DEVELOPMENTS IN BOREHOLE EXTENSOMETRY

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Abstract
Progressive development of the deep-well extensometer over a period of 30 years facilitated the evolution of fundamental concepts and predictive capability in studies of aquifer-system compaction and land subsidence due to fluid withdrawal. Early taut-cable extensometers have been largely superseded by freestanding or counterweighted pipes, which typically have dimensionless strain resolutions of a few parts in 10^7, over depths of 200 to 1000 meters. Recording of high-resolution, low-drift compaction and expansion data is critically dependent on minimizing the effects of friction in all components of the system, and on virtually eliminating erroneous thermal and mechanical signals. Long-term records from standard extensometers, in conjunction with water-level piezometers, have made it possible to determine, in-situ, the aquifer-system properties that control land subsidence. Newer extra-high resolution extensometers permit definition of the compressibility and hydraulic conductivity of a thin, individual aquitard by means of a short-term pumping test.

Introduction
In three decades of studies by the United States Geological Survey (USGS) of land subsidence due to ground-water withdrawal, the progressive development of the deep-well extensometer has played a key role in the evolution of concepts, models, methodologies, quantitative results, and predictive capability. The first part of this paper will briefly trace the development of the USGS instrumentation, the concepts suggested by the records obtained, and their ultimate verification through the development of predictive models capable of accurately matching the recorded subsidence history. The second part will define and elaborate what have come to be recognized as the fundamental requirements of a successful borehole-extensometer system.

Historical Development
The Survey's first borehole extensometer, or compaction recorder, was conceived by J. F. Poland, G. H. Davis, and J. H. Green, and was installed in the summer of 1955 in the San Joaquin Valley of California. Japanese investigators had used somewhat similar devices since the 1930's, but their achievements did not become known in the United States for about 30 years. Poland and others (1984) provide a very useful summary of the experience obtained with various types of extensometers developed in Japan and Mexico, as well as in the United States. To the extent permitted by considerations of internal completeness and continuity, the present paper avoids repetition of the material presented by Poland and others (1984).

Early extensometers—The first USGS extensometers used a tensioned cable to measure changes in the distance between a subsiding land surface and a bottom-hole anchor set near the base of the pumped aquifer system. The extensometer cable ran over two fixed pulleys to the tensioning counterweight, and its apparent movement relative to the instrument platform, or datum, was recorded by a standard water-stage recorder (Lofgren, 1961). Within a few years, these simple devices proved conclusively, for the first time, that the land-surface subsidence measured by repeated leveling surveys was attributable to compaction of the confined aquifer system; further-
more, they demonstrated that the time distribution of such compaction was was related in a general, though not always simple, way to be the time time distribution of head decline in the pumped aquifers.

Data, concepts, and models—The close correlation, over a period of about 3 years, between head change in the pumped aquifers and aquifer system deformation measured by a 460-m cable extensometer is shown in figure 2A. The observed head change is a direct measure of the change in effective stress in the aquifers and of change in stress applied to the interbedded aquitards. Therefore, these data may be plotted one against the other in the form of a stress-strain diagram (fig. 2B). The reciprocal slope of the stress-compaction trend line is $S^e$, the component of the aquifer-system storage coefficient attributable to deformation of the matrix, or granular skeleton (Riley, 1968). For this site $S^e = 3.0 \times 10^{-3}$. The hysteresis shown by the somewhat open loops reflects the phase lag between applied stress change and aquifer-system deformation. This phase lag results from the impedence to flow of water in and out of storage in the aquitards, as a function of their low permeability and appreciable thickness. The deformations seen here are fully elastic and recoverable, because the stresses do not exceed the maximum past stress (preconsolidation stress). The average vertical compressibility for the 335-m thickness of interbedded aquifers and aquitards at this site
AQUIFER-SYSTEM THICKNESS = 1,100 FEET

**FIG. 2** Head change and recorded aquifer-system deformation:
A. Fluctuations in head (stress) and thickness of the confined aquifer system; B. Drawdown-compaction (stress-strain) relationship.

is $9.1 \times 10^{-10} \text{m}^2/\text{N}$, or $8.9 \times 10^{-6} \text{ m}^{-1}$ when expressed in terms of $S_{\text{ske}}$, the skeletal component of elastic specific storage (Riley, 1969).

Figure 3 illustrates a different situation in which each year the maximum past stresses in at least some portions of some aquitards are exceeded for part of each pumping season. This results in large increments of nonrecoverable deformation during the deeper part of each annual drawdown cycle—those parts below the line B-B' on the stress-
change hydrograph. If this process continues long enough or demands for water are reduced, the response eventually becomes entirely elastic, as in figure 2. On the stress-compaction graph in figure 3 the line A-A'-A" defines the upper limit of stress fluctuation within which the deformation is essentially elastic.

Using the several slopes available from stress-strain plots of this kind, Riley (1969) showed that it is possible to estimate not only the elastic storage coefficient, but also the much larger inelastic or virgin storage coefficient, and the critical threshold value or preconsolidation stress at which the response changes from elastic to inelastic. If additional geologic data on the number and thickness of aquitards are available, the specific storage, or compressibility, can be estimated; in addition, the time-response characteristics of the system can be used to derive an average vertical permeability for the aquitards (Riley, 1969).

Helm (1975, 1976, 1977, 1978) incorporated this conceptual model and the in-situ parameters derived therefrom into a numerical aquitard-compaction model which reproduced very closely the known history of subsidence at a number of sites in California. His method facilitates an iterative optimization of the parameter values, which initially may be quite crude. Helm's one-dimensional model is a straight-forward application of Terzaghi's theory of time-dependent soil consolidation, and provided the first clear-cut demonstration that all observed details of the aquitard compaction process could be accurately simulated using this theory. The parameter inputs required by the model
FIG. 4 Typical field records of rebound and compaction of an extensometer installation, 260 m deep, near Eloy, Arizona: A. Record produced by cable element; B. Record produced by counterbalanced pipe element.

Errors due to down-hole friction—A typical record from a cable-extensometer recorder chart is reproduced in figure 4A. In 1978 this extensometer installation, 260 m deep with a 20.9 cm casing, produced a stepped record characteristic of moderate cable-casing friction. The average amplitude of the near-vertical steps (about 0.6 mm) indicates the approximate width of the stick-slip portion of the total frictional deadband. The upper and lower stick-slip deadbands are shaded in figure 4A. A reversal in the trend of deformation displaces the recorded change across the deadband, with the result that the maximum (or minimum) is truncated and an apparent phase lag is introduced in the record.

It should be noted that the magnitude of frictional steps recorded in normal operation cannot be used as a reliable indicator of the deadband width. These steps reflect the difference between static and sliding friction. Thus, the rest point at the end of a stepwise adjustment of extensometer length constitutes a point approximately on the outer edge of the sliding-friction deadband, which may represent more than half the total (sliding plus static) deadband width (fig. 4A). A good extensometer operating with no discernible static (stick-slip) friction may still have a significant sliding friction deadband.
Errors resulting from the fractional deadband may significantly limit and distort the information content of the record, especially where the forcing function (aquifer head change) contains frequent episodes of drawdown and recovery. The deformation responses to such reversals in trend are particularly useful for defining the hydrodynamic lag in the dissipation of excess pore pressures. In the application of Helm's aquitard-compaction model to stress-strain data it is principally the response to trend reversals that constrains the values of hydraulic diffusivity and preconsolidation stress.

In order to permit a clear distinction between attenuation and phase shift due to hydrodynamic lag, versus similar effects due to instrument friction, the instrument characteristics should be defined through a deadband test. Such a test is readily accomplished by alternately increasing and decreasing the uplift force on the extensometer cable sufficiently to move the cable past major points of friction against the casing. Typically, the process requires producing a strain of 1-to-10 x $10^{-5}$ in the cable. As the disturbing force is gradually removed, the cable springs back toward its "true" length, but does not fully attain it. Thus the recorder pen comes to rest above or below the "true" position, depending on the direction from which the "true" position is approached. The rest points constitute the approximate upper and lower limits of the sliding-friction deadband. The midpoint between them may be taken as representative of the undisturbed length of the cable under the applied counterweight tension. If the initial response to an expected reversal in stress—for example, the beginning (or end) of a pumping period—is to be accurately recorded, the extensometer may be manually preloaded to the high (or low) side of the sliding-friction deadband, as in performing half of a deadband test. It is then ready to respond to the first small increment of compaction (or expansion).

Pipe extensometers—In the late 1960's, Poland's group began experimenting with free-standing pipe extensometers (fig. 1B), having learned of the Japanese success with this type of design. Initial experiences indicated that relatively large-diameter extensometer pipes (2 or 2 1/2-inch nominal diameter) could generate virtually step-free records operating without centralizers to depths of several hundred meters in relatively small (4-inch, nominal) casings (Poland and others, 1984). This tends to be true despite the fact that in a well more than perhaps 70 m deep the pipe will bend enough under its own weight to induce some frictional contact with the casing. It is surmised that the heavy-duty couplings in the pipe string function as relatively low-friction centralizers in small-diameter casing. In the Houston, Texas, area a free-standing pipe 936 m deep is reported to be generating a very good record (Robert Gabrysch, oral commun., 1984). In this installation the element is 2-inch (60.3 mm outside diameter) steel tubing in a 5 1/2-inch (118.6 mm) inside diameter casing. The radial clearance between the couplings and the casing is 0.898 inch (22.8 mm).

Smaller diameter pipes in larger casings are less successful, because they bend enough under their own weight to exert large friction-inducing lateral forces against the lower parts of the casings. The friction problem is exacerbated if the well is significantly out of plumb, causing a long length of pipe to bear against the low side of the casing. Poland and others (1984) reported that a 1 1/2-inch (48.3 mm outside diameter) pipe in a 10 5/8-inch (260 mm inside diameter) casing 381 m deep produced a stepped record with vertical offsets of 0.15 to 0.3 mm. The actual width of the total frictional deadband probably was at least 1.0 mm.

In most situations, especially with extensometers of more than 200-m depths, the pipe tends to perform better than the cable because its much
Type "F" recorder, amplifying 10:1

Piers, 3" pipes
set 5 m below
land surface

Balance
beam

Counter
weights

Concrete pad

A

B

FIG. 5 Counterbalanced pipe extensometer: A. Schematic of components at land surface; B. Detail of knife edges and bearing plates supporting balance beam and extensometer pipe.

greater cross-sectional area enables it to overcome downhole friction with minimal induced change in length. It should be noted, however, that in a well whose diameter and straightness are sufficient to eliminate casing-cable contact throughout its depth, a taut cable or even a light wire or tape will provide an excellent extensometer element. Riley (1970) used a 50-meter invar surveying tape as the extensometer element in a virtually friction-free installation that had a resolution of ± 1 \( \mu \text{m} \).

High-resolution extensometers—In an effort to improve the record illustrated in figure 4A, the cable at this site was replaced with a 2-inch pipe, and an asymmetric counterweighted lever (balance beam) was used to support the upper end of the pipe. The installation was based on the design schematically illustrated in figure 5. The 90 kg counter-weight, acting on the 8-to-1 mechanical advantage of the balance beam, suspended the upper half of the extensometer pipe in tension and minimized frictional contact with the well casing. The resulting improvement is illustrated by the step-free record shown in figure 4B for February and March, 1983. The total deadband is estimated to be about 0.06 mm.

High-resolution records obtained with pipe extensometers encouraged the author to undertake to record the minute deformation of a thin overconsolidated confining clay, in response to nearby pumping from an underlying aquifer. The total compaction of the 4.3-m thick clay bed was not expected to exceed 0.5 mm, which suggested a desired resolution of 0.005 mm and a thermal drift of less than 0.025 mm per month. These criteria translate into a frictional force between pipe and well casing of no more than 30 newtons (N), and an uncompensated change in average temperature along the 32-m pipe of no more than 0.07°C.

The design adopted was a free-standing pipe extensometer incorporating special features for minimizing down-hole friction and the effects of near-surface soil instability and temperature change (fig. 6). A frictionless electronic linear-motion transducer (LVDT) sensed land-surface movement, which was recorded on magnetic tape by a digital data logger (fig. 6A). To prevent changes in temperature and bouyant support of the pipe due to drawdown in the casing when the aquifer is pumped, a cement plug capped by an impervious but flexible polymer grout was placed in the bottom of the well (fig. 6B). A heavy vinyl sleeve, pressurized and internally lubricated by glycerine, preserved the integrity of the grout seal around the lower part of the 60.3-mm extensometer pipe without transferring frictional loads from the 102-mm plastic casing to the pipe.
To promote a constant-temperature environment, the extensometer pipe, instrument piers, well casing, and pier casings were filled to land surface with water. Above ground components of the system were covered by an insulated heated shelter, thermostated to ± 0.2°C.

The elastic compaction (0.55 mm) and rebound of the confining bed measured during 14 days of pumping at $2.0 \times 10^{-4} \text{m}^3\text{S}^{-1}$ and 15 days of recovery are illustrated in figure 7. The raw data from this extensometer and two similar units extending to depths of 36.6 m and 41.5 m show no discernible deadband effects at a resolution of 0.002 mm. Responses of about 0.01 mm to diurnal barometric fluctuations are clearly defined in the raw data, but do not show at the scale of figure 7. However, temporary compaction due to rainfall loading is readily apparent (fig. 7A).

Application of Helm's aquitard-compaction model to the data from this pumping test produced a plot of computed compaction and rebound (Helm, 1977, personal comm.) that is shown as the dashed lines on figures 7A and 7B. From this simulation the following aquitard properties were derived: vertical hydraulic conductivity is $2.7 \times 10^{-5} \text{m/day}$; matrix compressibility (expressed as the skeletal component of specific storage) is
FIG. 7 Elastic compaction and rebound of the 4.3-m confining clay during a pumping test near Lake City, Florida: 
A. Measured and computed history of vertical deformation; 
B. Measured and computed stress-strain relationships.
3.9 x 10^{-5} \, \text{m}^{-1} \); the aquitard is overconsolidated to a stress level that exceeds the prevailing overburden stress by at least 6 m of water head.

Comparative stress-strain plots depicting the measured and computed transient response to pumping drawdown and recovery (fig. 7B) are sensitive indicators of the accuracy of this simulation process; their usefulness derives from the fact that the stress-strain relationship is strongly influenced by hydraulic conductivity during the early stages of rapid drawdown and recovery, but is controlled largely by specific storage during later stages, when head change and compaction are proceeding very slowly.

Stress-strain plots based on the measured and computed deformation shown in figure 7A were, for most part, so nearly identical that the plot of computed response was offset to the right by $2 \times 10^{-4} \, \text{ft (0.061 mm)}$ in drafting figure 7B, to facilitate distinction between the two curves. However, the computed curve departs significantly from the measured curve during the early phases of drawdown. This departure is attributable to the immediate, mechanically-coupled aquitard response to flow-induced centripetal strain in the pumped aquifer. Wolff (1970) observed such strains, as manifested at land surface, and also measured the associated transitory increase in pore pressure ("reverse water-level fluctuation") in the aquitard. The small ($6 \times 10^{-3} \, \text{mm}$) initial expansion of the aquitard seen in figure 7B is believed to be the first direct measurement of the transverse (vertical) extension associated with radial compression near a pumping well. The one-dimensional aquitard-compaction model simulates neither the horizontal compression due to radial flow nor the accompanying vertical extension in accordance with Poisson's ratio; therefore, the computed deformation does not track the measured deformation during the first minutes of rapidly changing horizontal strain following starting (or stopping) of the pump.

The absence of a progressive departure between the computed and measured stress-strain curves (fig. 7B) implies that the linear stress-strain law incorporated in the simulation is a reasonably accurate representation of the actual deformation process, within the range of stress applied. It also implies a virtual absence of thermal or other forms of instrument drift over the 29-day duration of the test. Thus the experiment demonstrated the feasibility of constructing a nearly frictionless and drift-free extensometer sensitive enough to permit determining, in situ, the hydraulic conductivity and compressibility of a single stratum, by means of inducing a relatively small, controlled stress for a short period of time.

**Design and Operational Considerations**

The design and operational requirements for an ideal borehole extensometer system may be addressed in terms of the six principal components of the system:

1. The base, or anchor, which constitutes the bottom-hole reference point.
2. The casing of the extensometer well.
3. The instrument platform, which constitutes the extensometer datum at land surface.
4. The extensometer element (pipe or cable).
5. The above-ground mechanisms that support the element.
6. The measuring devices that record movement of the land-surface datum.

These six components are discussed in some detail in the following paragraphs, with the goal of providing a summary of fundamental design criteria and operational procedures, many of which have not previously been explicitly described.
Extensometer base—In the most general case, in which total compaction is to be recorded, the base or anchor of the extensometer (fig. 1) should be established somewhat deeper than the maximum anticipated depth of induced pore-pressure decline, which may be substantially greater than the maximum depth of producing wells. If information on the vertical distribution of aquifer-system compaction is desired, additional extensometers may be established with bases set at the boundaries of subintervals of interest within the aquifer system. Stability of the anchor requires that it not settle into soft or disturbed sediments at the bottom of the borehole, and that the bottom of the hole not heave up because of readjustment of stresses after drilling. Experience suggests that these problems, if encountered at all, tend to be self-limiting, of brief duration, and readily identifiable on the continuous recorder charts. As a conservative approach the anchor should be set on or in a cement plug 3 to 5 m thick.

A potentially more insidious problem is the transmission of gradually increasing downward stress from within and above the interval of compaction downward to the environment of the anchor, through skin friction with the casing string (the pile effect). The process is comparable to the development of what soils engineers term "negative skin friction" on a pile. These downward directed skin-friction forces acting on a pile commonly develop if a pile is driven through a soft soil layer that is compacting because of reduction in pore pressure or the placement of a fill. According to Lambe and Whitman (1969) a relative displacement of about 2.5 cm is sufficient to mobilize fully the skin friction of soil on a pile. Johannessen and Bjerrum (1965) describe a field test in which 55 m steel piles were driven through a soft marine clay, which was then loaded with 10 m of fill. The surface of the fill subsided about 1.2 m, reflecting consolidation of the clay. Negative skin friction produced an overall shortening of the pile of 14.3 mm and forced its tip into the underlying bedrock. Stresses in the pile near the tip were calculated to be of the order of $2 \times 10^5$ kPa (approaching the yield strength of steel), and total negative skin friction was about $2.2 \times 10^6$ N.

The severely wrinkled, crushed, and sheared well casings commonly encountered in subsiding areas provide abundant evidence that these casings can transmit substantial downward forces to the sediments adjacent to and immediately below the bottom of the casings. The magnitude of the transmitted force is limited by the ultimate strength of the casing, which typically may be in the range of 1-to-3 $\times 10^6$ N. If an existing well is to be converted to an extensometer installation, it should be deepened about 15 m to place the cement plug and subsurface benchmark below the bulb of sediments that are stressed by the deforming casing. A newly constructed extensometer well should incorporate at least one slip joint in the casing string about 10 m above the bottom, to minimize downward transmission of stress. Other benefits of slip-joint construction are discussed below.

Well casing—Negative skin friction effect on the load-bearing casing tends to redistribute stresses adjacent to the borehole so as to reduce somewhat the compaction within the interval of pore-pressure decline, induce compaction below that interval, and induce expansion above that interval. The net result is that the extensometer progressively under-records aquifer-system compaction and land-surface subsidence. The problem can be minimized or eliminated by constructing an extensometer well using telescoping slip joints installed in the casing string near the upper and lower boundaries of the compacting interval, and within the interval at spacings suggested by the stratigraphy and the magnitude of anticipated compaction.

Poland and others (1984) illustrate various telescoping casing and slip-joint constructions used in Japan, Mexico, and the United States. In
addition to minimizing the role of the casing as an unwanted load-bearing member in the system being measured, these constructions enhance the longevity of the installation by postponing the onset of casing deformation and failure.

A newly constructed extensometer well can be completed using a heavy bentonite mud especially prepared for optimal sealing and plugging. An umbrella or basket packer near the bottom of the casing (fig. 6B) is necessary to hold the mud in the annulus when the casing is cleaned out. Such a completion procedure may be expected to delay and reduce the effects of skin friction, by reducing the tendency for the formation to cave and squeeze around the casing, and by providing a lubricated contact between the casing and formation. Where an annular seal is required to prevent vertical migration of poor quality water, using these specialized muds in preference to cement grout should be considered. If cement grout must be used, it should be emplaced opposite formation intervals that are expected to experience minimal compaction, and it should be of low density so as not to settle through the mud column.

Extensometer datum—Using a concrete pad to support the instrument platform, as was done with early installations (fig. 1), allows moisture, temperature, and biological changes in the soil to disturb the datum. Such changes usually are concentrated in the upper 4 to 6 m of soil. Their effects can be minimized by establishing the instrument platform on pipe piers, typically 2 to 4 inches in nominal diameter, that are forced into the bottom of oversized holes bored 5 to 8 m below the surface (figs. 5A and 6A). The pier wells are cased to ensure permanent decoupling of the piers from the shallow soil. Separation of the piers from the extensometer well by a radial distance of 1.0 to 1.5 m places the datum outside the cylinder of local disturbance that may develop if the well casing exhibits increasing protrusion during the life of the installation.

Seasonal and diurnal temperature variations in the pier wells are comparable to those in the extensometer well, and induce length changes in the piers that are comparable to (and therefore tend to cancel) the temperature-induced length changes in the corresponding upper 5 to 8 m of the extensometer element. Thus the piers transfer to the instrument platform above land surface a stable, approximately temperature-compensated, near-surface datum that may be expected to remain nearly invariant relative to the top of the compacting interval. For critical, ultra-sensitive measurements it may be necessary to control temperatures within the instrument shelter to within ± 0.5°C, or better.

A concrete pad, decoupled from the extensometer and pier wells, may be employed as the foundation for the fulcrum that supports the counterweight lever or balance beam. In a properly designed system, vertical movement of the fulcrum due to pad instability will cause a balance beam to tip but will not impart any spatial disturbance or change in load to either the extensometer element or the instrument platform.

Extensometer element—The most difficult problem typically encountered in obtaining optimal performance from a deep-well extensometer is ensuring that the measuring cable or pipe maintains an invariant length. Virtually all wells deeper than about 50 m depart from straightness sufficiently to force contact between the measuring element and the well casing. During compaction, downhole friction between the element and the shortening well casing induces changes in the stress distribution in the element. These stress changes characteristically produce time-varying and more-or-less indeterminant length changes that degrade and distort the record of aquifer-system deformation. Downhole friction typically is the limiting factor in determining extensometer resolution. In extra-
sensitive installations, temperature and buoyancy effects may also become significant.

Abandoned production wells that have often been used for low-cost cable extensometer installations were seldom straight when first drilled and subsequently were subject to severe casing deformation and failure under the stresses of aquifer-system compaction. Under these conditions, the extensometer cable typically is seized by the casing at friction points within and above the compacting interval, and is temporarily constrained to move downward in partial or total compliance with the deforming casing and subsiding overburden; the result is that little or no movement of the cable relative to the instrument platform is recorded for a time. Continuing compaction and shortening of the casing below a locked friction point results in concomitant shortening of the adjacent section of cable and, therefore, a reduction in the tensile stress in that part of the cable. The accumulating imbalance between the progressively diminishing stress in the lower part of the cable, below the friction point, and the constant counterweight stress in the upper part of the cable eventually overcomes the friction in a stick-slip dislocation recorded as an abrupt stair-step in the compaction record (fig. 4A). In a typical cable installation the intermittent adjustments across many such friction points combine to generate a record consisting of numerous steep or vertical steps of somewhat irregular amplitude and spacing. A chain reaction is often discernible, as the slippage across one friction point disturbs the stress distribution across adjacent points and causes the readjustment to propagate up and down the cable. Step amplitudes of 2-to-5 \times 10^{-6} \text{ times the cable length} must be considered typical for cable extensometers; however, frictional stepping can be an order of magnitude more severe in wells more than 500 m deep that depart from verticality by 5 degrees or more.

For a given amount of aquifer-system compaction, the unbalanced force available to overcome friction is the product of the shortening of the locked portion of the extensometer element, its elastic modulus, and its cross-sectional area, divided by the length of locked element that is subject to stress reduction due to shortening. Thus, small cable diameter and a deep extensometer contribute to aggravated frictional stepping. Contrary to possible intuition, the use of heavier counterweights in a cable system does not increase the force available to overcome friction, but does pull the cable more tightly against bends, breaks, and rough surfaces in the crooked casing, thus tending to increase downhole friction. In general, counterweight mass should not greatly exceed that required to support the weight of the cable in a stable, taut alignment.

The standard cable used in USGS extensometers is a nominal 1/8-inch (3.175 mm) diameter stainless steel, 1 X 19 strand, reverse-lay aircraft control cable, having a cross-sectional area of 6 \text{ mm}^2 and a weight of 0.047 kg/m. This cable resists corrosion, does not untwist under tension, and has shown no signs of fatigue elongation (Lofgren, 1969). Counterweight loads of 6 to 8 kg per 100 m of cable probably are most appropriate, although loads several times greater than that have often been used.

The use of a pipe as the extensometer element, although substantially more expensive than a cable, offers a major advantage in overcoming downhole friction, because of the pipe's much greater stiffness. A typical pipe element of nominal 2 1/2-inch diameter (730 mm outside diameter) has a cross-sectional area about 180 times larger than the standard 1/8-inch cable. Some of this intrinsic advantage is lost, however, because in deep wells the pipe bends enough under its own weight to assume a sinusoidal or spiral configuration that forces it into...
frictional contact with even a straight, vertical casing. Relatively small pipes operating in relatively large casings bend enough to exert large friction-producing lateral forces against the lower parts of the casings. Better results are achieved when the radial clearance between pipe couplings and casing is only 10 to 25 mm. If a well deviates appreciably from the vertical, the weight of the extensometer pipe will tend to force long sections of the pipe against the lower side of the bends in the casing, creating substantial friction.

In many cases the performance of the pipe extensometer can be greatly enhanced by suspending some or most of the weight of the pipe from a counterweighted lever system (fig. 5). If the hole is approximately straight, and especially so in its upper portion, most of the weight may be counterbalanced, so that most of the pipe hangs in tension and does not tend to bow against the casing. If there are one or more substantial bends in the lower portion of the casing, the point of neutral pipe stress may be positioned near or somewhat below the uppermost bend so as to minimize the weight forcing the pipe against the outside of the bends. The most intractable situation arises when there is significant bending in the upper as well as lower parts of the casing. A compromise must then be attempted between excessive compressional flexure in the deep part of the pipe versus excessive tensional pull against intervals of maximum curvature in the upper part of the well. From these considerations it is evident that a directional, or deviation, survey of the well bore can be very helpful in determining the pipe specifications and approximate uplift force. In some cases it may be desirable to employ a tapered element composed of several segments of different sized pipe, the diameter increasing with depth (Poland, and others, 1984).

Changes in extensometer length due to the typically small temperature changes below the compensated near-surface interval are, as a general rule, important only in special-purpose, extra-high precision installations. However, if a perforated well casing allows air flow in and out of unsaturated sand or gravel layers at depth, the resulting "inhaling" of surface air during periods of relatively high barometric pressure can produce substantial changes in the temperature and length of the extensometer. In other situations, large pumping drawdowns of initially shallow water levels may expose portions of the extensometer to temperature changes large enough to induce significant length changes. The effects of air or water movement in the well casing can be controlled by sealing the well to prevent fluid communication with the surrounding sediments. In some cases, collection of temperature data at various depths in the borehole and pier wells may be essential to correct for uncompensated thermally induced length changes. Use of electronic data loggers as described in a later section, greatly facilitates the collection of temperature data.

Length changes due to change in buoyant support can also be controlled by sealing the well, if desired. It has been assumed that buoyancy-induced changes, if significant, could be corrected computationally through application of Archimedes' Principal. Such corrections have not been routinely made. In most installations calculated buoyancy effects can be reduced to tolerable magnitude (<0.5 mm) by ensuring fluid communication between the water in the pipe and that in the casing, so that the levels fluctuate together. To the best of this writer's knowledge, no controlled field experiments on buoyancy effects have been performed.

For reasons of economy it has been common practice to screen or perforate extensometer wells in one or more depth intervals deemed to be representative of the average head within the compacting aquifer system; thus both the head-change and deformation data necessary for defining
stress-strain relationships could be obtained in the same well. This practice not only produces some buoyancy errors, but also may cause significant thermally-induced changes. Temporal variations in vertical head distribution may alter the velocity of interaquifer flow within the well bore enough to cause substantial changes in the thermal environment of the extensometer. The preferred practice of minimizing water-level fluctuations in the extensometer well and installing a nearby array of point-sensing piezometers eliminates these sources of error and permits a more rigorous definition of the vertical distribution of stresses causing deformation.

Support mechanisms—If a counterweighted balance beam is employed to maintain tension on a cable or to support part of the weight of a pipe, the active pivots should be knife edges supported by flat horizontal steel plates (fig. 5B). The use of flat supporting surfaces allows for flexibility in positioning the knife edges, to accommodate individual variations in installations. To achieve the required neutrally stable balance configuration, all pivots must be located in a common plane. If fixed rather than freely suspended counterweights are used, their center of gravity should fall in the plane defined by the center pivot and the knife edge supporting the pipe or cable. These precautions ensure that the tipping of the balance beam that occurs with subsidence of the fulcrum does not alter the system geometry in such a way as to change the uplift force on the extensometer element. Vertical movements of the fulcrum caused by instability of the concrete pad will make the balance beam tip, but will not affect the compaction record. As subsidence accumulates, the balance beam is releveled when tipping exceeds about 5 degrees, by adjusting the suspension nut (fig. 5B) or rotating the cable-suspension pulleys (fig. 1A) during regular servicing of the instrument.

When a substantial fraction of the weight of an extensometer pipe is to be suspended from a balance beam, it is convenient to use an asymmetric lever that provides a mechanical advantage in the range of 8:1 to 12:1 (fig. 5A). The required uplift force (typically 1000 to 5000 kg) can then be developed with a manageable counterweight mass, and loads on the fulcrum and pad are minimized. No attempt should be made to use the long moment arm as a means of amplifying the compaction signal for recording purposes, because to do so would contaminate the compaction record with an amplified recording of pad instability.

The use of a counter-balance system incorporating a mechanical advantage of about 10:1 confers a very important operational advantage, by facilitating the controlled application and removal of large and precisely variable uplift forces on the pipe. This makes it easy to test the ability of the extensometer to return accurately or approximately to an original length after substantial induced excursions in both directions. Such deadband tests are essential to quantifying the frictional properties of an extensometer, to characterizing its overall performance, and to developing confidence in the reliability of its record. Optimal performance commonly results from a trial-and-error process of adjusting the counter-balance force in increments and testing the frictional deadband with each different counterweight load.

As the land surface subsides around the extensometer element, progressively increased protrusion of the pipe or cable must be accommodated. With a cable system the counterweight suspension need only be shortened occasionally, as required. Protrusion of a pipe is initially accommodated by screwing down the releveling nut on the threaded suspension rod (fig. 6). With continuing compaction, however, short sections of the pipe must eventually be cut off, or preferably unscrewed, from the top of the pipe. Continuity of a high-precision
record is best assured by finishing the upper end of the pipe with a prefabricated assembly consisting of several short sections of pipe (about 20 cm long) connected by threaded couplings (fig. 5A). Each section contains a precisely located hole for the suspension pin that ties the pipe to the threaded suspension rod and thence to the counter-balance lever. If a free-standing rather than counter-balanced pipe is used, the pin serves as the anchor for the tape that drives the compaction recorder (fig. 1B). The holes are drilled in a machine shop at accurately determined and recorded spacings, and a vertical line is scribed on the assembly to insure that the pipe section and couplings are not rotated out of their original alignment. The assembly is fitted to the upper end of the extensometer pipe and positioned so that the holes and suspension pin are parallel to the counter-balance lever. This arrangement provides two degrees of freedom in coupling the pipe to the lever and thus accommodates minor misalignment. As subsidence progresses individual sections are removed from the top of the assembly as necessary, and the threaded suspension rod is pinned to the pipe through the next lower hole. The predetermined hole spacing then becomes a constant added to the record of accumulated compaction.

Measuring devices—Continuous analog records of aquifer-system compaction or expansion have usually been generated by simple mechanical chart recorders (figs. 1 and 5). Movement of the instrument platform relative to the extensometer element causes a chart drum to rotate against a clock-driven pen. The commercially available water-stage recorders used by the USGS as compaction recorders require the addition of a second gear train to achieve a scale amplification of 10:1. In addition, the chart drums must be balanced, and the gear train adjusted for smoothest operation. An anti-backlash counterweight of about 5 grams, suspended from thread wrapped around the chart drum, is required to provide a constant minimal pre-load on the gear train. Resolution of the inked trace typically is \( +1 \times 10^{-4} \) ft \((0.03 \text{ mm})\), although specially modified instruments have been built that provide \( +2 \times 10^{-5} \) \((0.006 \text{ mm})\) ft resolution with 50:1 amplification. The recorder is positioned on the instrument platform so that the plane of rotation of the recorder drive pulley is parallel to the plane of oscillation of the counterweighted balance beam.

The recent development of reliable, moderately priced, battery-powered, multi-channel data loggers makes it feasible to collect aquifer deformation and related data directly in computer-compatible digital format. Thus it is possible to eliminate the tedious, expensive, and error-prone chores of manually picking data points from analog charts, tabulating and graphing the data, and keying them into a computer for analysis and modeling. A highly sensitive, linear, electrical analog of extensometer movement can be generated using a linear variable differential transformer (LVDT) as the displacement transducer. Pressure transducers sensing the heads in co-located piezometers can be monitored with the same data logger. Other parameters of interest, such as temperatures at and below the surface, barometric pressure, and precipitation can also be recorded. To conserve battery power the sensors can be switched on briefly at the desired sampling rate, perhaps once per hour, under data-logger control. Data are collected over a period of a month or more on magnetic tape or in solid-state memories for subsequent transfer to a computer.

If electronic sensing and recording are employed, it is essential to provide a supplementary direct-reading mechanical measuring system, such as a dial gauge, for calibration and to maintain data continuity in case of electronic failure or an off-scale condition resulting from excessive movement. The relatively limited dynamic range of transducer systems,
compared to a mechanical recorder, may require fairly frequent, even monthly, rezeroing of the transducer during periods of rapid subsidence. Under these circumstances it is necessary to have a precise and convenient mechanical adjustment system that reliably preserves the fundamental instrument reference. A micrometer-adjustable transducer mounting is suitable (fig. 6A). Redundant mechanical and electronic recording can be linked very effectively and simply to provide the advantages of an immediately visible analog record as well as computer-compatible digital data.

Regardless of the type of extensometer and recording systems employed there should be affixed to the extensometer element two permanent reference marks whose distance from a well-defined measuring point on the instrument platform can be measured with an appropriate level of accuracy (at least ±0.1 mm), using a machinist's slide caliper, depth gage, or similar device. Continuing compaction eventually requires removing the upper mark and reattaching it below the (originally) lower mark. In this manner an uninterrupted, self-checking record of periodic compaction measurements is established independently of the recording systems.

Summary and Conclusions

The USGS experience with operating borehole extensometers in a wide range of circumstances may be generalized in the form of six fundamental requirements. Briefly stated these are:

1. The base of the extensometer system—that is, the bottom-hole anchor or subsurface benchmark—must be stable with respect to the bottom of the hydrostratigraphic depth interval of interest.

2. The well casing must not disturb the system being measured by acting as a significant load-bearing structure within the compacting sedimentary column.

3. The instrument platform, which constitutes the extensometer datum at land surface, must be stable with respect to the top of the interval of interest.

4. The extensometer element (pipe or cable) must maintain an invariant length. A corollary of this requirement is that the borehole must be as straight and plumb as possible, to minimize downhole friction.

5. Above-ground mechanisms (counterweights, levers, pulleys, etc.) used to support the extensometer element must have negligible friction and must exert a constant uplift force on the element, regardless of movement of the land surface and instrument platform relative to the element.

6. The measuring and recording devices used to monitor displacement of the instrument datum (land surface) relative to the extensometer element must be linear, accurate, stable, and sensitive, and must not impose significant frictional or spring loads on the extensometer. They should also provide sufficient redundancy to insure that the record of cumulative displacement will not be lost during periods of routine instrument maintenance, equipment failure, or modification.

With careful design and construction these idealized requirements may be closely approximated; the resulting instruments have virtually no drift, very low noise, and strain resolutions that may exceed 1 part in 10^7. Aquifer-system deformations attributable to barometric pressure change, rainfall loading, and head changes of less than 10 mm can be resolved. Long-term records from standard extensometers, in conjunction with water-level piezometers, have made possible the determination of the aquifer-system properties that control land subsidence. Newer, extra-high resolution extensometers permit definition of the compressibility and hydraulic conductivity of thin, individual aquitards by means of short-term pumping tests.
References

Wolff, R. G., 1970, Relationship between horizontal strain near a well and reverse water level fluctuation: Water Resources Research, v. 6, no. 6, p. 1721-1728.