _____ ft

Calculated Grout Volume Required _____ gal

Inclinometer Probe Tracks Correctly: Yes/No

Length of Grout Pipe to Quick-Connect Shoulder (E) _____ ft

Stick-up of Grout Pipe _____ ft (Should be E + F − C − D)

Water Flows Through Grout Pipe: Yes/No

Grout Mix Used _____

Total Volume of Grout Used to Fill Hole _____ gal

Grout Inside Inclinometer Casing: Yes/No

If Yes, Comments _____

Actual Inclinometer Casing Top Elev. Before Cutoff (B′) _____ ft

As-built Inclinometer Casing Bottom Elev. (A′) _____ ft

Inclinometer Probe Tracks Correctly: Yes/No

Length of Inclinometer Casing Cut Off at Top _____ ft

As-built Inclinometer Casing Top Elev. After Cutoff _____ ft

As-built Groove Orientation at Casing Top _____
(Also draw diagram showing groove orientation, and orientation reference for inclinometer probe)

Groove Spiral Survey Needed: Yes/No Acceptance Test Satisfactory: Yes/No

Components Used During Acceptance Test (identification numbers of probe, readout, cable)

_____

NOTES ON BACK OF SHEET: (Notes on drilling, casing installation, grouting, problems encountered, delays, unusual features of the installation, or any other events that may have a bearing on inclinometer casing behavior.)

Figure G.1. Installation record sheet for inclinometer casing.

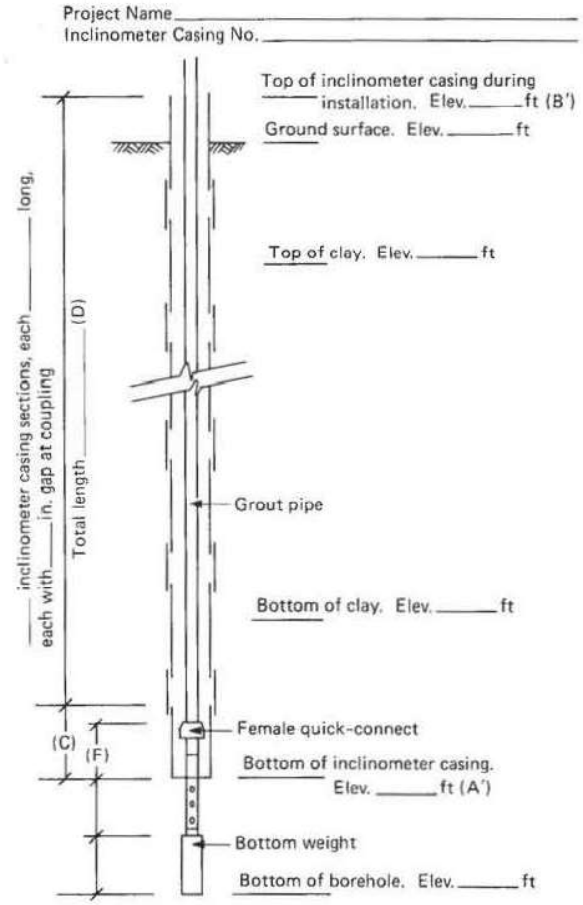

Figure G.2. Continuation of installation record sheet for inclinometer casing.

manufacturer. Use of the double-shutoff arrangement requires a special heavy-duty bottom cap assembly, which should be attached to the full wall thickness of the casing. Bottom cap connection must be fully grout-tight, often requiring filling casing grooves alongside cap with mastic. Tensile strength of connection must be sufficient to sustain total buoyancy force during grouting.] Allow solvent cement to dry overnight.

4. Estimate the buoyancy force that will be imposed on the casing when the annular space is filled with grout. [Use guidelines given in Chapter 17.] Assemble a weight, for attachment to the bottom cap, such that its buoyant weight is somewhat greater than the buoyancy force. Attach the weight to the perforated pipe on the bottom cap. Record length on record sheet. Attach a lowering line to the bottom cap.

5. Measure the length of the bottom casing section (C in Figure G.2). Determine the required initial gap between casing sections. [Base this on anticipated extension and compression.] Determine the number of standard casing sections required (see Figure G.1) and actual total length of inclinometer casing, and record. Lay out sufficient sections of casing for the depth of the borehole (estimated as ____ sections) on suitable aboveground clean surface such as sawhorses. If strong sunlight is anticipated, shade the casing. Inspect inside each casing section for groove burrs, and remove with casing brush. Measure groove spiral in each section [describe procedure, as in Chapter 12, if necessary], and mark magnitude and direction on outside of each section with waterproof marking pen. Reject any sections with excessive spiral. Sort casing sections and couplings into installation sequence to minimize cumulative spiral, and number in sequence.

6. Preassemble one coupling on to each casing section, to allow ____ in. [or ____ mm] extension and ____ in. [or ____ mm] compression at this connection. [These distances will depend on whether telescoping is possible at both or only one end of each coupling. If telescoping is possible at both ends, additional dimensions will be needed for Step 9. Connecting details depend on manufacturer, often requiring sealing mastic and tape to ensure grout-tightness. Care must be taken to avoid creating spiraled casing, and alternate couplings should usually be twisted left and right before fixing. Coupling sliding should be tight enough to hold in place during installation, but not too tight to inhibit later telescoping.] Do not attach a coupling to the upper end of the bottom casing section, as installation will be made with male end upward. [Often it is expedient to preassemble more than one casing section together, but generally 20 ft (6 m) is the maximum convenient length for handling.]

7. Plumb the drill rig carefully. Determine the required depth of borehole, allowing adequate depth for the perforated pipe on the bottom cap, weight, settling debris, base fixity, and stable length for inclinometer probe checks [if required]. Record on record

Table G.1. Materials and Equipment Required for Inclinometer Casing Installation[a]

Quantity	Description
____	Blank installation record sheets, on clipboard
____	Blank sheets for borehole log
____[b]	____ in. o.d. telescoping plastic inclinometer casing in ____ ft lengths
____[b]	____ in. o.d. telescoping inclinometer couplings, with necessary metal hardware
____	Top caps for inclinometer casing
____	Special heavy-duty bottom cap assemblies, with male quick-connect and perforated pipe: not attached to inclinometer casing
____ pint	Solvent cement (for bottom caps)
1	Pop-rivet gun (for bottom caps)
____[b]	Pop-rivets
1	Hand drill with two drill bits (for pop-rivets)
2	Wrenches or other tools for attaching coupling hardware
____ rolls	Sealing mastic [e.g., Scotch 2210 vinyl mastic rolls, 4 in. × 10 ft (100 mm × 3 m)]
____ rolls	Sealing tape [e.g., Scotch 33 vinyl plastic electrical tape, 1.5 in. × 44 ft (38 mm × 13 m)]
____	Bottom weights, ____ lb each
____ ft[b]	¼ in. (6 mm) manila rope for lowering line
1	Working surface for preassembly of casing (e.g., sawhorses), with shade cover if necessary
1	Inclinometer casing brush, with attached 20 ft (6 m) rope; also, means of attaching brush to bottom of grout pipe
1	Equipment for measuring groove spiral before installation
1	Builder's level for plumbing drill rig
1	Drill rig, with drilling and sampling tools [specify]
____ ft[b]	____ flush-joint drill casing
1	Clamping arrangement for withdrawing drill casing by attaching to outside
1	Cylindrical dummy, ____ in. o.d. for checking borehole depth
1	Grout mixer, suitable for mixing____/____ grout, with pump, hose and valve between pump and grout pipe, window screen
____ lb[b]	Materials for grout [Indicate mix required, and quantity of each ingredient. Allow at least 20% spare for waste. Use Figure 17.8 and add appropriate conversion factors in this table: see Appendix H, Section H.10.]
1	Calculator (for determining grout volumes)
1	Clean water supply, hose and valve [garden hose with gun-type spray fitting is ideal] for filling inclinometer casing with water during installation: alternatively, funnel and pail
2	Casing installation clamps
1	Inclinometer probe
____ ft	Graduated electrical cable for inclinometer
1	Inclinometer readout unit, with battery charger
1	Cable pulley and clamp
____ ft[b]	Grout pipe: 1 in. (25 mm) standard black steel pipe, threaded and coupled. Bottom thread connects to female thread on female quick-connect; top thread connects to grout hose
3	Female quick-connects, with o.d. to clear inner ends of metal hardware at couplings
____ rolls	Teflon tape (for grout pipe couplings)
____ sets	Top protective arrangements [e.g., length of 8 in. (200 mm) pipe with either screw cap or hinged cap with padlock, wooden barricade with flagging tape, and bright paint]
____	Paint for numbering installation
____	½ in. (13 mm) paint brushes
1 set	Equipment for surveying groove spiral after installation of casing
1	Pocket knife
1	Scissors
1	100 ft (30 m) measuring tape
1	Hacksaw and spare blades
1	Flat file
1	Pliers

Table G.1. Materials and Equipment Required for Inclinometer Casing Installation (*Continued*)

Quantity	Description
____	Clean rags
____	Paper towels
1	Field notebook
____	Waterproof marking pens
1	Camera and film (for record photographs)

[a][Additional equipment needed for reading includes field data sheets and calculation sheets. If automatic recording or data processing will be used, the following may also be needed: casette tapes, recorder paper, computer program, special connectors and switches, cassette tape reader. Arrangements should also be made for a backup reading system in the event of malfunction.]
[b][Add quantity for spares to replace components damaged during installation and for possible deeper boreholes than expected.]

sheet. Advance the borehole, employing drilling procedures that minimize soil disturbance and using ____ drill casing [flush-joint casing is preferred, inside diameter should allow a minimum of 0.5 in. (13 mm) diametral clearance at sealed couplings] and take samples [depends on site-specific needs]. Maintain a conventional borehole log. Record depth to top and bottom of clay and actual borehole depth. Wash out to bottom, using the *reverse circulation method* [Chapter 17], until water runs clear. Verify that the borehole is fully open to the bottom, by lowering a dummy with diameter approximately 0.25 in. (6 mm) less than the inside diameter of the drill casing.

8. Verify that all grouting materials and equipment are at the site and that the grout pipe is clean inside. Calculate required grout volume, and enter on installation record sheet [Use Figure 17.8.]
9. Insert inclinometer casing into drill casing, male end upward, with bottom section at lower end, lowering on lowering line and filling inclinometer casing with water. Maintain groove orientation parallel and perpendicular to toe of future embankment, adding inclinometer casing sections as installation proceeds, sealing all couplings thoroughly, setting lower end of each coupling to allow ____ in. [or ____ mm] extension and ____ in. [or ____ mm] compression. Use the special casing clamps to support the inclinometer casing temporarily on top of the drill casing while new sections are added.
10. When the bottom weight reaches the bottom of the borehole, verify correct groove orientation, and adjust as necessary by raising off the bottom and working slowly around while pulling and lowering on the lowering line. Set back on bottom of borehole. The top of the inclinometer casing should be above the top of the drill casing. Verify correct inclinometer probe tracking by running the probe down and up both groove pairs, with inclinometer cable connected to readout unit and power on. If the probe will not pass along the casing, or if it returns with one or more wheels disengaged from the grooves, withdraw inclinometer casing and diagnose problem. Couple grout pipe to female quick-connect and insert within inclinometer casing, using Teflon tape on all threads. Keep track of pipe lengths, and record total length to the female quick-connect shoulder. Keep pipe water-filled: this is very important because mating the quick-connects with air in the grout pipe is likely to cause soil particles to enter the quick-connects and prevent later closure. Maintain tension on the lowering line so that the bottom weight does not penetrate below the borehole bottom. Mate quick-connect. Verify that distance from top of grout pipe to top of inclinometer casing checks out, using the installation record sheet (Figure G.1). Verify that the inclinometer casing is at the correct elevation and that the lowering line is tight. (If the lowering line is left slack, the inclinometer casing can sometimes descend and the grout outlet holes in the perforated pipe may become sealed.)
11. Pump water through grout pipe and observe return from drill casing, to check that circuit is open. If the installation can be completed in a continuous operation (e.g., without an

overnight), proceed with the following steps. If not, raise the grout pipe to close the check valves and tie grout pipe to drill rig and, on resuming work, lower the grout pipe and again check the circuit.

12. Verify that the drill casing can be raised. Do not rotate the drill casing because rotation may cause spiraling in the inclinometer casing. Seal the top of the inclinometer casing, around the grout pipe, using rags and tape to prevent grout entry. Mix grout [include required mix and mixing sequence], circulating through pump and back into mixing tank until there are no lumps. Pump grout into grout pipe, using window screen as a filter over the suction intake, until grout overflows from drill casing, keeping track of grout volume pumped. Cut lowering line. Verify that the seal at the top of the inclinometer casing is intact, and withdraw all drill casing, without rotating. Top up with grout. Record grout volume used, and compare with calculated volume required. Withdraw grout pipe, allowing quick-connects to close. Remove female quick-connect and wash thoroughly. Flush grout pipe with water. Insert open-ended grout pipe within inclinometer casing and wash out. There should be no grout in the wash water. If grout appears, keep flushing and watch grout level outside inclinometer casing. Use a stiff brush attached to grout pipe to clean grooves as necessary. If grout is entering inclinometer casing, withdraw inclinometer casing, flush with water, flush hole, reinstall drill casing, diagnose problem, and start again. If in doubt, act quickly and withdraw inclinometer casing. Record actual top and as-built bottom casing elevations on installation record sheet. Repeat inclinometer probe tracking test.

13. After grout has set, cut inclinometer casing to length with a horizontal cut, record as-built top elevation on installation record sheet, insert top cap, construct permanent protective arrangements. Leave space within protective arrangements for attachment of the cable pulley and clamp to the top of the inclinometer casing; ensure that the inclinometer casing is concentric within the protective arrangements. Paint the instrument number on the protective arrangements.

14. Record the as-built groove orientation at the casing top. If problems have been experienced during installation such that excessive groove spiral is suspected or if accurate directional deformation data are required, make a groove spiral survey.

15. Establish an orientation reference for the inclinometer probe, to be used for all readings, and record on installation record sheet. [For a biaxial inclinometer, generally accepted practice is to orient the *A* transducer so that it will register deformation in the principal plane of interest as a positive change].

16. Take a minimum of two sets of inclinometer readings, compare the readings, study the *check-sums,* and evaluate whether data are within expected tolerances. This constitutes the *acceptance test*. Record the identification numbers of components used during the acceptance test.

APPENDIX H

CONVERSION FACTORS

To convert from a unit in the first column to a unit in the second column, multiply by the factor in the third column. For example,

$$2 \text{ inches} = 2 \times 25.4 \text{ millimeters} = 50.8 \text{ millimeters}.$$

To convert from a unit in the second column to a unit in the first column, divide by the factor in the third column. For example,

$$2 \text{ millimeters} = \frac{2}{25.4} \text{ inches} = 0.0787 \text{ inches}.$$

H.1. LENGTH

To Convert From	To	Multiply By
inches	millimeters	25.4
inches	meters	0.0254
inches	microns	25400
feet	meters	0.3048
yards	meters	0.9144

H.2. AREA

To Convert From	To	Multiply By
square inches	square millimeters	645.2
square feet	square meters	0.0929
square yards	square meters	0.8361

H.3. VOLUME

To Convert From	To	Multiply By
cubic inches	cubic centimeters	16.39
cubic centimeters	milliliters	1.000
cubic feet	cubic meters	0.0283
cubic feet	liters	28.32
cubic feet	U.S. gallons	7.48
cubic yards	cubic meters	0.7646
U.S. gallons	cubic inches	231
U.S. gallons	liters	3.785
U.S. gallons	cubic meters	0.00378
British gallons	cubic inches	277
British gallons	liters	4.546

H.4. MASS

To Convert From	To	Multiply By
pounds-mass	kilograms	0.4536
short tons[a]	pounds-mass	2000
short tons	kilograms	907.2
metric tons[b]	kilograms	1000
metric tons	short tons	1.102
long tons[c]	pounds-mass	2240
long tons	short tons	1.120

[a]The short ton is currently used widely in the United States.
[b]The metric ton is sometimes spelled *tonne*. ASTM recommends that metric ton be restricted to commercial usage and that the term *tonne* be avoided altogether.
[c]The long ton is the Imperial avoirdupois ton, now largely superseded by the use of SI units.

H.5. FORCE

To Convert From	To	Multiply By
pounds-force	newtons	4.448
kilograms-force	newtons	9.807
short tons-force	newtons	8896
kips	pounds-force	1000
kips	newtons	4448
metric tons-force	kilograms-force	1000
metric tons-force	short tons-force	1.102
long tons-force	pounds-force	2240
long tons-force	short tons-force	1.120

H.6. PRESSURE AND STRESS

To Convert From	To	Multiply By
pascals	newtons per square meter	1.000
pounds per square inch	kilopascals	6.895
pounds per square inch	feet head of water[a]	2.307
pounds per square inch	kilograms per square centimeter	0.0703
pounds per square inch	atmospheres[b]	0.0680
pounds per square foot	kilopascals	0.0479
kilograms per square centimeter	kilopascals	98.07
kilograms per square centimeter	pounds per square inch	14.22
atmospheres[b]	kilopascals	101.3
bars	kilopascals	100
bars	pounds per square inch	14.50
short tons per square foot	kilopascals	95.76
metric tons per square meter	kilopascals	9.807
feet head of water[a]	inches head of mercury	0.8826

[a] At 4°C.
[b] At standard temperature and pressure.

H.7. DENSITY AND UNIT WEIGHT

To Convert From	To	Multiply By
pounds per cubic foot	kilograms per cubic meter	16.02

H.8. TEMPERATURE

$$\text{Temp. in °F} = (9/5 \times \text{Temp. in °C}) + 32$$
$$\text{Temp. in °C} = 5/9(\text{Temp. in °F} - 32)$$

H.9. PLANE ANGLE

To Convert From	To	Multiply By
arc-minutes	arc-seconds	60
degrees	arc-minutes	60
degrees	radians	0.01745
radians	arc-seconds	2.063×10^5
gons[a]	radians	0.0157
gons	arc-seconds	3240

[a] 1 gon = 1 new degree = the 400th part of a circle.

H.10. USEFUL CONVERSION FACTORS FOR PREPARATION OF GROUT MIXES

1 U.S. gal = 231 in.^{3} = 3.79 liters

1 ft^3 = 7.48 U.S. gal

1 British gal = 277 in.^{3} = 4.55 liters

Density of water = 62.4 lb/ft^3 = 1000 g/cm^3

1 U.S. gal of water weighs approx. 8.3 lb

1 U.S. gal of cement weighs approx. 12.6 lb

1 U.S. gal of powdered or granular bentonite weighs approx. 9.0 lb

1 British gal of cement weighs approx. 6.9 kg

1 British gal of powdered or granular bentonite weighs approx. 4.9 lb

1 ft^3 of cement weighs approx. 94 lb

1 ft^3 of powdered or granular bentonite weighs approx. 67 lb

1 U.S. bag of cement usually weighs 94 lb

1 U.S. bag of powdered or granular bentonite usually weighs 50 lb or 100 lb

1 U.S. bag of hydrated lime usually weighs 50 lb

1/1 water/cement ratio by volume is equivalent to 0.67/1 by weight

H.11. PREFIXES FOR SI UNITS

The following prefixes are used in the SI (Système International: the international system of units) system:

Factor	Prefix	Symbol
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^1	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n

REFERENCES

Abbreviations

AIME	American Institute of Mining, Metallurgical, and Petroleum Engineers
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia
ICOLD	International Congress on Large Dams
ISRM	International Society for Rock Mechanics
SM & FE	Soil Mechanics and Foundation Engineering
USCOLD	United States Committee on Large Dams

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JOHN DUNNICLIFF is a geotechnical instrumentation specialist who has served as a consulting engineer on numerous projects both in the U.S. and overseas. He received master's degrees in soil mechanics and foundation engineering from Oxford and Harvard Universities, respectively.

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