Appendixes

Appendix A. Instrument capabilities for measuring land-surface displacement

INSTRUMENT	AVAILABILITY	INSTRUMENT CHARACTERISTICS	DATA COLLECTION CHARACTERISTICS: REMOTE OR DIRECT	DATA COLLECTION CHARACTERISTICS: ENTER SUBSIDENCE AREA	RANGE	ACCURACY	SENSITIVITY TO ENVIRONMENT	CALIBRATION AND MAINTENANCE	EASE/COST OF INSTALLATION	EASE/COST OF OPERATION	POWER REQUIREMENTS	EASE/COST OF DATA REDUCTION	COST OF INSTRUMENT
Steel tape (structure and surface strain, surface and structure crack movement)	Lufkin; Chesterman; Kueffel & Esser	Portable, rugged, long life	Direct	Yes	100 ft usually; available in 3 to 300 ft lengths	±0.01 ft	Temperature; wind; tension	Periodically clean, oil, and calibrate against standard tape	Install reference points	2 tapemen plus 1 man to set stakes; use with tensioning device, taping pins, plumbbob	None	Simple	100 ft: $30 to $300
Invar tape (structure and surface strain, surface and structure crack movement)	Keuffel & Esser	Portable, prone to breaking	Direct	Yes	50 ft to 100 ft	±0.005 ft	Wind; tension	Clean periodically	As above	2 tapemen; use with tension frames and weights; for high accuracy repeat readings with 3 tapes	None	Simple	100 ft: $300 150 ft: $400
Precision level (automatic or tilting with optical micrometer) with invar rod (structure and surface settlement; with tape or tape extensometer for ground tilt)	Jenoptik; Kern; Wild; Leitz; Zeiss	Portable, rugged, long life	Direct	Yes	Maximum change in elevation between sights approx. 13 ft; sight length greater than 7 ft and less than 150 ft	±0.002 ft to ±0.005 ft over mile circuit	Wind; bright sunlight	Check telescope alignment annually	Install reference points and bench marks	1 instrument man; 1 rod man	None	Simple; need 1 engineer; may use computer to reduce large volume of data	Level: $850 to $1500; rod: $700
Precision theodolite with tape for baseline (triangulation) (surface and structure settlement and strain)	Kern; Wild; Jenoptik; Leitz	As above	Direct	No		1 sec instrument read to 0.2 sec by angle repetition: 1:20,000 to 1:50,000; best positional accuracy ±0.001 in ±0.005 ft	Temperature; wind; vibration; direct sun; temperature sensitivity minimal with invar tape	As above	Install reference points and 3 instrument stations	1 surveyor; and 1 rod man if targets not fixed; 2 men needed for taping of baselines between instrument piers	None	As above; computer programs readily available	Precision Theodolite: $3000 to $9000
Optical electronic distance measurement device (EDM) (use with theodolite if not built-in) (structure and surface strain)	First developed 1948; AGA; Kern	Portable; retroreflectors may be portable or fixed to reference point	Direct	Yes-rod man only	20,000 ft	±0.02 to 0.2 ft plus 1:25,000 to 1:650,000 Mekometer 3000: ±0.0007 ft plus 1:1,000,000 (as good as invar)	Temperature and pressure along line of sight; smog can disrupt readings; may be used day or night	Calibrate against 50 meter invar tape every two years	Install reference points	1 surveyor plus 1 laborer if retroreflectors portable or adjustable; lower cost per mile of traverse than conventional methods	Rechargeable battery for 1 day's work	Distance usually automatic; a few provide only phase shift and surveyor must convert to distance	Typical EDM: Mekometer 3000: $34,000; reflectors: $0.50 to $410
Infrared EDM (use with theodolite if not built-in) (structure and surface strain and settlement)	Wild; AGA; Kern; Keuffel & Esser; Zeiss; HP; Precision; Cubic Corp; Tellurometer	As above	Direct	Yes-rod man only	1000 to 16,000 ft; minimum; 1 ft	Typically 0.02 ft plus 1:100,000 to 1:300,000; Tellurometer MA 100; 0.002 ft over 300 ft	Temperature and pressure; less sensitive than other EDM's; can use day or night and in bright sun	As above	As above	As above	Rechargeable battery for 1 day's work	Distance usually automatic; most have automatic correction for temperature and pressure	Reflectors: $0.50 to $260 each; EDM: $3000 to $7000 without theodolite; Tellurometer MA 100.
Infrared EDM (3-D trilateration) (structure and surface settlement and strain)	As above	As above	Direct	No	As above	As above	As above	As above	Install reference points and instrument stations	1 surveyor	As above	As above; reduce distances to EDM to coordinates	As above
Laser EDM (structure and surface strain)	Developed late 1960's; AGA	As above	Direct	Yes-rod man only	5000 to 20,000 ft	±0.01 to 0.08 ft and 1:1,000,000; ±0.015 over 19 miles	Temperature and pressure; smog; dust; fog; air turbulence; sensitive to vibration	As above	As above	1 surveyor and 1 rod man	Lower power consumption than other EDM's; rechargeable battery for 1 day's work	Distance automatic	
EDM tachymeter (distance, angles, horizontal distance and elevation automatically computed) (structure and surface settlement; and strain)	AGA geodimeter models 700 and 710; Wild model DI-3S	Portable	Direct with portable reflectors Remote with fixed reflectors	Yes-rod man only	1000 to 15,000 ft	.02 ft plus 1:1,000,000 to .02 ft plus 5:1,000,000	Temperature; pressure; vibration; dust	As above	Install reference points; install instrument stations if used	1 surveyor and 1 rod man, if targets not fixed	Rechargeable battery for 1 day's operation	Automatic data reduction; surveyor may have to enter horizontal or vertical angle to get horizontal distance and elevation (DI-3S only)	$18,000; $10,000 (DI-3S without theodolite); reflectors $0.50 to $260 each

INSTRUMENT	AVAILABILITY	INSTRUMENT CHARACTERISTICS	DATA COLLECTION CHARACTERISTICS: REMOTE OR DIRECT	DATA COLLECTION CHARACTERISTICS: ENTER SUBSIDENCE AREA	RANGE	ACCURACY	SENSITIVITY TO ENVIRONMENT	CALIBRATION AND MAINTENANCE	EASE / COST OF INSTALLATION	EASE/COST OF OPERATION	POWER REQUIREMENTS	EASE / COST OF DATA REDUCTION	COST OF INSTRUMENT
Rod extensometer with dial gauge (ground or structure strain and crack movement)	Terrametrics; Structural Behavior Engineering Laboratories or user fabricated; Nason (1971)	Permanent for monitoring period; recoverable rugged and dependable	Direct	Yes	Displacement ranges to 1.0 in., resettable gauge length 10 in. to 20 in.; if user fabricated gauge length may be 10 feet	Sensitivity of 0.0001 in.	Susceptible to vandalism unless protected; sensitive to temperature	Calibrate with standard reference bar; easy to replace	Embed reference points in soil, rock or structure and attach bar; provide protection for instrument	Simple; one person to read; can use camera recorder and replace film periodically	Battery for camera	Convert dial readings to displacement; temperature correction	$100 to $800
Steel tape extensometer (ground or structure strain, convergence)	Sinco; Irad; Terrametrics; Interfels; Soiltest	Portable; dependable	Direct	Yes	Displacement ranges of 0.01 in. to 100 ft; gauge length 2 ft to 100 ft	±0.01 in.	Reference points susceptible to damage; sensitive to temperature	Problems with tape breaking; calibrate with standard reference bar; oil periodically and check tensioning device	Embed reference points in soil, rock or structure	Simple; one or two people to attach extensometer to reference points, apply tension and read; two people need two hours for 15 readings	None	Direct readout of distance makes data reduction simple; temperature corrections	$500 to $1500
Invar wire extensometer (ground or structure strain, convergence)	Telemac; Kern	Portable	Remote	Yes	Displacement ranges of 2.5 in. to 4.0 in.; gauge length of 3 ft to 150 ft	±0.0008 in. to 0.002 in.	Reference points susceptible to damage; insignificant temperature effects	Calibrate with standard reference bar; clean periodically and check tensioning device as well as zero drift of readout	As above	As above	12 VDC	Digital readout of distance makes data reduction simple	$4800
Rod extensometer with LVDT (ground and structure strain and crack movement)	User fabricated; Kennedy (1971)	Permanent for monitoring period; may be recoverable; suitable for long-term monitoring	Remote	No	Displacement ranges of 0.10 in. to 6 in.; gauge length 5 ft to 10 ft	±0.001 in. possible; infinite resolution	Electronics not very sensitive to vibration or temperature, but susceptible to changes in line resistance, cable length, or input voltage variance; may be subject to corrosion, vandalism and sensitive to temperature	Check for zero drift; easy to replace; calibrate with standard reference bar	Embed reference points in soil, rock or structure, and attach bar; provide protection for instrument; establish zero reading; enclose in telescoping casing for monitoring convergence	Simple, one person to take reading	None	Direct reading of distance makes data reduction simple; apply temperature correction	LVDT $200; transducer amplifier and recorder readout $800; cable $14/20 ft
Rod extensometer with machinist's scale (ground and structure strain and crack movement)	User fabricated; Utter and Tescn (1965)	May be permanent for monitoring period or may be portable	Direct	Yes	Displacement ranges of 0.1 in. to 10 ft; typical gauge length 3 ft to 10 ft	Sensitivity of 0.01 in.	Susceptible to corrosion, vandalism and sensitive to temperature	Clean periodically, calibrate with standard reference bar; easy to repair	Embed reference points in soil, rock or structure; provide protection for instrument	Simple; one person to take reading	None	As above	Materials and labor $500
Rod extensometer with micrometer (surface or structure strains and crack movement)	Micro-precision Engineering Livermore, CA Burland and Moore, 1973	Portable	Direct	Yes	Displacement ranges of 0.001 in. to 3.0 in.; typical gauge length 10 ft	±0.005 in.; sensitivity of 0.0004 in.	Reference points susceptible to damage; sensitive to temperature unless invar	Clean periodically; calibrate with standard reference bar; easy to repair	Embed reference points in soil, rock, or structure	One or two people to move bar, adjust micrometer and take reading	Penlight battery	Direct readout of distance makes data reduction simple, temperature correction	Materials and labor $600

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Single point or multi-point Terzaghi differential settlement manometer (structure settlement)	Serata; Galileo	Readout and hoses can be permanent or portable	Direct	Yes	Up to 50 ft of settlement; distances up to 1000 ft between reference points	±0.25 in.	Susceptible to barometric pressure variation, heating due to sunlight, temperature variations, and vandalism; water cannot be used in freezing conditions	Hoses must be free of air bubbles, dirt, algae, little difficulty to repair or replace hoses; survey elevation of readout stations before each observation	Install reference points on structure; provide protection for readout and hoses if permanent installation	Simple; two technicians for portable system, one for permanent installation; repeat measurement for each data point, and allow ample time for stilling oscillations	None	Convert pressure differences or graduated scale reading to elevation	Multiple points and terminal point apparatus $150 to $500; deairing unit $300 to $800
Single point simple hose manometer (structure or surface settlement)	Soil and rock instrumentation; also user fabricated; Dunnicliff (1971)	Permanent for monitoring period; may be recoverable	Direct	No, if hose is long enough	Up to 20 ft of settlement	±0.50 in.	As above	Hoses must be free of air bubbles, dirt, algae; difficult to repair or replace hoses; survey elevation of readout station before each observation	Hose placed in trench of uniform grade below frost depth and buried; provide protection for readout device; readout must be installed below lowest point along hose	Simple; one person to take reading	None	As above	Readout $150; tubing $0.30/ft deairing unit $300 to $800
Single point or multi-point electrical contact type hose manometer (structure or surface settlement)	Soil and Rock instrumentation; Soil Instruments	As above	Direct	As above	Up to 3 ft of settlement	±0.10 in.	As above; problems with electronics likely; mercury is used in freezing temperatures	As above	As above; install readout at same elevation as manometer hose	Simple; one person to adjust readout, establish electric contact, and take reading	Battery	As above	100 ft long manometer with readout, electronics, mercury and nitrogen regulation, single point $250, multi-point $450; deairing unit $300 to $800
Single point overflow type manometer (structure or surface settlement)	Telemac; Soil Instruments; Galileo	As above	Direct	As above	Up to 3 ft of settlement	±0.20 in.	Susceptible to barometric pressure variation, heating due to sunlight, temperature variations, freezing conditions and vandalism	As above	As above; overflow cell is buried; readout must be installed below lowest point along hose	Simple, one person to add water, confirm overflow and get reading	None	Convert graduated standpipe or pressure gage reading to elevation	Overflow cell $32; graduated standpipe $35; tubing $25/100 ft; deairing unit $300 to $800
Full profile overflow type manometer (structure or surface settlement)	Telemac	Permanent for monitoring period; recoverable	Direct	As above	Up to 10 ft of settlement	±0.30 in	As above	As above	Casing is placed in trench and buried; readout and pulley system installed in pit with protection provided	One person to move prove, add water, confirm overflow and get reading	None	As above	Readout: manual $3000; digital $4500
Full profile air balloon in liquid filled tube settlement device (structure or surface settlement)	Soil Instruments	Probe and readout are portable	Direct	As above	Up to 10 ft of settlement	±0.60 in.	Susceptible to variations in temperature and pressure; cannot be used in freezing conditions; possible electric problems with transducer and readout	Periodic calibration of transducer; calibrate steel tape with reference tape or bar; survey elevation at each readout station before each observation	Tube placed along trench, kept straight, brought to surface on gentle curve, and buried	One person to move probe and take reading	Battery	Convert electric readouts to elevation	Available with electromagnetic torpedo to monitor horizontal movement $1500; casing $3/ft
Full profile two liquid pressure balance manometer (structure or surface settlement)	User fabricated; O'Rourke (1977)	Permanent for monitoring period; may be recoverable	Direct or Remote	As above	Up to 20 ft of settlement	±0.25 in.	As above	As above; calibration risers along tube allow for in-situ calibration along profile	Tubing with calibration risers placed along trench of uniform grade below frost depth and buried	One person to move two liquid interface along tube, calibrate and take readings	None for manual readout; battery for automatic readout	Convert readings on pressure gage to elevation for manual readout. Automatic readout gives scaled chart recording of tubing elevation	Tubing $0.30/ft; manual readout $4000; automatic readout $5500
MPBI with fixed electrolytic level sensors (surface settlement)	User fabricated; Cooke and Price (1973)	Permanent for monitoring period; recoverable	Remote	No	±30 minutes; can be mechanically extended to 6 degrees down, 3 degrees up	3 min.	Sensitive to moisture, changes in line resistance and cable length; temperature does not affect calibration, but zero reading is sensitive to temperature variation and twist of casing	None; difficult to remove sensors for repair or replacement	Install sensors in flexible casing along trench and bury	Simple, one person to adjust levels and take reading	Battery or AC main	Convert voltage or digital readout to displacement	

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Electrolytic type tiltmeter (ground tilt)	BAC	Portable; long service records; permanent installation for best accuracy	Remote	Yes	0.5 to 1.0 degree	1.0 to 2.0 seconds of arc	Sensitive to temperature; possible electric problems including zero drift due to residual instability of metals and cements; permanent installation may be subject to vandalism	Check for zero drift	Install base plates on reference stations	One person with moderate training to take reading; portable device must be mounted on base plate for each reading	Battery	Convert digital readout to tilt angle	readout $1500; stations to $100 each
Spirit level type tiltmeter (ground tilt)	Galileo	Portable; rugged long operating life	Direct	Yes	0.5 to 1.0 degree	5.0 to 10.0 seconds of arc	Moderately sensitive to temperature; reference points may be subject to vandalism	Check zero by readings at 180 degrees	As above	Simple; one person to mount level and read	None	Simple; direct readout of tilt angle is given	readout $1200; stations to $100 each
Vibrating wire type tiltmeter (ground tilt)	Telemac; Maihak	Portable, rugged long term stability	Remote	Yes	1.5 degree	0.3 to 10.0 seconds of arc	Relatively insensitive to temperature or moisture; reference points may be subject to vandalism	None	As above	One person to mount tiltmeter and take reading; time and training required depends on readout device used	Battery	Convert vibrating frequency, analog reading, or digital readout to tilt angle	Tiltmeter $1200; readout $3000 to $4500
Force balance servo-accelerometer type tiltmeter (ground tilt)	Sinco; Terra; Technology; Schaevitz; Geotesting	Portable; moderately delicate	Remote	Yes	±30 degrees	10.0 to 80.0 seconds of arc	As above	None	As above	One person with moderate training to mount tiltmeter and take reading	Battery	Convert digital readout to tilt angle	Tiltmeter $2900; readout $1100
Rod extenso-meter with micrometer and spirit level (ground tilt)	Micro Precision Engrg; Galileo	Portable; rugged	Remote	Yes	0.5 to 1.0 degree	5.0 to 10.0 seconds of arc	Moderately sensitive to temperature; reference points may be subject to vandalism	Check zero by readings at 180 degrees	Reference points embedded in soil, rock or structure	One person with moderate training to mount bar, adjust level and read	None	Simple; direct readout of tilt angle is given	$3500
Rod extenso-meter with leveling bubble and levelling screw, and linear potentiometer, LVDT, or dial gauge (ground tilt)	User fabricated; Hendron, et al, (1975), Nason (1971)	Permanent for monitoring period	Direct	Yes	5.0 degrees	50.0 seconds of arc	Susceptible to corrosion and vandalism unless protected	None	Extensometer mounted on reference points embedded in soil, rock or structure	Simple, one person to adjust screw and take reading	None	Convert leveling screw reading to tilt angle	$1500 to $3500

Appendix B. Capabilities of existing subsidence monitoring instruments

PROPERTIES / INSTRUMENT	AVAILABILITY	OPERATING PRINCIPLE	DEPTH RANGE	RANGE OF VERTICLE DISPLACEMENT	MANUFACTURER'S SENSITIVITY	ACCURACY	MAXIMUM DOWNHOLE TEMPERATURE: RATED OR (ESIMATED)	MAXIMUM DOWNHOLE PRESSURE: RATED OR (ESTIMATED)	MATERIAL COMPOSITION	OPERATION and INSTALLATION (IMPORTANT FEATURES)	MAINTENANCE RE-QUIREMENTS & ESTI-MATED SERVICE LIFE	SELECTED REFERENCES
WIRE-TYPE BOREHOLE EXTENSOMETER: weight-tensioned: weight anchored; with rotary potentiometer or water-level recorder at surface (USGS compaction meter)	Sinco; user-fabricated (4)	Note (a) Measure vertical-displacement between two markers at depth by comparing results of adjacent installation; access to borehole not necessary but wire must be free to move between borehole and transducer outside well. A straight hole (<1/2° inclination) is desirable to reduce friction (3)	Maximum: 600m; Typical; up to 300m	Total: 25-50mm, resettable with water-level recorder; 2.7m maximum with rotary potentiometer.	±0.3mm	Total 1 to 1.5 mm (3) reported. Note: friction drag at stress reversals may limit total length accuracy to ±3 to ±8 mm (5)	(500° C. (2) above which strength loss may become important); no provision for downhole temperature measurement.	not applicable	wire usually stainless steel; may be plastic coated; typically 1/8 in. AISI 302 stranded aircraft cable	Movement between surface and anchor seen as rotation of pulley at surface; counter-weight at surface maintains constant tension on wire ideally, but friction of wire may affect tension (6)	Weight anchors maybe lifted out of borehole to replace wire; Under severe geothermal conditions, pitting corrosion rate may be 0.15 mm•month. So a 3 mm wire would sever in 1-1/2 years. Note: Due to general corrosion, the wire may last 100 years, given a rate of 0.5g/m^2•day	(1) Toliva, 1970 (2) Phillips and Sykes, 1970 (3) De Loos, 1973 (4) Lofgren, 1969 (5) Riley, 1969 (6) Bull and Miller, 1975 (7) Lofgren, 1961
WIRE-TYPE BOREHOLE EXTENSOMETER; weight-tensioned; with grout or mechanical anchor; dial gauge or sensor at surface	Interfels; user-fabricated (1), (2)	as above	Typical: up to 100m	Total: 10-50mm resettable	±0.5 to 1.0mm	Total: 1.5 to 3mm estimated	as above	not applicable	as above; wire may be encased inplastic tubing	Multiple wire installations possible, but may not be practical in deep holes; see note a; easy to reset range	Anchor and wire system usually not removeable; life under severe geothermal conditions may be 1-1/2 years	(1) Waddell, 1964 (2) Sellers, 1969 (3) Cording et al, 1975
WIRE-TYPE BOREHOLE EXTENSOMETER; spring-tensioned; with grout or mechanical anchor; and dial gauge or micrometer sensor at surface	Terrametrics; Peter Smith; Serata	Wire stretched between anchor at depth and spring-loaded reference point at surface. Movement between surface and anchor seen as displacement of sensing rod contact spring	Maximum: 450m Typical: 15-90m	Total: 90-150mm	±0.03mm	Total: ±0.1mm to 2.5mm reported; Under mining conditions, accuracy of single measurment reported to be ±0.2 to 3mm, while survey accuracy tying in borehole collars was ±6mm	as above	not applicable	as above	Multiple wire installations possible, but may not be practical in deep holes; see note a; easy to reset range. Relatively rugged compared to electrical transducers. Stretch of wire due to change in spring tension added to readout value.	as above	(1) Potts, 1964 (2) Dunnicliff, 1970
WIRE-TYPE BOREHOLE EXTENSOMETER; cantilever tensioned; with grout or mechanical anchor; and cantilever-mounted electrical resistance strain gauge sensor at surface	Terrametrics	Wire stretched between anchor and cantilever spring at surface. Movement between surface and anchor causes bending of cantilever and resistance change in strain gauge	Typical: 150m	Total: 15mm resettable	±0.01mm	Total: ±0.5mm estimated	as above	not applicable	as above	Multiple wire installations possiblem but may not be practical in deep holes. See note a. Sensitive to moisture; zero drift can cause problems	as above; except sensor may require recalibration or replacement at more frequent intervals	(1) Sellers, 1969 (2) Dunnicliff, 1970
WIRE-TYPE BOREHOLE EXTENSOMETER; spring tensioned; mechanical or grout anchor; rotory potentiometer sensor at surface	Sinco	Wire stretched from anchor, over pulley (to which potentiometer is coupled)to spring. Movement between surface and anchor seen as pully rotation	Typical: 100m assumed	Total: 50mm resettable	±0.05mm	Total: ±1.5mm estimated	as above	not applicable	as above	as above	as above	(1) Dunnicliff, 1970
WIRE-TYPE BOREHOLE EXTENSOMETER; cantilever tensioned; mechanical or grout anchor; cantilever-mounted vibrating-wire strain gauge sensor at surface	Telmac	Wire stretched between anchor and cantilever spring at surface. Movement between surface and anchor causes bending at cantilever and changes natural frequency of vibrating wire	Typical: 100m	Total: 50mm	±0.01mm	Total: ±1.5mm estimated	as above	not applicable	Stainless steel wires	as above; but somewhat more resistant to environmental problems	as above	(1) Dunnicliff, 1970
ROD-TYPE BOREHOLE EXTENSOMETER; with mechanical or grout anchor; with dial gauge or micrometer sensor	Irad; Interfels; Terrametrics: Huggenberger Soil Instruments	Movement between anchor and surface appears as translation of top of rod relative to surface; Displacement of top of rod detected by sensor	Maximum: 500m Typical: 30-180m	Total: 10-50mm resettable Add rod lengths as required in extention: in compression, can cut rod as needed	±0.01mm to ±0.03mm	Total: ±0.02mm to ±0.6mm estimated	as above	not applicable	Rod generally stainless steel; occasionally aluminum. May be plastic coated of cased in plastic tube. Anchor usually cadmium plated mild steel, or cast iron. Rod is typically small diameter 6mm solid rod - 17mm pipe.	Note C: Access to borehole not required; but top of rod must be free to move between borehole and transducer. Rod installed in flexible tube if hole unstable and requires grouting. A straight hole (1/2° inclination) is desirable to reduce friction. If multiple installation not practical for deep hole, measure vertical displacement between 2 markers at depth by comparing results of adjacent installations.	Typical rod (pipe) wall thickness is 3mm. Based on pitting corrosion rate of 0.15mm/mo(1). The service life would be about 1-1/2 years. If some pinholes can be tolerated, service life may be as long as 100yrs., based on a general corrosion rate of 0.5m^2/day.(1)	(1) Toliva, 1970 (2) Cording, et al., 1975 (3) Seller, 1969
ROD-TYPE BOREHOLE EXTENSOMETER; with mechanical or grout anchor; with linear potentiometer sensor	Interfels; Sinco; Irad; Soil Instruments	as above	Typical: 30m to 180m	total: 10-150m	±0.01mm to 0.1mm	Total: ±0.2 to ±2mm, estimated	as above	not applicable	as above	as above	as above; Wiper-contacts of potentiometer may degrade and wear and require replacement or recalibration within 1 year.	
ROD-TYPE BOREHOLE EXTENSOMETER; with mechanical or grout anchor; with LVDT sensor	Interfels	as above	Typical: 30m to 180m	Total: 12 mm, resettable	±0.01mm to ±0.1mm	Total: ±0.2 to +2mm estimated	as above	not applicable	as above	as above	as above; except service life of LVDT should be somehat longer than for potentiometer if adequately sealed.	
ROD-TYPE BOREHOLE EXTENSOMETER; with mechanical or grout anchor; with vibrating wire strain gauge sensor	Maihak	as above	Typical: 30m to 180m estimated	Total: 6 to 100mm	±0.003mm to ±0.03mm	Total: ±0.05 to ±1.25mm reported; but friction may make +0.05mm unrealistic	as above	not applicable	as above	as above	as above; except service life of vibration wire strain gauge should be several years	

TABLE 2.11 CAPABILITIES OF EXISTING SUBSIDENCE MONITORING INSTRUMENTS •VERTICAL DISPLACEMENTS• Sheet 2 of 4

PROPERTIES / INSTRUMENT	AVAILABILITY	OPERATING PRINCIPLE	DEPTH RANGE	RANGE OF VERTICLE DISPLACEMENT	MANUFACTURER'S SENSITIVITY	ACCURACY	MAXIMUM DOWNHOLE TEMPERATURE: RATED OR (ESIMATED)	MAXIMUM DOWNHOLE PRESSURE: RATED OR (ESTIMATED)	MATERIAL COMPOSITION	OPERATION and INSTALLATION (IMPORTANT FEATURES)	MAINTENANCE REQUIREMENTS & ESTIMATED SERVICE LIFE	SELECTED REFERENCES
ROD-TYPE BOREHOLE EXTENSOMETER, with mechanical or grout anchor; attached wire at surface with scale readout	User fabricated (1)	Movement between surface and anchor seen as translation of top of rod relative to surface; wire attached to rod goes over pulley and is tensioned by a weight. Elevation of wt or rotation of pulley also are measurements of displacement	Typical: 100m	1m	±2.5mm	Total: ±15mm estimated	as above	not applicable	as above	as above	as above	(1) Howell, Wright, and Dearinger, 1976
ROD-TYPE BOREHOLE EXTENSOMETER, with two concentric rods; mechanical anchors; and dial gauge readout (DOUBLE-POINT BOREHOLE EXTENSOMETER)	Irad; Telemetrics	Inner rod anchored at base of borehole. Outer rod extends only partway down the hole and is anchored. Movement between surface and other anchor seen as translation of top of appropriate rod relative to surface; position of inner or outer rod relative to fixed measuring surface read with dial gauge	Maximum: 15m	Total: 100-300m Can be increased in extension with extension rods by 600m	±0.01	Total: ±0.5mm estimated	as above	not applicable	Outer rod: galvanized steel (Irad); probably 15mm. Inner rod: stainless steel.	See note (c); Hole can be grouted if extensometer tools placed in protective tubes; not for use in cased holes	Probably not recoverable for replacement. Corrosion resistance will be higher for all stainless steel assembly; removal of galvanized coating will be rapid; sealing may impede movement between concentric pipes. Service life probably less than 1 year due to corrosion of outer rod and due to scaling	
PIPE-TYPE BOREHOLE EXTENSOMETER, anchored by own weight, attached wire at surface with water level recorded readout	User fabricated (1), (2), (3)	Movement between surface and anchor seen as translation of top of pipe relative to surface; wire attached to pipe goes over pulley and is tensioned by weight. Elevation of weight or rotation of pulley are also measurements of displacement	Maximum: (3)1200m Typical: 300-600m	Total: 25-50mm resettable	±0.01mm to ±0.03mm	Total: 0.2 to 0.6mm estimated	as above	not applicable	Cast iron (3); low alloy steel possible; pipe typically 50mm to 100mm diameter	Pipe usually installed in metal cased hole, often abandoned well; pipe usually found ~5 to 10m below base of casing. See note (c)	Pipe stands on shoe; can probably be removed for replacement, but with difficulty. Typical wall thickness for pipe cited is 4mm for general corrosion rate of 6g/m•d(4); it would last a maximum of 10 years in a sever geothermal environment.	(1) Fulchner, 1977 (2) Komaki, 1969 (3) Hirono, 1969 (4) Toliva, 1970
MULTIPLE BASE LENGTH EXTENSOMETER, with inductance sensors, mechanical metal anchors	Telmac	Central rod, able to move freely in hole, contains inductance-type sensors. When rod moves relative to concentric anchors, inductance sensors detect relative position of each anchor	50m estimated; Maximum of 1 sensor per meter	Maximum: 125mm	0.01mm	Total and interval: 0.02 mm claimed	50°C	(500 KN/m^2 estimated)	Probably stainless steel	Access to hole not necessary, but instrumented rod must be free to displace toward surface. Will not work in metal casing; probably o.k. if anchors installed outside flexible plastic casing	Central rod containing electronics has no mechanical coupling to anchors, so probably could be replaced. Under geothermal conditions, central rod and electronics housing may suffer pitting and corrosion. Electronics as designed not suitable for geothermal environment; life in non-geothermal environment probably 1 yr. Longer if rod replaced	
MULTIPLE BASE LENGTH EXTENSOMETER, with reed switch sensors; and magnetic markers	User fabricated (1, 2, 4)	Permanent, moveable central rod contains reed switches, at approximately same spacing as magnets anchored outside borehole casing. Reed switches may be paired or single. Rod installed so initially each reed switch approximately opposite magnet. Movement of measuring rod needed to align reed switch with corresponding magnet measured with micrometer. Can replace rods with tape for easier handling	30-70m	Total: 150-250mm Intervals: 150-250mm	±0.02mm to ±0.1mm	±0.1mm(1) reported with rods ±0.15mm(2) with tape	(50°C estimated; possibly higher since reed switches can operate to 200°C)	(700 KN/m^2 estimated based on depth range)	Rod: thin-walled stainless steel tube with precision connectors. Tape: Stainless steel. Brass housing for reed switches	Access to hole not necessary, but instrument must be free to displace toward surface. May be slightly influenced by steel casing and accuracy reduced due to distortion of magnetic field.	Central rod can be withdrawn or replaced but with loss of accuracy. Stainless steel tape or tube would become severely pitted in 1 1/2 years of service, based on pitting corrosion rate of 0.15mm/month. (3) Electronics as designed not suitable for geothermal environment Life probably 1 yr under non-geothermal conditions; longer if rod replaced	(1) Burland, Moore and Smith, 1972 (2) Smith and Burland, 1976 (3) Toliva, 1970 (4) Burland and Moore, 1973

TABLE 2.11 CAPABILITIES OF EXISTING SUBSIDENCE MONITORING INSTRUMENTS •VERTICAL DISPLACEMENTS• Sheet 3 of 4

PROPERTIES / INSTRUMENT	AVAILABILITY	OPERATING PRINCIPLE	DEPTH RANGE	RANGE OF VERTICLE DISPLACEMENT	MANUFACTURER'S SENSITIVITY	ACCURACY	MAXIMUM DOWNHOLE TEMPERATURE: RATED OR (ESIMATED)	MAXIMUM DOWNHOLE PRESSURE: RATED OR (ESTIMATED)	MATERIAL COMPOSITION	OPERATION and INSTALLATION (IMPORTANT FEATURES)	MAINTENANCE REQUIREMENTS & ESTIMATED SERVICE LIFE	SELECTED REFERENCES
CHAIN-TYPE EXTENSOMETER, mechanical or grout anchor, with linear potentiometer or LVDT sensor	Soil Instruments; Interfels	Device consists of a linear sensor housing in a steel case, and fixed to a concrete anchor or anchor plate. A moveable rod extends from the sensor case at 2nd anchor, 1 m or more away. Movement between anchored sensor case and 2nd anchor detected by sensor. Extensometers can be coupled by using 2nd anchor of 1st extensometer to anchor sensor case of next extensometer	Typical: 60-100m, but lead wire could extend several hundred m. from last sensor to readout	Maximum: 10mm to 300mm per sensor	±0.1mm to ±1.0mm	Interval: ±2 to 5mm estimated Total: assuming 10 sensors @10 ft centers, ±7 to ±16mm estimated	(0-50°C, estimated)	(1000KN/m^2 estimated)	Probably stainless steel	Generally used in dams or fills. Requires well compacted fill or soft grout around anchors and no casing in hole. Rods may be protected by flexible plastic casing. Only lead wires exit at surface; no access to borehole necessary	Cannot be repaired or replaced. Life limited by sensors; LVDT probably more reliable than linear potentiometer. Life probably 1 year under non-geothermal conditions	
SONDE-TYPE EXTENSOMETER, with induction sensor and metal markers	Telmac; Maihak; Terrametrics; Sinco; Soil Instruments	Probe lowered down hole on cable; when it passes anchored metal marker, current change induced in secondary coil and detected at surface. Depth of marker is length of cable played out	Typical: 75m to 100m; Maximum: 300m	Ideally unlimited; but depends on casing; up to ≈ 17% strain possible, based on typical elastic compressibility of casing	±0.1mm to ±1.5mm	Interval: 1.25 to 5mm reported Total: 5 to 10 mm estimated	up to 110°C	(3000KN.m^2 estimated, based on depth range)	Casing usually plastic. Metal markers may be any common metal. Instrument housing stainless steel	Best when hole within 3° of vertical. Markers anchored outside flexible plastic casing. Access to hole required. Not for use in metal casing	If probe can be modified to take geothermal conditions, will be easy to maintain since removed between readings	
SONDE-TYPE EXTENSOMETER, with 2 or 3 induction sensors; and "casing collars" as markers (CASING COLLAR LOCATOR)	Provided as a service only; by Dresser-Atlas, Schlumberger, and others	Sonde consists of 2 or 3 probes rigidly connected in series. Works like above sonde but senses change in metal thickness at collars; distance between adjacent markers determined by cable played out between probe detection upper marker (collar) and lower probe detecting lower marker (collar). Depth of probe also determined by wheel on tool which tracks against edge of casing. Wheel has several attached magnets, and each partial rotation of wheel detected by reed switch tool. With triple sensor data can be calibrated in-situ using known distance between 1 pair of sensors	Maximum: 1500m	Ideally unlimited; but depends on compressibility of metal casing and casing/ground bond	±3mm[(4)] improved to about ±0.1mmat Gronigen[(2)]	Interval: ±15mm reported (1) for double; ±3.5mm for triple (2) Total: ±0.05m(2)	(Probably up to 120°C; typical for production logging tools.) At Gronigen[(2)], induction sensors connected by invar mandrel to minimize temperature effect	(Probably 70,000KN/m^2 maximum typical for production logging tools)	Instrument housing stainless steel. Casing: low-alloy steel, standard oil-well casing	Operates in cased hole. Accessible hole required. Works best in holes where casing collar has a recess to provide sharp signal [(2)]	as above	(1) Allen, 1960 (2) deLoos, 1973 (3) Allen, 1971 (4) Allen, 1968
SONDE-TYPE EXTENSOMETER, with reed switch sensor (lowered on cable) and magnetic markers	Soil Instruments; Terra Technology; ELE	Probe lowered down hole on cable. When it passes anchored magnetic marker, reed switch closes and detected at surface. Depth of marker is length of cable played out, and is measured with steel tape	Typical: 100m	Ideally unlimited, but depends on casing. Up to 17% strain possible.	±1-2mm[(1)]	Interval: 1-2mm reported[(1)]; Total: ±2.5mm reported for 30m; ±5mm estimated for 100m. Accuracy limited by steel tape	(Probably up to 120°C as above; Reed switched can tolerate up to 200°C)	(1000 KN/m^2 estimated; based on depth range)	Probe in brass or stainless steel housing. Magnet probably Alnico. May be coated with epoxy[(1)]	Operates in hole cased with non-magnetic casing. Accessible hole required; Magnets anchored to ground outside casing or attached to flexible casing cemented to ground. Magnets may also be pneumatically forced into ground.	as above	(1) Burland, Moore, and Smith, 1972 (2) Marsland and Quarterman, 1974
SONDE-TYPE EXTENSOMETER, with two reed switch sensors and magnetic markers (lowered on rods)	Soil Instruments;	Probe lowered down hole on coupled rods. Probe consists of two reed switches spaced 0.5-1.0m apart; magnets also spaced at this depth. Depth of marker determined by rod used to lower probe. Distance between adjacent markers determined by rod movement between upper reed switch detecting lower magnet. Incremental rod travel measured with micrometer	30m estimated	Total: as above Interval: 150-250mm	±0.05mm	±2mm estimated ±0,1mm claimed by mfg.	(50°C, estimated)	(300KN/m^2 estimated based on depth)	Stainless steel rods; stainless steel housing	As above; requires hole with minimal curvature since not very flexible	as above	
SONDE-TYPE EXTENSOMETER, with radioactive bullet markers and 2 or 3 gamma-ray detectors (GAMMA-RAY LOGGER)	Provided as a service only; by Dresser-Atlas, Schlumberger, and others	Sonde consists of 2 or 3 probes (usually rigidly) connected in series. Signal is sent to surface when x-ray detector locates bullet. Depth determined by amount of cable played out and rotation of tracking wheel-(see casing-collar locator). Distance between adjacent markers determined by amount of cable played out between upper probe detection of upper bullet and lower probe detection of lower bullet. With 3 detectors, can use 1 pair for in-situ calibration	1500m	Unlimited because bullets outside casing in formation	±0.1mm	Depends on logging rate; works best at slow rate (1.5m/min[(1)]or less[(4)]). Accuracy probably higher than for casing collar locator once strain exceeds elastic limit of casing; Interval: ±30mm error in 2-detector tool[(2)] can be reduced to ±3mm error in 3-detector tool[(1)]; Total: ±10 to 120mm[(1)]	(200°C, estimated; typical for x-ray logging tools) Tool cooled with dry ice (3)	(140,000 kN/m^2; typical for x-ray logging tools)	Bullets are 10μ Curie Cesium 137(1) at Gronigen and 1-6μ Curie in Japan(4) Invar housing[(1)1cp]	Operates in cased, open hole; since bullets are shot into formation with perforating gun, best to them install before casing. Otherwise, to prevent leakage, only production zone can be marked. May be impossible to place bullets in hard formations such as anhydrite and dolomite.(1) Can install free-hanging casing length inside completed borehole with R/A bullets welded at known intervals to use as in-situ calibration for tool. In Japan, welded buttons to production casing to get compaction of casing as well as ground(4).	If tool can be modified to meet geothermal environment, should be easy to maintain since portable. Some problem may arise if R/A bullets are dislodged or diffuse into formation	(1) deLoos, 1973 (2) Allen, 1969 (3) Allen, 1977 (4) Sano, 1969 (5) Allen, 1971
SONDE-TYPE EXTENSOMETER, with latching pawls to detect casing collars	Soiltest; Sinco; Soil Instruments; Geotesting	When probe lowered down through small dia,. coupling into larger diameter casing, pawls will lock if pulled upward against smaller x-section. Depth measured on graduated tape at these x-sections	Typical: 100m	Total interval: 3-6% vertical strain; limited to allowable movement per coupling	±1 to ±3mm	Interval: ±10m estimated Total: ±40mm estimated Best when hole within 25° of vertical	(50°C, estimated)	(1000 kN/m^2 estimated; but should operate if some leakage occurs)	Chrome/brass or galvanized steel	Requires cased hole with telescoping tubing and collars which have a different I.D. from casing. Latching mechanism released when probe hits hole bottom, allowing withdrawal. Requires applied upward force at regular intervals to detect collars	Tool has moving mechanical parts; although portable, may be difficult to modify for geothermal conditions	

PROPERTIES / INSTRUMENT	AVAILABILITY	OPERATING PRINCIPLE	DEPTH RANGE	RANGE OF VERTICLE DISPLACEMENT	MANUFACTURER'S SENSITIVITY	ACCURACY	MAXIMUM DOWNHOLE TEMPERATURE: RATED OR (ESIMATED)	MAXIMUM DOWNHOLE PRESSURE: RATED OR (ESTIMATED)	MATERIAL COMPOSITION	OPERATION and INSTALLATION (IMPORTANT FEATURES)	MAINTENANCE REQUIREMENTS & ESTIMATED SERVICE LIFE	SELECTED REFERENCES
SONDE-TYPE BOREHOLE INCLINOMETER; with pendulum and LVDT sensor	Galileo; Dames and Moore	As probe inclines, pendulum remains vertical. The LVDT measures the displacement of the bottom of the pendulum relative to the instrument case. Depth determined by amount of cable played out at measuring point.	300m estimated	12°	±1 min	±10 min estimated	(50°C, estimated based on typical electronics)	(3000 KN/cm^2, estimated based on depth)	Probably stainless steel housing; casing usually grooved PVC.	To get orientation, must install in grooved or square casing, survey initially for spiral; for best results, casing should be telescoping if cemented or keyed to surrounding ground. Casing may be inserted inside flexible grouted casing. Take readings at intervals corresponding to tool length.	Probe temporary; if it can be modified to meet geothermal conditions, it should be easily maintained. Scaling and distortion of casing groves may limit life. Casing materials now used not suitable for geothermal environment.	
SONDE-TYPE BOREHOLE INCLINOMETER; with pendulum and linear potentiometer sensor	Sinco	As probe inclines, pendulum remains vertical. Pendulum contacts resistance element fixed to case. Resistance varies with angle between pendulum and instrument case. Depth determined by amount of cable played out at measuring point.	300m	12° - 25°	3 min	±20 min estimated	(as above)	1400 KN/m^2	Probe has brass housing, casing usually aluminum or plastic	as above	as above	Wilson, 1962
SONDE-TYPE BOREHOLE INCLINOMETER; with pendulum and servo-accelerometer	Terra-Technology; Geo-Testing; Sinco	As probe inclines, pendulum remains vertical. This system measures force required to return pendulum to initial alignment in probe. Depth determined by amount of cable played out at measuring point.	300m	Typical: 25° 45-90° available	±10 sec	±1 min reported (1)	Typical: 50°C, up to 90°C available	Typical: 3500 KN/m^2 up to 140,000 KN/m^2 available	Probe has stainless steel housing; wheel may be aluminum, stainless steel, or hard plastic; cable cased in hard polyurethane or neoprene.	as above	as above	(1) Brownwell, Ryan and Toth, 1971
SONDE-TYPE BOREHOLE INCLINOMETER; with pendulum and air pressure device	TerraTech, developmental	As above except: Tilt measured by pneumatic force (air pressure) required to return pendulum to original alignment in probe.	100m estimated		±35 sec	±3 deg estimated	(50°C estimated)	(1000 KN/m^2 estimated	Probably stainless steel housing	as above	as above	Dunnicliff, 1970
SONDE-TYPE BOREHOLE INCLINOMETER; with cantilevered pendulum and vibrating wire strain gauges	Maihak; Telemac; Geonor; ELE	Cantilever with weight at unsupported end bends as probe tilts. Bending of cantilever measured by vibrating wire strain gauge.Depth determined by amount of cable played out at measuring point.	300m estimated	Typical: 6-30°	±30 sec - ±2 min	±3 to 4 min reported	(50°C estimated based on typical electronics)	(3000 KN/m^2, estimated based on depth)	Probably stainless steel housing. Casing usually grooved, PVC.	as above	as above	
SONDE-TYPE BOREHOLE INCLINOMETER; with cantilevered pendulum and bonded electrical resistance strain gauges	Soil Instruments: Soiltest	Cantilever with weight at unsupported end bends as probe tilts. Bending of cantilever measured by electrical resistance strain gauges.Depth determined by amount of cable played out at measuring point.	200m	5° to 30°	±15 sec to ±40 sec	±1 min(1) reported for shallow depths	(as above)	(2000 KN/m^2, estimated based on depth)	Chrome plated brass or stainless steel housing; neoprene sheathed cable, stainless steel wheels.	as above	as above	(1) Kallstenius and Bergau, 1961
SONDE-TYPE BOREHOLE INCLINOMETER; with pendulum, compass and camera	Sperry Sun; Schlumberger	As probe inclines, pendulum remains vertical. Camera photographs pendulum position relative to compass fixed to case. Depth determined by amount of cable played out at measuring point.	Deep holes more than 6km	2° to 130° available			Maximum: 315°C for 5hrs; with special instrumentation; Typical: 175°C	140,000 KN/m^2	Probably stainless steel housing.	Instrument determines both orientation and tilt; camera operated by timer; accuracy of depth measurement associated with angle measurement will be low unless used as a single-shot device.	Probe temporary; if can be modified to meet geothermal conditions, should be easily maintained	
SONDE-TYPE BOREHOLE INCLINOMETER; pendulum, linear potentiometer, compass and rotary motor	Eastman	For compass orientation, rotary motor rotates mirror until indicator facing north. For angle from vertical as probe tilts, pendulum remains vertical. Pendulum contacts resistor fixed to case. Resistance varies with angle between pendulum and instrument case.	450m - 540m	more than 30°; can used at any angle	1° for tilt; 2° for orientation		(50°C estimated)	6300 KN/m^2	Chrome plated bronze case	Determines inclination and orientation; device also contains TV camera	as above	
SONDE-TYPE BOREHOLE INCLINOMETER; with gyro-compass camera, and pendulum	Service tool only; by Sperry Sun, Schlumberger	As probe inclines, pendulum remains vertical. Camera photographs pendulum position relative to gyro-compass, fixed to case.	6.2km reported; maximum range probably 9km	2° to 90°		±15 min tilt; 1° to 3° orientation	190°C reported, with thermal shield for up to 11.5 hrs.	(112,000 KN/m^2 estimated, based on depth and muds reported)	Housing K-Monel	Determines inclination and orientation	as above	Oil and Gas Journal, 1971
SONDE-TYPE BOREHOLE INCLINOMETER; with needle-pointed pendulum and punchable chart	Totco	as probe inclines pendulum remains vertical. At pre-set time point of pendulum punched chart fixed to probe, giving inclination of probe. Depth determined by amount of wire-line played out.	6-10Km estimated	7, 14, 21 deg	8 min	15 min estimated	Special models available for warm(<150°C and hot(<300°C estimated) holes.	(100,000 KN/m^2 estimated, based on depth)	Probably stainless steel housing	Make reading at one depth only - gives tilt only - not orientation. Must be retrieved to determine tilt. Tilt simply determined by examining chart with magnifying glass, will operate in any type of hole, cased or uncased.	as above	
FIXED BOREHOLE DEFLECTOMETER with cantilever mounted electrical resistance strain gauge sensors	Telemetrics	Steel tubes anchored in hole and connected to adjacent tubes by cantilever. Angular movement between two tubes causes cantilever to bend. Bending sensed by strain gauges.	54m with 6m intervals between cantilevers		±3 sec	±20 sec	50°C	(540 KN/m^2 estimated based on depth)	Tubes are stainless steel	Designed for use in uncased hole but could be installed in flexible casing. Orientation must be determined when installed	Permanent; may be impossible to recover or repair; electronics will require modification for geothermal environment; stainless steel housing may leak after several years service, due to pitting or corrosion.	
FIXED BOREHOLE DEFLECTOMETER with inductive sensor	Interfels	Steel tubes anchored in hole and connected by tensioned wire. Position of wire changes as angular movement between tubes occur. Movement detected by inductive sensors	54m with up to 8 measuring elements	35min/element; resettable	±2 to ±20 sec	±1 to 3 min estimated	(50°C estimated)	(540 KN/m^2 estimated based on depth)	Probably stainless steel housing	as above	as above	
FIXED BOREHOLE DEFLECTOMETER with pendulum, electrical contacts with micrometer	SGI	Pendulum remains vertical as probe tilts. When tilt exceeds a preset value, pendulum has swung far enough to touch electrical contact and complete circuit. Micrometer can be turned from surface to deflect pendulum to determine angle	10m estimated	0 - 1 deg. to several degrees(1)	±6 min to ±7 sec	± 3 deg estimated	(50°C estimated)	(100 KN/m^2 estimated based on depth)	Probably stainless steel housing	Install in flexible tube. Determine orientation when instrument installed. Requires mechanical connection between surface and instrument	as above; probably not suitable for geothermal environment	(1) Kallstenius and Bergau, 1961

Appendix C. List of symbols used in text, part I

Symbol	Term
A	Cross-sectional area
A_P	Area of point of sampling spoon
a	Area of manometer
b	Thickness; effective stress due to buoyant weight of submerged deposits
b′	Thickness of aquitard
C	D/R
C_C	Compression index
C_V	Coefficient of consolidation
D	Depth to compressing beds
dh/dt	Rate of subsidence
E	Young’s modulus
e	Void ratio; e_0, initial void ratio
G	Specific gravity
H	Total subsidence
H_0	Initial thickness
h	Applied stress; difference in head; head at given elapsed time
h_a	Average head in aquitard
h_C	Head in confined system
h_0	Head at zero time
h_u	Head in unconfined system
J	Seepage stress
K	Hydraulic conductivity
K′	Vertical hydraulic conductivity
L	Length of flow
M_V	Coefficient of volume compressibility

Symbol	Term
$\bar{N}$	Average of N (blows)
n	Porosity
p	Total stress (geostatic pressure); water level
p′	Effective stress (effective overburden pressure)
p_a	Applied stress
P_O	Reference water level
Q	Amount of liquid production; quantity of water discharged in unit time
R	Radius of stressed system
R_u	Ultimate bearing resistance
r_s	Specific retention
S	Storage coefficient; effective stress due to weight of unsaturated deposits
S_C	Final subsidence
S_o	Sorting coefficient
S_s	Specific storage
S'_s	Specific storage of aquitard (compressible bed)
S_{ke}	Component of S attributable to elastic deformation of the aquifer-system skeleton
S_{ske}	Component of S_s due to elastic deformation of aquifer-system skeleton
S_{kv}	Component of S attributable to inelastic (virgin) deformation, of aquifer-system skeleton
S_{skv}	Component of S_s due to inelastic (virgin) deformation of aquifer-system skeleton
S_{sw}	Component due to compressibility of water
S'_{sk}	Component of specific storage due to compressibility of aquitard
S'_{skv}	S_{kv}/b'; b′ is aggregate thickness of aquitards
s	Amount of subsidence; drawdown
T	Transmissivity; time factor
t	time
U	Degree of consolidation
U_t	Excess pore pressure at time t
U_W	Pore pressure (fluid pressure or neutral stress)

Symbol	Term
$\bar{V}$	Flow velocity vector
w	Moisture content, per cent of dry weight
w_L	Liquid limit
w_P	Plastic limit
Y_s	Specific yield
z	Depth
αke	Compressibility of aquifer-system skeleton in elastic range of stress
αkv	Compressibility of aquifer-system skeleton in virgin range of stressing
β_w	Compressibility of water
γ	Submerged unit weight
γ_b	Buoyant unit weight of saturated deposits
γ_d	Dry unit weight
γ_m	Moist unit weight
γ_s	Unit weight of solids
γ_w	Unit weight of water
$\Delta p'$	Change in effective stress
ν	Diffusivity; Poisson’s ratio
τ	Time constant

Appendix D. Glossary, by Laura Carbognin and Working Group

The purpose of this glossary is to explain the meaning of terms currently recurring in studies on land subsidence due to ground-water withdrawals. Because this volume is for readers with diverse backgrounds and for interested untrained personnel, the definitions given here are simplified. For a more detailed explanation, the bibliography suggests some books which will help the reader.

AQUICLUDE

An areally extensive body of saturated but relatively impermeable material that does not yield appreciable quantities of water to wells. Aquicludes constitute boundaries of aquifer flow systems; term is synonymous with confining bed.

AQUIFER

An areally extensive body of saturated permeable material that will yield significant quantities of water to wells and springs. An aquifer includes the unsaturated part of the permeable body. Aquifers may be classed as unconfined or confined, depending upon the presence or absence of a water table. An aquifer may also be called a water-bearing stratum. Unconsolidated alluvial deposits of sand and gravel, porous sandstones, or fractured limestones are examples of water-bearing formations

AQUIFER SYSTEM

A heterogeneous body of interbedded permeable and poorly permeable layers that functions regionally as a water-yielding hydraulic unit. It comprises two or more aquifers (permeable formations) separated by laterally discontinuous aquitards that locally impede ground-water movement but do not greatly affect the overall hydraulic continuity of the system.

AQUITARD

A saturated, but poorly permeable, bed that locally impedes ground-water movement and does not yield water freely to wells, but which may transmit appreciable water, to or from adjacent aquifers.

ARTESIAN

The term artesian derives from Artois (Lat. Artesium), a northern province of France where naturally flowing wells were drilled in 1750. Today the term artesian is applied to any well tapping a pressure aquifer or simply to the aquifer itself. Artesian is synonymous with confined.

ARTESIAN AQUIFER

An aquifer in which the water level rises above the base of the upper confining bed when penetrated by a well. In recent years artesian aquifer has been used as a synonym for confined aquifer.

BENCH MARK

A relatively permanent mark, natural or artificial, furnishing a survey point at a known elevation in relation to an adopted datum. Bench marks, or marked points, connected by precise leveling, constitute the control of land-surface settlement.

COEFFICIENT OF COMPRESSIBILITY (L^2F^{-l})

Compressibility is the aptitude of the soil to be deformed. It is expressed by means of a coefficient which is the ratio between a void ratio decrease from e_o to e and an increase in effective stress. The value $a_v = e_0$-eΔp represents the coefficient of compressibility for the range p_0 to p_0 + p. Units usually are cm^2kg^{-1}.

COEFFICIENT OF VOLUME COMPRESSIBILITY (L^2F^{-l})

The compression of a clay (aquitard) per unit of original thickness, due to a unit increase of effective stress, in the load range exceeding preconsolidation stress. It is expressed by the equation

$$m_v = \frac{a_v}{1 + e_0}$$

in which e_0 is the initial void ratio. Units usually are cm^2 kg^{-l}.

COMPACTION

A decrease in the volume of a mass of sediments from any cause. In this guidebook, compaction is defined as the decrease in the thickness of sediments, as a result of an increase in vertical compressive stress, and is synonymous with "one-dimensional consolidation," as used by engineers. The term compaction is applied both to the process and to the measured change in thickness.
In thick fine-grained beds, compaction is a delayed process involving the slow escape of pore water and the gradual transfer of stress from neutral to effective. Until sufficient time has passed for excess pore pressure to decrease to zero, measured values of compaction are transient.

COMPACTION, RESIDUAL

Compaction that would occur ultimately if a given increase in applied stress were maintained until steady-state pore pressures were achieved, but had not occurred as of a specified time because excess pore pressures still existed in beds of low diffusivity in the compacting system. It can also be defined as the difference between (1) the amount of compaction that will occur ultimately for a given increase in applied stress, and (2) that which has occurred at a specified time.

COMPACTION, SPECIFIC (L^3F^{-l})

The decrease in thickness of deposits, per unit of increase in applied stress, during a specific time period.

CONE OF DEPRESSION

A cone of depression in the water table, developed around a pumping well and extending throughout the area of influence of a well (also see drawdown). For an artesian aquifer, this can be called the "cone of pressure relief" (Tolman, 1937).

CONFINED AQUIFER

Same as artesian aquifer.

CONSOLIDATION

The gradual reduction in the water content (void ratio) of a saturated soil, as a result of an increase in the pressure acting on it, because of the addition of overlying sediments or the application of an external load. A laboratory test called a one-dimensional consolidation test (odometric test), is performed on soil samples to evaluate consolidation. From such a test the coefficient of consolidation, c_v, usually reported in $cm^2 sec^{-1}$, is calculated as the ratio

$$c_v = \frac{K \quad 1}{m_v \gamma_w}$$

where K is the hydraulic conductivity, m_v is the coefficient of volume compressibility, and γ_w is the unit weight of water. The theory of consolidation, developed by Terzaghi, leads to a relation between degree of consolidation and time:

$$U\% = \frac{c_v t}{H^2}$$

In this expression U is the degree of consolidation, that is, the percentage of total consolidation occurring in some time t; c_v is the coefficient of consolidation; and H is half of the sample's thickness when the odometric test is performed.

DRAWDOWN

As water is withdrawn from an aquifer by a pumped well, the ground-water level is lowered. Drawdown is the distance the water table or pressure surface is lowered at a given point (see also cone of depression).

EXTENSOMETER

An instrument used for measuring vertical deformation of fine-grained beds in the subsoil under stress. Vertical extensometers commonly are installed when land subsidence follows ground-water withdrawal. Extensometers also are used to measure small horizontal displacements.

HEAD, HYDRAULIC, OR STATIC

The static head is the height, referred to a standard datum, of the surface of a column of water that can be supported by the static pressure at a given point. The static head is the sum of the elevation head and the pressure head.

HYDRAULIC CONDUCTIVITY, K (LT^{-1})

If a porous medium is isotropic and the fluid is homogeneous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. In the metric system it may be expressed in cm sec^{-1}; in English units it may be expressed in feet day^{-1} (see also permeability).

HYDRAULIC GRADIENT

The change in static head per unit of distance in the direction of the maximum rate of decrease in head if not specified. If different, direction is specified.

HYDROCOMPACTION

The process of volume decrease and density increase that occurs when moisture-deficient deposits compact as they are wetted for the first time since burial. This type of land settlement has also been called "shallow subsidence."

LAND SUBSIDENCE

Sinking or settlement of the land surface, due to diverse causes and generally occurring on a large scale. Usually the term refers to the vertical downward movement of the land surface although small-scale horizontal movements may be present. The term does not include landslides which have large-scale horizontal displacements, or settlement of artificial fills.

PERMEABILITY

The capacity of rock or soil to transmit fluid under the combined action of gravity and pressure. Permeability is expressed as the velocity with which water, under the influence of a given difference in head, passes through a porous medium having a certain cross section and thickness. Permeability is dependent on the size and shape of the pores of the porous medium and it can be reduced by compaction (see also hydraulic conductivity).

PHREATIC AQUIFER

Same as unconfined aquifer.

PHREATIC SURFACE

Same as water table.

PIEZOMETRIC SURFACE

An imaginary surface coinciding with the head of the water in an aquifer. (Also see potentiometric surface.)

POTENTIOMETRIC SURFACE

A surface which represents the static head. As related to an aquifer, it is defined by the levels to which water will rise in tightly cased wells (USGS) Also called piezometric surface in many countries.

REBOUND

An upward movement of soil as a consequence of a decrease in effective stress. In fine-grained soils, rebound is usually much less than the amount of compaction, since the latter is mostly irreversible.

RECOVERY

The water-level rise in a well occurring upon the cessation of discharge from that well or a nearby well.

STRESS, APPLIED (FL^{-2})

The downward stress imposed at an aquifer boundary. It differs from effective stress in that it defines only the external stress tending to compact a deposit rather than the grain-to-grain stress at any depth within a compacting deposit.

STRESS, EFFECTIVE (FL^{-2})

Stress (pressure) that is borne by and transmitted through the grain-to-grain contacts of a deposit, and thus affects its porosity or void ratio and other physical properties. In one-dimensional compression, effective stress is the average grain-to-grain load per unit area in a plane normal to the applied stress. At any given depth, the effective stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area) of sediments between the water table and the specified depth, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the saturated sediments above the specified depth. Thus, effective stress may be defined as the algebraic sum of the two body stresses, gravitational stress and seepage stress. Effective stress may also be defined as the difference between geostatic and neutral stress.

STRESS, GEOSTATIC (FL^{-2})

The total load per unit area of sediments and water above some plane of reference. It is the sum of (1) the effective stress and (2) the neutral stress.

STRESS, NEUTRAL (FL^{-2})

Fluid pressure exerted equally in all directions at a point in a saturated deposit by the head of water. Neutral pressure is transmitted to the base of the deposit through the pore water, and does not have a measurable, influence on the void ratio or on any other mechanical property of the deposits.

STRESS, PRECONSOLIDATION.(FL^{-2})

The maximum antecedent effective stress to which a deposit has been subjected, and which it can withstand without undergoing additional permanent deformation. Stress changes in the range less than the preconsolidation stress produce elastic deformations of small magnitude. In fine-grained materials, stress increases beyond the preconsolidation stress produce much larger deformations that are principally inelastic (nonrecoverable).

STRESS, SEEPAGE (FL^{-2})

When water flows through a porous medium, force is transferred from the water to the medium by viscous friction. The force transferred to the medium is equal to the loss of hydraulic head. This force, called the seepage force, is exerted in the direction of flow.

SUBSIDENCE/HEAD-DECLINE RATIO

The ratio between land subsidence and hydraulic head decline in the coarse-grained beds of the compacting aquifer system.

UNCONFINED AQUIFER

A geologic formation of permeable material that has a water table as the upper surface.

WATER TABLE

The upper surface of the zone of saturation in a phreatic aquifer in which the pressure is atmospheric.

WELL, ARTESIAN

A well that takes water from a pressure water body.

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Appendix E. Metric conversion table

Multiply inch-pound unit	By	To obtain metric unit
inch	25.4	millimetre (mm)
foot (ft)	0.3048	metre (m)
foot per mile (ft/mi)	0.1894	metre per kilometre (m/km)
mile (mi)	1.609	kilometre (km).
pound ----------------------------	0.45 ----	kilogram (kg)
square foot (ft^2)	0.0929	square metre (m^2)
square mile (mi^2)	2.590	square kilometre (km^2)
acre	0.405	hectare (ha)
acre-foot (acre-ft)	1,233	cubic metre (m^3)
gallon (gal) ----------------------	3.785 ---- 0.003785	litre (l) cubic metre(m^3)
cubic foot (ft^3)	0.0283	cubic metre (m^3)
acre-foot per square mile (acre-ft/mi^2)	476	cubic metre per square kilometre (m^3/)km^2)
gallon per minute (gal/min)	$6.309x10^{-5}$	cubic metre per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.0109	cubic metre per second per square kilometre [(m^3/s)/km^2]
ft per year (ft/yr) ---------------	$9.7x10^{-7}$ ---	centimetres per second (cm/s)
gallon per day per square foot (gal/d/ft^2)	4.716x10-5	centimetre per second (cm/s)
ton (short)	0.9072	metric ton (t)
gallon per day per foot (gal/d/ft)	$1.433x10^{-3}$	square centimetre per second (cm^2/s)
pound per cubic foot (lb/ft^3)	16.05	kilogram per cubic metre (kg/m^3)
pounds per square inch (psi)	0.07	kilograms per square centimetre (kg/cm^2)