# 2 Field measurement of deformation, by Joseph F. Poland, Soki Yamamoto, and Working Group

## 2.1 INTRODUCTION

Decline of the water level in wells causes increase in effective stress--that is, increase in the part of the overburden load that is supported by the sediments being stressed. The resulting strain is primarily expressed as a vertical shortening or compaction of the stressed sediments and consequent subsidence of the land surface. Horizontal displacement also occurs but in a lesser amount.

In this chapter we will describe briefly the methods used for measuring vertical displacement of the land surface (subsidence or uplift), vertical displacement of subsurface deposits (compaction or expansion), horizontal displacement of the land surface, and horizontal displacement of subsurface deposits.

## 2.2 VERTICAL DISPLACEMENT

### 2.2.1 Precise leveling by spirit leveling

The elevation of bench marks at land surface commonly is determined by precise leveling, using an engineer’s level and a level rod. This is the most practical method for measuring vertical displacement of bench marks in monitoring subsidence. Equipment and procedures are described briefly in most engineer’s handbooks and in detail in "The Manual of Geodetic Leveling" (Rappleye, 1948). Once a network of bench marks has been established and surveyed by precise leveling, a second survey at some later date will show whether vertical movement has occurred, where, and how much.

The bench-mark net should be designed to cover the area known or suspected to be subsiding, and to extend into a broader regional network at two or three reference bench marks assumed to be stable because they are on bedrock or for some other reason. The bench-mark net can be tied to a tidal bench mark if the subsiding area is near the seacoast. Spacing of bench marks in the net is normally in the range of 400 to 1,000 m, but may be much closer in areas of special interest, such-as ties to structures, or a closely spaced set of bench marks to define movement on surface faults. Bench marks should be placed where danger of destruction is minimal. They are installed as permanent marks that in the past usually have consisted of a brass cap, suitably identified, and grouted into a concrete block or post, into bedrock, or attached securely to the top of a pipe or rod. As the need for greater accuracy and for eliminating surficial disturbances has increased, "deep-seated" bench marks are being installed in increasing numbers. They consist of rods 5 to 10 m long, driven into the ground and protected by an outer sleeve through the top 3-4 m, the zone of surficial disturbances (such as frost-heave, dessication, swelling, oxidation, root growth, and animal burrowing). This type of cased-rod bench mark is particularly well suited for use in monitoring areas of present or potential land subsidence where annual elevation changes of a few mm may be of interest if they represent elastic response of an aquifer system, but should be eliminated if they represent surficial disturbance.

To reduce vandalism, a mark that is less obvious than a brass cap should be used. A convex-headed bolt or pin, projecting a few mm above the concrete or pipe-cap, or a carriage bolt with a nut on the embedded end can be used. The bench-mark designation can be scribed in the concrete before it hardens.[1]

[1] Detail on installation and protecting of bench marks is available in a publication of the National Oceanic and Atmospheric Administration (NOAA). Rockville, MD, USA 20852. Entitled Geodetic bench marks, by R. P. Floyd, it is NOAA Manual NOS NGS1, 1978, 50 pages.

Near-surface deposits may contain organic materials subject to bacterial decomposition and consequent settlement of the land surface when the water table is lowered in order to grow crops. Such conditions exist in the peat beds of the Fens in England, in the Florida Everglades (Stephens and Johnson, 1951), and in the Sacramento-San Joaquin Delta in California (Weir, 1950). In such areas, bench marks installed to measure change in elevation of subjacent deposits should be rods or pipes driven firmly into the subjacent deposits and preferably protected from change in the thickness of the overlying organic deposits by an outer pipe sleeve. Furthermore, structures that extend down to the subjacent deposits, such as bridge piers or tidal gages, can serve as sites for the establishment of additional bench marks.

Figure 2.1 shows the network of level lines established by the United States Coast and Geodetic Survey (now National Geodetic Survey) in the subsidence area of the Santa Clara Valley in northern California. This network, which is 400 km long, was first leveled in 1934 and has been releveled 11 times since then. Note that three transverse lines extend southwest into consolidated rock and across the well-known San Andreas fault, and three extend east across the Hayward fault. Both faults are active.

In bench-mark surveys of subsiding areas, the leveling may be of first or second order. First order class I leveling is double run and requires that the allowable discrepancy between duplicate lines does not exceed $3\sqrt{K}$ mm where K is the length of the bench-mark line in kilometres. Second order class I leveling requires a closure of not to exceed $6\sqrt{K}$ mm and costs half to two-thirds as much per kilometre as first order class I. Partly because of the difference in cost between first-order leveling and second-order leveling, it is common practice in resurveying a network in a subsiding area to select principal lines for first-order releveling and secondary lines for second-order releveling. It is extremely important that ties to "stable" ground, to consolidated rock, or to tidal gages, should be included in the first-order leveling.

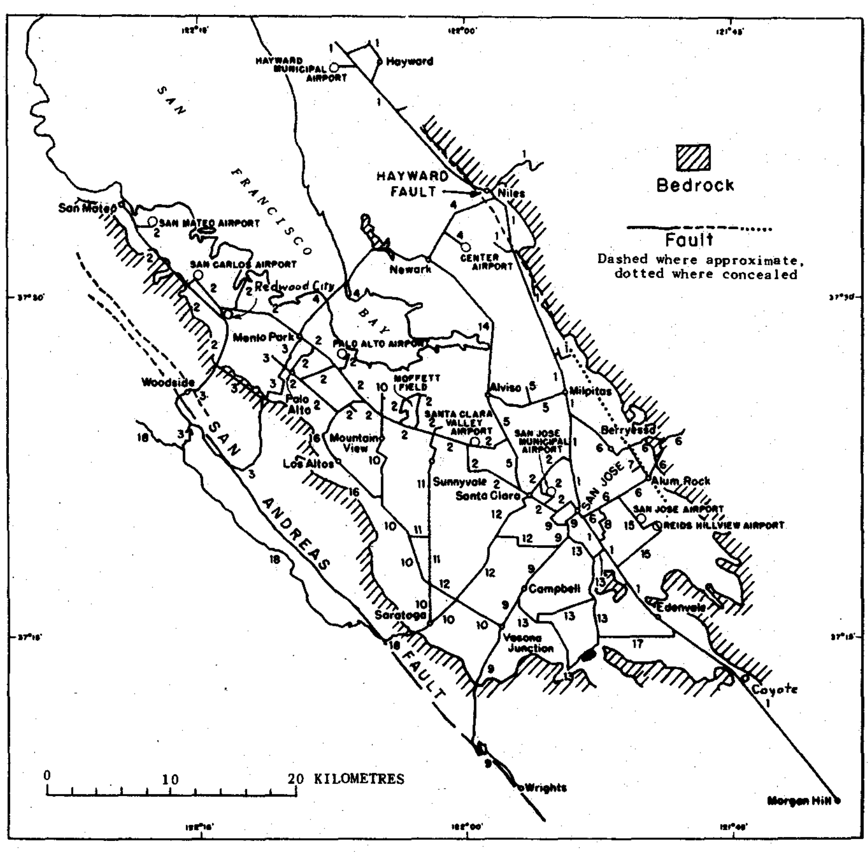


Figure 2.1 Map showing network of level lines in the San Jose subsidence area, Santa Clara Valley, California (modified after National Geodetic Survey; numbers identify level lines).

The releveling pattern at Niigata, Japan, is illustrated in Figure 2.2. The principal first-order leveling lines are identified by the larger circles ("First Class Bench") and those for second-order leveling by the smaller circles. Furthermore, the network is divided into three zones based on rate of subsidence and the economic significance of subsidence: the coastal area northeast of Uchino is releveled every half year, the zone northeast of Yahiko once a year, and the inland zone north of Nagaoka every two years.

Saving time is another reason for using second-order leveling on the secondary lines in a subsiding area. The second-order leveling will cover the distance about twice as fast as first order leveling. In an area that is subsiding 15 to 30 cm per year, a junction point could settle 1 to 3 cm by the time a loop is closed. Any procedures that reduce loop closing time are beneficial. The time of year when the leveling is done is important in a heavily pumped basin, for example, one where the annual fluctuation of artesian head is 10-30 m. Commonly the water level in wells is drawn down in the spring and summer and rises in the autumn and winter when withdrawal is less. Hence, effective stresses are much greater in the summer than in the winter

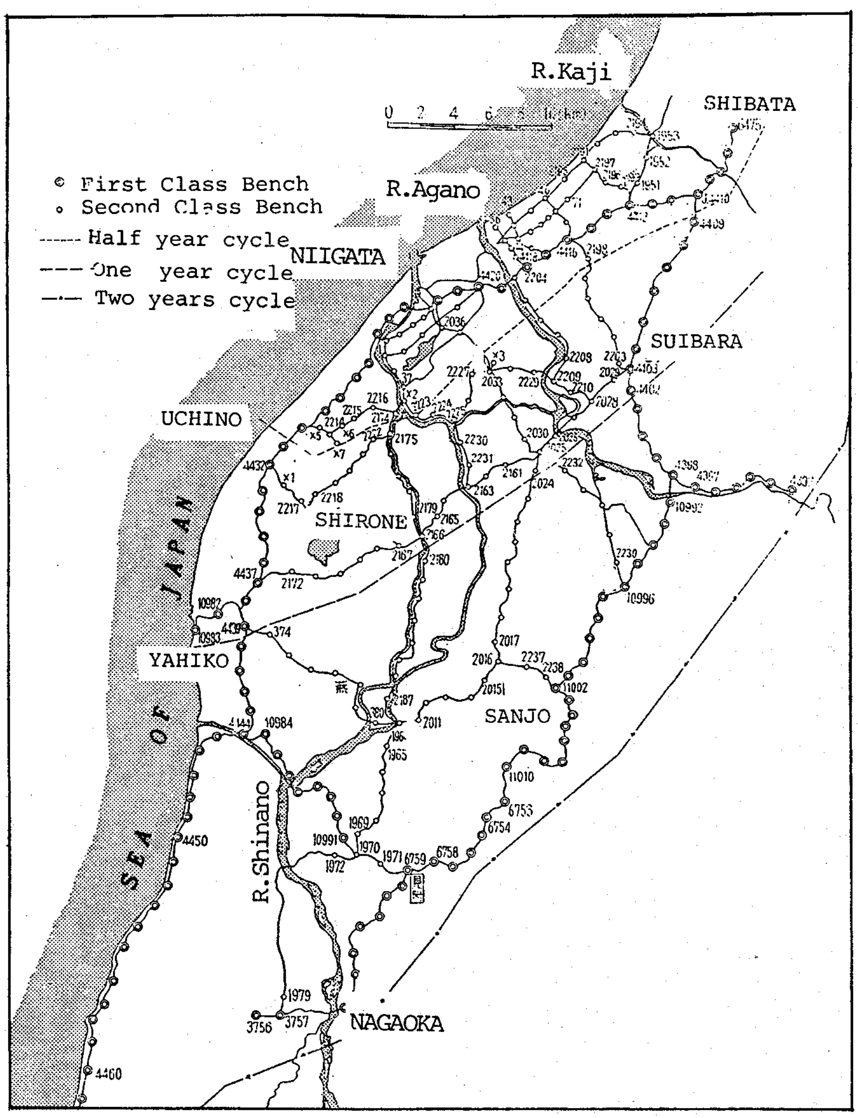


Figure 2.2 Distribution of bench marks in Niigata, Japan.

and the full annual compaction of the aquifer system may occur in 5 to 6 months (see Lofgren, 1968, Figure 3). In such areas, leveling should be accomplished during or immediately following the period of rising water level when compaction and subsidence are minimal.

All the subsidence maps in the case histories of Part II were prepared from change in the elevation of bench marks surveyed at two different times by the leveling procedure. If the bench-mark net has been releveled several times, the magnitude and distribution of subsidence along a line of bench marks can be shown as a series of profiles, one for each releveling, referred to a common base. Figure 9.14.4 is an example of a series of 10 subsidence profiles drawn from surveys from 1919 to 1967, all referred to a 1934 base. 1934 was the first year that the entire line of bench marks was surveyed.

Leveling is a labor-intensive procedure, and as a result the cost has doubled in recent years. The cost of constructing a pipe extensometer that extended to the base of the fresh ground-water reservoir or to the depth tapped by the deepest water wells might well be less than the cost of one releveling of an extensive bench-mark network 300 to 600 km in length. An extensometer placed near the center of a subsidence area could furnish a continuous record of land-surface position and thus would be a subsidence monitor, provided that (1) no compaction of sediments occurred at depths beneath the extensometer footing, and (2) no vertical tectonic movement developed. As a subsidence monitor, it would furnish information needed to decide when to relevel the bench-mark net. Furthermore, under such circumstances, the top of the inner pipe of a pipe extensometer (see Figure 2.5B) would be a reference bench mark of constant elevation and hence a fixed tie for releveling the net. Such a constant reference bench mark near the center of a bench-mark net could eliminate the need for releveling to a regional reference bench mark many kilometres distant.

A guidelines manual for surface monitoring of geothermal areas (Van Til, 1979) was prepared recently to serve as a guide to monitoring the magnitude and direction of land-surface movements prior to, during, and following withdrawal of geothermal fluids from the ground. This manual not only discusses the design of systems and procedures for monitoring subsidence but also describes the capabilities and limitations of instruments available for monitoring purposes. Anyone concerned with the design or operation of a subsidence monitoring system should find the Van Til manual very helpful. Table D-1 from this manual, summarizing instrument capabilities for measuring land-surface displacements, is included as Appendix A in this guidebook.

### 2.2.2 Other techniques for measuring land-surface displacement

Other instruments utilized in measuring or monitoring differential vertical displacement at land surface are the theodolite with retroreflective targets, capable of measuring vertical angles to 1 second of arc or better, manometers for monitoring settlement of structures or land surface, and tiltmeters for measuring ground tilt. Van Til (1979) has summarized in tabular form the availability, performance characteristics, accuracy, and installation and operating requirements of 8 types of manometers and 6 types of tiltmeters used for monitoring vertical displacements at land surface (see Appendix A). Tide gage records, float measurement on water bodies, and changes in drainage pattern also can be very helpful in defining differential elevation changes or tilting.

### 2.2.3 Extensometer wells

#### 2.2.3.1 Single and double pipe extensometers

Extensometer wells that have been developed to measure vertical movement or change in thickness of sediments or rocks are similar in principle but vary in detail. Japanese scientists pioneered in the development of this type of observation well. In the early 1930’s they installed the "single pipe well" (also called "single tube well") at several sites in Japan.

The single pipe well (Figure 2.3A), if installed to a shallow depth and passing through soft clay to an aquifer of sand or gravel, may accurately record by increased protrusion of the pipe at land surface the amount of compaction that has occurred in the soft clay. However, at depths greater than 50 to 100 m, the weight of the overlying sediments develops substantial lateral pressure on the pipe. This pressure, which increases with depth, increases the frictional resistance to movement and hence enhances the tendency for the pipe to move vertically in accord with the surrounding sediments. Thus, as the depth to the compacting interval increases, the percentage of the compaction that will appear as increased pipe

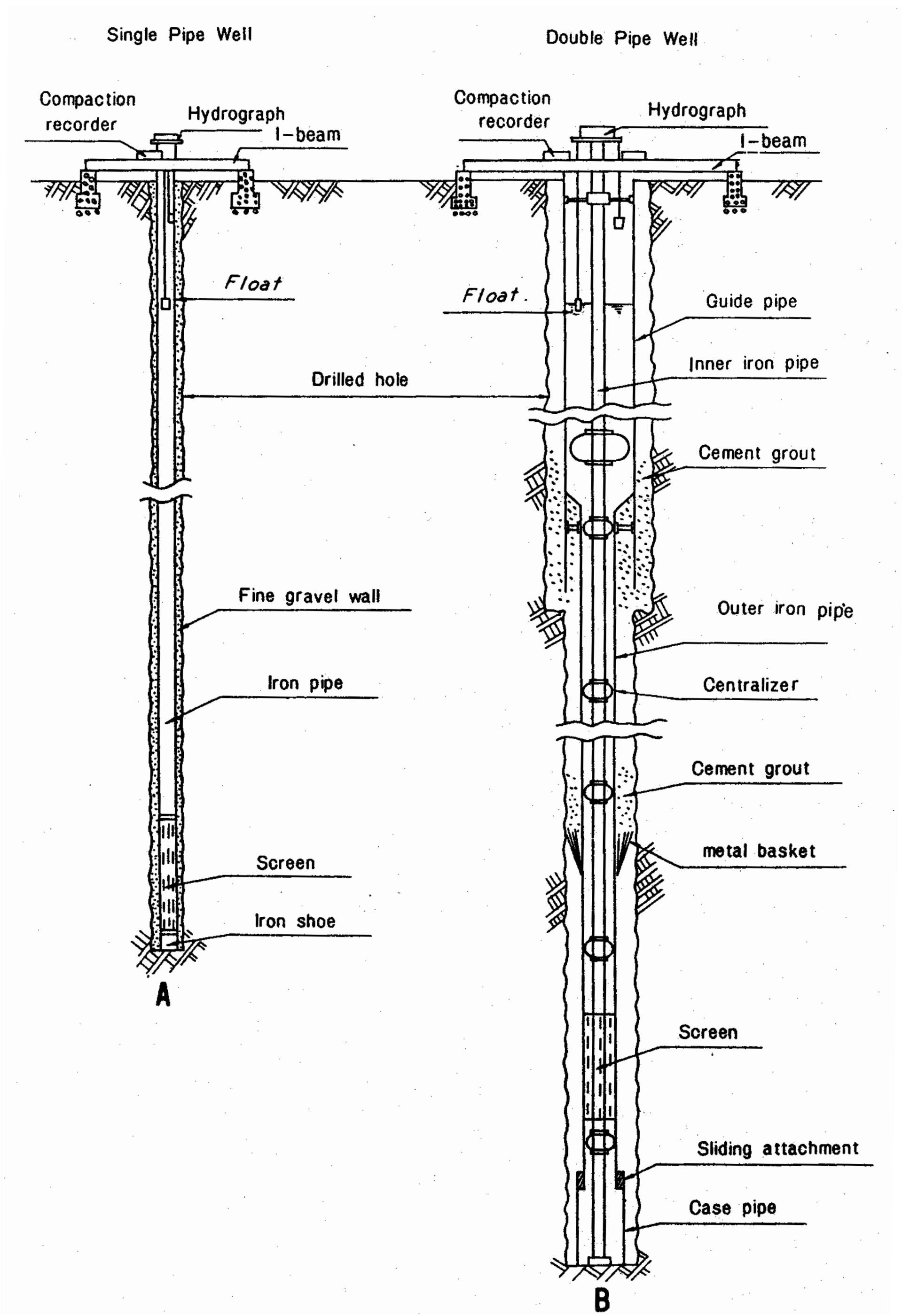


Figure 2.3 Diagram of Japanese extensometers. A, Single pipe well; B, Double pipe well (from Tokyo Metropolitan Gov't, 1969, Fig. 18).

protrusion above land surface decreases and compressional shortening of the pipe at depth increases. Therefore, although increased protrusion of a single pipe well above the land surface is an indicator of subsidence, it should not be considered a reliable measure of the magnitude of compaction for depths greater than 30 to 60 metres.

As demand for ground water increased in Japan and water wells were drilled to greater depths, Japanese scientists designed a "double pipe well" (Figure 2.3B) to measure compaction accurately. A double pipe well was installed at Osaka in 1938. The double pipe well consists of two concentric iron or steel pipes, inserted into a vertically bored hole. The inner pipe is isolated from the sediments by the outer pipe, and is centered within the outer pipe by centering devices (centralizers). The apparent rising of the inner pipe indicates the relative downward displacement of the I-beam based on the land surface with respect to the top of the inner pipe. Thus, the amount of compaction of the sediments between the land surface and the bottom of the inner pipe can be recorded. The water level in the outer pipe represents the pore-water level or artesian pressure of the aquifer, transmitted through the screen section installed in the outer pipe. This water level is registered by a float-operated water-level recorder when the space between pipes permits.

Note (Figure 2.3B) that the outer pipe is suspended in the well, with a slidable sleeve of oversize casing hanging on the base of the outer pipe and resting on the well bottom. By this means, the weight of the outer pipe is removed from the well bottom and suspended at the land surface.

At the Funabashi-2 well in Chiba (Figure 2.4) the diameter of the outer tube to 60 m depth is 350 mm to accommodate a water-level float, but below that depth is reduced to 200 mm. The diameter of the inner tube is 80 mm. The annulus between the outer tube and the hole wall is cemented at 60 m and 75 m depth. The bottom part of the outer tube has the sliding sleeve ("casing tube") attachment to prevent loading of the well bottom by the weight of the outer tube. The sleeve, closed on the bottom with a bearing plate, is landed on a solid sandy layer and supports the inner tube. Thus, the outer tube can move independently from the inner tube and the sleeve. Figure 2.4 also shows the design of the centralizer--the device centering the inner tube in the outer tube (B)--and details of the instrumentation for recording compaction (or subsidence) and water-level fluctuation (C). If the double tube extensometer well extends through and beneath the base of the compacting sediments, the extensometer records gross compaction, which equals land subsidence if no tectonic movement contributes to the change in land-surface elevation. However, if the bottom of the well is within the compacting interval, the extensometer records compaction--a partial component of the land subsidence.

The validity of the extensometer record depends on the stability of the base of the inner tube with respect to the geologic formation, the stability of the instrument platform with respect to land surface, the degree in which friction between the outer and inner tubes can be minimized, and the accuracy of the measuring apparatus.

The weight of the capped sleeve is composed of its dead weight and the weight of the inner tube. In the Funabashi-2 well, at the bottom plate of the sleeve, the load on the sand-gravel layer is about 2.9 metric tons. Meyerhof (1956) derived a formula to evaluate an ultimate bearing resistance $R_u$ by the number of blows on the sampling spoon during performance of a standard penetration test:

$$R_u = 40\ \bar{N}A_P,$$

where $\bar{N}$ is the average of N blows per foot in a depth interval between 1.0 d downward and 4.0d upward from the base of the tube, $A_p$ is the area of the base of the tube, and d is the diameter of the pile. The diameter of the sliding sleeve (casing tube) in the Funabashi well is 225 mm (Figure 2.4). Thus, $A_p = 0.040\ m^2$. In general, the N value of the sand layer in the Diluvium (Pleistocene) is more than 30. Considering the large factor of safety we can use a reduced formula of

$$R_u = 30\ \bar{N}A_P = 30 \times 30 \times 0.040\ m^2 = 36\ tons.$$

Then in this case with 0.040 $m^2$ base area, the steel tube of the well can bear about a 36-ton load. According to the above calculation, the Funabashi-2 well will not sink into the sand-gravel layers. Differences between the results of compaction recorders and dial gauges and also differences between the results of water-level recorders and taped measurement are very small. Hence, it is concluded that extensometer wells having the same construction as the Funabashi-2 well should furnish a good record of compaction or subsidence, provided down hole friction is minimal (the well bore is close to vertical).

2.2.3.2 Anchored-cable and pipe extensometers

The United States Geological Survey (USGS) has developed extensometers (compaction recorders) of two types, anchored-cable and free-pipe, both of which are illustrated in Figure 2.5. The anchored-cable extensometer (A) was first installed in 1955 in an unused irrigation well 620 m deep on the west side of the San Joaquin Valley. The extensometer consists of a heavy anchor

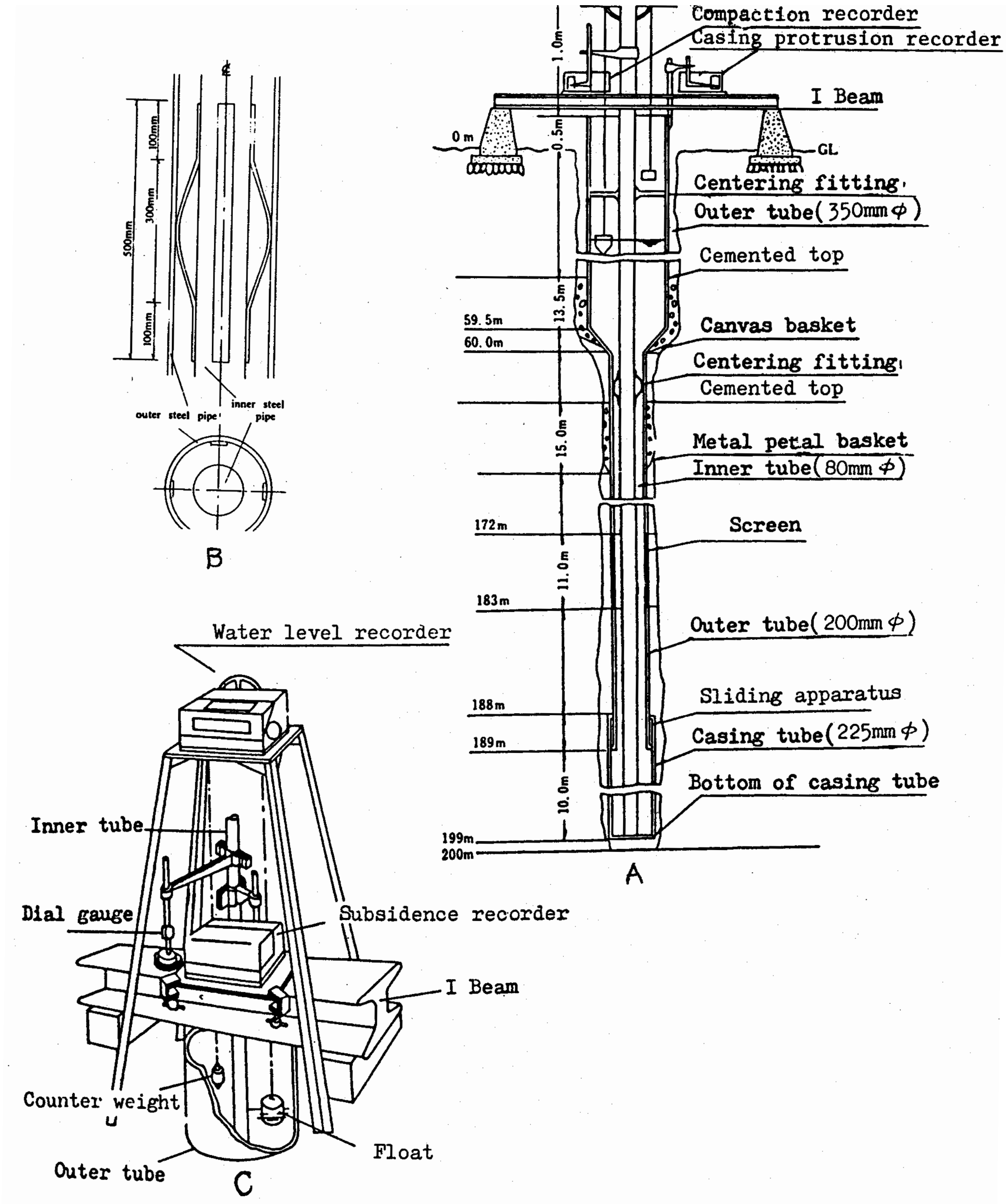


Figure 2.4 Structure of Funabashi observation well (double-tube type). A, Sectional view; B, Centralizer detail; C, Recorder detail.

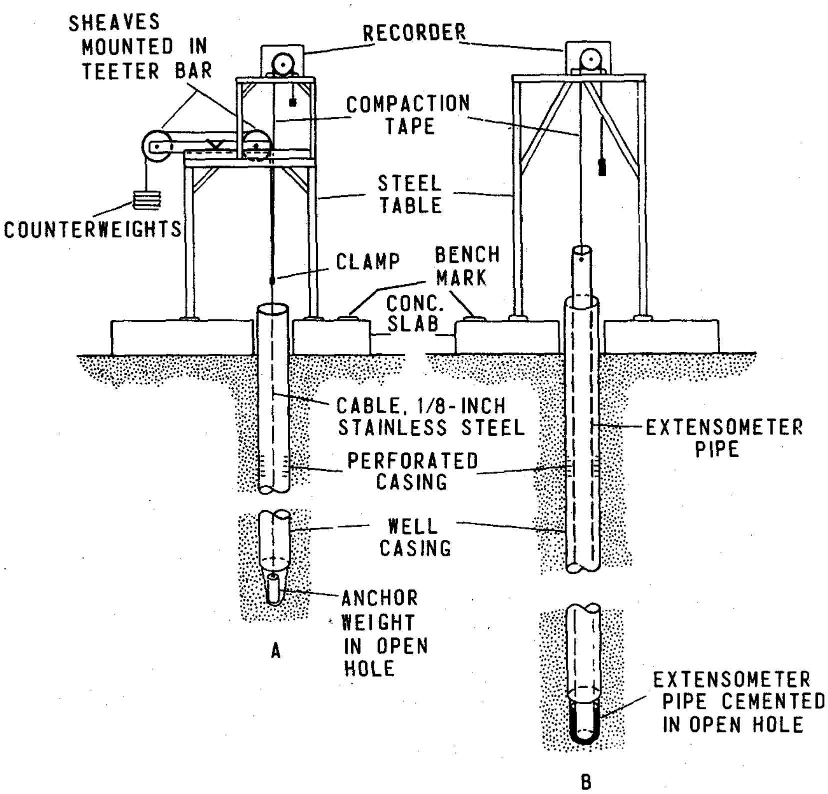


Figure 2.5 Recording extensometer installations. A, Anchored-cable assembly; B, pipe assembly.

(subsurface bench mark) emplaced in the formation beneath the bottom of a well casing; the anchor is attached to a cable that passes over sheaves at the land surface and is counterweighted to maintain constant tension. The cable is connected to a recorder that supplies a time-graph of the movement of the land surface with respect to the anchor--the compaction or expansion of the sediments within that depth range. The inked curve on the recorder chart commonly is amplified 10:1 by suitable gear combinations. The accuracy of the anchored-cable extensometer depends on the plumbness and the straightness of the well casing, the durability and stretch characteristics of the downhole cable, and especially on the success of minimizing cable-casing friction. As pointed out by Lofgren (1969), the cable must remain at constant length during the period of record. If the length changes due to temperature changes, fatigue elongation, or untwisting, the length change is indistinguishable from the record of compaction. The cable now used is a 1/8-inch (3.175 mm) diameter preformed stainless steel, 1 x 19 strand, reverse-lay "aircraft" cable. In order to minimize frictional drag of the surface sheaves, a "teeter bar" on a knife-edge fulcrum (Figure 2.5A and Lofgren, 1969, Figure 8) was designed. Changes as small as 0.1 to 0.2 mm in the thickness of an aquifer system can be recorded with this equipment.

This type of extensometer is being used in California, Nevada, and Arizona in wells as much as 700 m deep. Detailed tests of the accuracy of a similar cable-type extensometer have been made at the Groningen gas field in The Netherlands (de Loos, 1973).

For reasons of economy, most cable extensometers have been installed in unused irrigation wells, after cleaning out the casing and deepening the hole about 10 m below the casing shoe. The anchor weight of roughly 100 kilograms is then lowered into the open hole in the sediments several metres below and independent of the well casing.

To eliminate much of the cable-casing friction problem and thus improve the accuracy of the extensometer record the USGS has installed since 1966 about 30 free-pipe extensometers in California, Arizona, Louisiana, and Texas, to depths as great as 1,000 m. These pipe extensometers (Figure 2.5B) are similar in principle to the Japanese double pipe well. However, they differ in some features. The inside diameter of the well casing (outer pipe) commonly is 4 to 5 inches (10 to 13 cm) and the outside diameter of the couplings on the inner (extensometer) pipe ranges from 2 to 3.4 inches (5.1 to 8.6 cm). Thus, the space between the casing and the extensometer pipe couplings is only about 2 inches (5 cm); hence, casing centralizers have not been used to center the extensometer pipe. Centralizers have been used, however, in the annulus between the casing and the borehole wall, to center the casing, especially when the law requires cement to be placed in this annulus to protect the ground water of good quality from contamination by water of poor quality at greater depth. Centralizers usually are spaced 15 to 30 m apart.

In about half the installations, a bearing plate on the bottom of the extensometer pipe is landed on the surface of a cement plug (placed in the open hole before the casing is run). In the remainder of the installations, the extensometer pipe is cemented in place in a pocket drilled below the casing shoe. In either case, the top of the cement plug is placed at least three m below the bottom of the casing shoe so that the dead weight of the casing does not stress the extensometer footing. Furthermore, this procedure minimizes the possibility that increasing downward loads, resulting from continuing compaction at shallower depths, will be transmitted through the casing to the extensometer footing. If the cementing of the extensometer footing is accomplished after that pipe has been run into the open-hole pocket, the cement slurry can be pumped into the pocket directly through the extensometer pipe. Care must be exercised, however, in calculating (1) the quantity of cement slurry needed to fill the desired interval of the pocket, and (2) the quantity of followup water needed to displace most of the slurry from the pipe into the pocket without thinning the slurry with water. If the pipe is raised several metres as soon as the followup water has been pumped into the pipe, the water pressure into the pipe and casing can be equalized and the pipe can then be lowered again to rest in the hardening slurry.

Three free-pipe extensometers have been operated since 1975 at a site within a subsiding area in Baton Rouge, Louisiana. These extensometers record compaction of the sediments and water-level change within each of the three depth zones. The extensometer pipes extend to depths of 254, 518, and 914 m. The installations and the record obtained through 1979 have been described by Whiteman (1980). The deepest extensometer indicates an annual land-surface fluctuation of about 4 cm, apparently an elastic response.

The conversion of an abandoned oil-test hole at Westhaven, California, into a dual extensometer and a dual water-level observation well is described in this guidebook because such abandoned oil-test holes are available in many countries, and the cost of conversion is only a small fraction of the cost of drilling and completing one or more new extensometer wells. Figure 2.6 is a diagrammatic sketch of the converted well. This summary of the conversion is condensed chiefly from Poland and Ireland (1965). When the oil-test hole was drilled, a surface string of 11-3/4 inch (29.84 cm) casing was installed from land surface to 611 m. Cement was pumped into the annular space around the casing, from the bottom shoe to land surface, providing a continuous seal to protect the fresh ground water. On abandonment a cement plug was placed in the well between 1930 and 2030 feet (588 and 619 m).

The blank casing was converted to a dual water-level observation well in April 1958. The 11-3/4 inch casing was gun perforated at two depth intervals, near the top and base of the confined aquifer system (see Figure 2.6). To obtain hydraulic separation of the two perforated intervals, a 4-inch diameter pipe with a packer flange at its base was run to a depth of 860 feet (262 m); a cement plug was then placed on top of the packer, thus sealing the annulus between the two casings. Initially, the inner pipe was suspended in tension by a casing hanger resting on the top of the 11-3/4 inch casing. Four months after the inner pipe was installed, the hanger appeared to be rising off the top of the 11-3/4 inch casing, indicating shortening of the casing between land surface and the cemented packer. Beginning in August 1963 the shortening of the full length of casing above the basal cement plug was measured by lowering an anchor weight on top of the cement plug and counterweighting the cable at land surface (see Figure 2.6). Thus the conversion of the oil-test hole provided two water-level observation wells and two extensometers: a pipe-type to 845 feet (258 m) and a cable-type to 1,930 feet (588 m) below land surface.

Monthly measurements from 1964 to the end of 1970, inclusive, indicated compaction from 0-845 ft (0-258 m) was 1.94 ft (0.59 m), and from the land surface to 1,930 ft (0-to-588 m) was 3.57 ft (1.09 m).

These observations at the Westhaven site indicate that even heavy oil-well casing encased in a cement jacket is too weak to resist the compressional force of the compacting sediments. Even in the shallow depth interval from land surface to 845 ft (258 m), the increased protrusion in seven years was only equal to 12 per cent of the subsurface shortening in that interval. It is concluded that in an area subsiding because of sediment compaction due to decrease in fluid pressure, the top of a well casing is not a stable reference bench mark, even if the casing

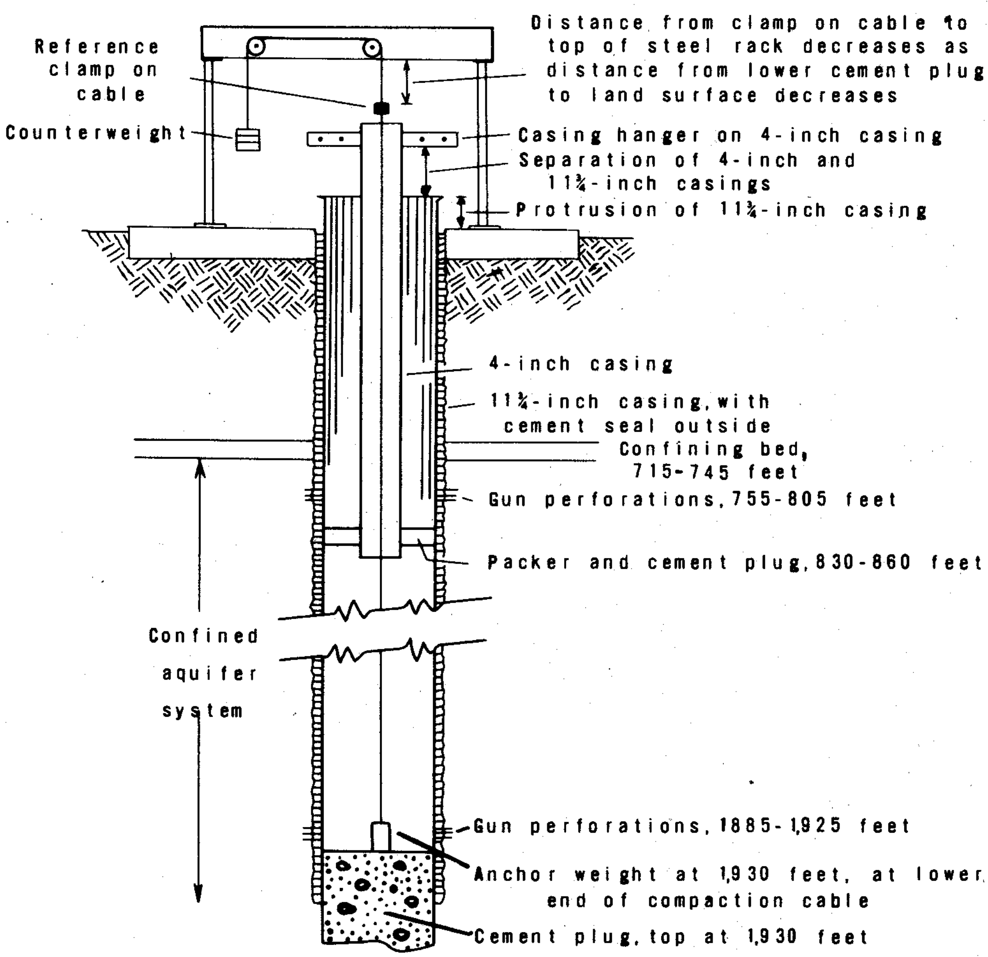


Figure 2.6 Diagrammatic sketch of wells used for measuring water levels and compaction: wells 20/18-1102 and 1103 (from Poland and Ireland, 1965).

extends below the compacting sediments. Also, the evidence is clear that increased protrusion of a casing above the land surface, even though an indicator of land subsidence, is not a reliable measure of either compaction or subsidence. Bull (1975, p. 41-45) cites additional evidence concerning the minor amount of casing protrusion compared to subsurface casing compression in wells on the west side of the San Joaquin Valley.

In Mexico City, however, observed protrusion of some water-well casings has been about the same magnitude as the subsidence. Poland and Davis (1969, p. 225-228 and pl. 6) show graphic pictures taken by Ing. R. Marsal in 1954 of the protrusion of casings of two wells drilled about 1923. They were drilled to a depth of about 100 m but most of the compaction occurs in the highly compressible lake clays in the top 50-60 m. The subsidence at the well sites from 1891 to 1959 was 5.9 m. In 1954, one casing protruded 5.45 m and the second 4.5 m. The protrusion of 5.45 by 1954 is about equal to the subsidence by 1954, proving that essentially all the compaction at the well site is occurring in the top 100 m of sediments, and probably mostly in the top 60 m. The lateral pressure to this depth may not be great enough to compress the outer casing as compaction occurs. However, the excessive protrusion is believed to be due in part to the fact that wells are drilled using more than one casing size.

In evaluating the characteristics of cable and pipe extensometers, the following factors should be considered:

1. If a cased well is available, the cable extensometer costs less to install than the pipe extensometer, chiefly due to the lower unit cost of the cable compared to the pipe.

2. The cable extensometer has minimal cable-casing friction when the well casing is of large diameter (30-40 cm); the friction increases when the well casing is of small diameter (10-15 cm), all other factors being equal.
3. In contrast, the pipe extensometer has minimal pipe-casing friction when the well casing is of small inside diameter (10-15 cm) and the overall space between pipe or pipe couplings and well casing is in the range of 4-6 cm. Alternately, if the well casing is of large diameter, use of pipe centralizers spaced 15 to 30 m apart between casing and pipe, as is done in the Japanese double pipe wells (Figure 2.3B), may produce a record as good as that obtained with the pipe-in-small-casing design. So far as known, no comparative test has been made.
4. The pipe extensometer commonly gives a more accurate record than the cable extensometer, all other conditions being equal.
5. If a well can be drilled so plumb and straight that the departure from verticality at the base does not exceed the inside diameter of the casing, the cable can be positioned to avoid any downhole cable-casing friction. Under such circumstances the cable extensometer is more frictionless than the pipe extensometer. However, a well drilled to a depth of 50 m and with a casing diameter (inside) of 0.3 m would have a departure of 0.3 m from verticality at the bottom if the drift from verticality was 0°20′. For a well 100 m deep, a departure from verticality of 0.3 m at the bottom would require that the drift be held to 0°10′. Thus, it would appear that the chances of drilling a well more than 100 m deep that is sufficiently plumb to eliminate any cable-casing friction are remote. The above discussion does not consider possible cable-casing friction caused by the tendency of rotary-bored holes to develop a spiral pattern.

A cable extensometer at the USGS Cantua site in the San Joaquin Valley, California, installed to a depth of 610 m in a well with 10 cm casing to 595 m, had so much cable-casing friction that the equipment recorded no compaction even when as much as 7.6 cm of compaction had occurred during the prior month. At the time of the monthly visit to service the equipment, the cable was stretched--that is, the counterweight was pushed down about 30 cm and then allowed to rise gently. This operation triggered enough down-hole slippage of the cable at friction points (cable-casing friction) to permit the cable to move upward and record the approximate compaction that had occurred since the last monthly visit. Bull (1975, p. 32 and Figure 25) has discussed the problem and reproduced a part of the stairstepped field record from the extensometer. This extensometer equipment was installed in a corehole. When drilled, the plumbness of the hole was surveyed at 30-metre intervals with a driftmeter. The drift from vertical was 1 degree at 90 m depth and ranged from 5 to 6 degrees between 244 and 580 m depth. In spite of the nonverticality of the hole (and of the casing), an interpolated cumulative compaction curve drawn through the low points of the stepped record produced a reasonably accurate long-term compaction curve for the deep Cantua site extensometer. The compaction plot for well N1 in Figure 9.P.8 is the 13-year record of 3.4 m shortening for sediments between land surface and a depth of 610 m.

At the Terra Bella site on the Friant-Kern Canal in the San Joaquin Valley, casing of 10-5/8 inch (27 cm) diameter was placed in a well to a depth of 377 m and an extensometer pipe of 1-1/2 inch (3.8 cm) diameter was inserted and landed at a depth of 381 m. No centralizers were used. Most of the record in the field compaction charts for this extensometer is composed of a series of stair-step adjustments with individual vertical displacements of 0.15 to 0.3 mm (1-5 to 3 mm at the 10:1 magnification). The overall space between the well casing and the extensometer pipe-couplings is nearly 20 cm, permitting too much flexing of the inner pipe and too many friction points. The compaction record at this site probably could be improved by adding centralizers to center the inner pipe in the casing, by increasing the size of the inner pipe, or by use of a lever and counterweight system at land surface to remove a substantial part of the dead weight of the extensometer pipe. This last procedure should produce the greatest reduction in pipe-casing friction.

Under most favourable conditions, the pipe extensometer as described in this manual will function satisfactorily to depths of 750 to 1,000 m. The most favourable conditions would require straight holes--holes drilled with deviation from the vertical of less than 1/2 degree-and a combination of well casing and extensometer pipe sizes, or use of centralizers, that minimizes pipe-to-casing friction.

The cable extensometer will supply approximate measurements to depths of 600 to 850 m, but the results are less accurate, in general, than with the pipe extensometer.

The depth to which the pipe extensometer equipment is operative--750 to 1,000 m--is adequate for studies of subsidence due to ground-water withdrawal in most of the world. Much ground water is pumped from aquifers less than 300 m deep and most from aquifers less than 600 m deep. However, improvement in the accuracy of compaction measurements at depths greater than 300 m is highly desirable. Furthermore, in connection with the study of subsidence due to other causes, or subsidence due to other types of fluid withdrawal, such as geothermal or oilfield fluids, there is need for improvement of extensometer design to increase the depth of useful measurements. For example, much or nearly all of the dead weight of the inner extensometer pipe can be removed by use of a lever and counterweight system at land surface. Most of the pipe would then be in tension and the frictional stress between pipe and casing should be greatly lessened at the time of compression (or expansion) of the well casing. This method has been applied by Ben E. Lofgren (oral communication, December 1975) to an extensometer 317 m deep in Imperial Valley, California, where more than two-thirds of the pipe weight has been removed by a counterweighted lever designed with a 10-to-1 mechanical advantage. Also, one highly sensitive extensometer was recently constructed in Arizona to a depth of 380 m using this method (F. S. Riley, oral commun., July 1979). In this installation the upper 75 per cent of the extensometer pipe was placed in tension while the lower 25 per cent remained in compression. The neutral point was positioned at a major bend in the casing, as determined by a borehole alignment survey. Before installation of the lever and counterweight this installation had severe friction problems and produced a record characterized by intermittent stair-step movements. After counterweighting the instrument produced a smooth record of continuous compaction.

Research is needed to determine the accuracy of such a lever and counterweight system through a wide span of unloading of the extensometer pipe, say from 25 per cent to 90 per cent. Comparison of simultaneous compaction records from a normally loaded pipe extensometer and a nearby counterweighted extensometer of the same depth and construction, in an area of active subsidence, would be very instructive. Several stages of unloading could be applied to the counterweighted extensometer.

Another way in which the weight of the pipe in a free-pipe extensometer can be reduced is by installing a tapered pipe assembly. For example, the bottom third of the pipe could be 2-1/2 inch, the middle third 2-inch, and the upper third 1-1/2 inch; or the assembly could be 2-inch, 1-1/2 inch, and 1-inch. For an extensometer 750 m deep, a free pipe of 2-1/2 inch constant diameter would weigh 6,580 kg. But if the pipe was installed with equal lengths (250m) of 2-1/2 inch, 2-inch, and 1-1/2 inch pipe, the weight on the bottom joint of the 2-1/2 inch would be decreased about 30 per cent (neglecting buoyancy effects). The decrease in weight should decrease the cost of the installation, and simplify the addition of a lever and counterweight at land surface, if desired.

#### 2.2.3.3 Slip joints

When extensometer or observation wells are being installed in an area that is subsiding at a rapid rate, it is advisable to consider the need for installing a series of slip joints in the casing during construction. When extensometers were being installed on the west side of the San Joaquin Valley of California in 1958-62, the ground-water reservoir was compacting as rapidly as 30 cm per year. Under such circumstances, it was anticipated that the casings of deep extensometers would last longer under severe compressive forces if slip joints were inserted in the well casing. Accordingly, at the Cantua site, for example, eight slip joints were placed at 60-metre intervals in the 4-inch casing 595 metres deep. Figure 2.7 shows details of the slip joint. Each slip joint has about 0.9 m of play between the open and closed position. Since installation in 1958, this extensometer has shortened about 3.5 m. Without slip joints, the elastic compression of the 4-inch (10 cm) casing from full tension when first suspended in the well to the elastic limit in compression would have been about 1.2 m. The additional shortening of 2.3 m beyond the elastic limit of the casing must have resulted from compressional failure of the casing or shortening of the slip joints, or both. Because this equipment is still functioning as an extensometer, we conclude that a major part of the 3.5 m of shortening must have occurred through shortening of slip joints.

#### 2.2.3.4 Telescopic extensometer

An experimental telescopic extensometer, designed by Ignacio Sainz Ortiz, was installed in Mexico City to a depth of 60 m in 1953. Figure 2.8 shows that in the 6-year period 1953-59, 36 cm of shortening occurred in the 60-metre thickness of near-surface deposits. In the first 20-30 m below the land surface lateral stresses against the casing are small. Nevertheless,

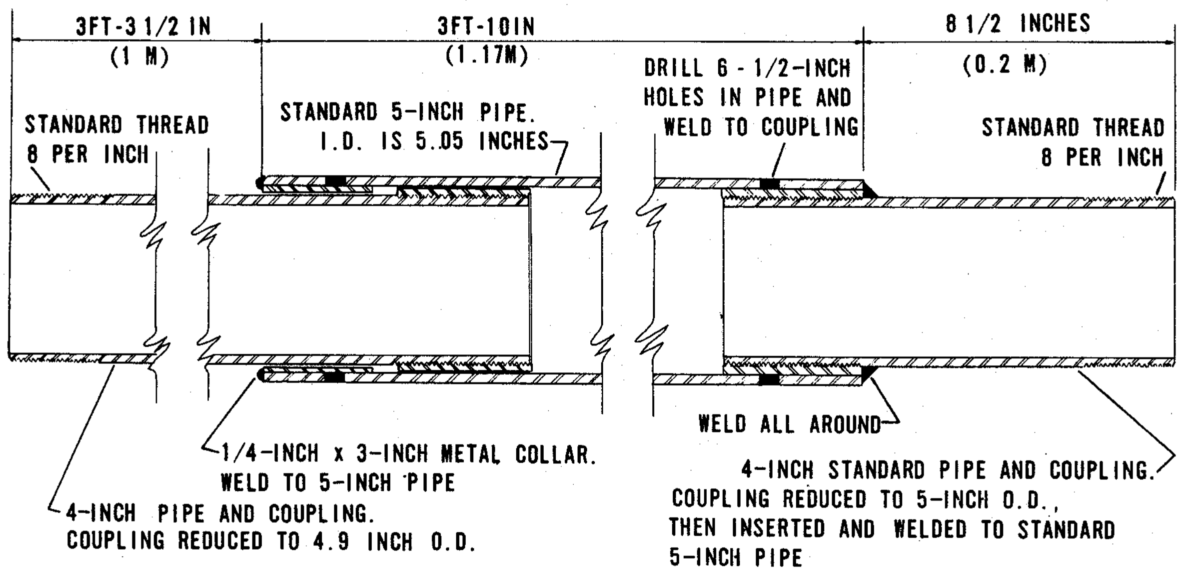


Figure 2.7 Diagram of slip joint.

considering the flexibility of the telescopic construction, the lateral stress should develop enough skin friction to cause the casing to shorten in accord with the surrounding sediments, even at the shallow depth range involved.

2.2.3.5 Extensometer records

Plots of cumulative compaction against time obtained from extensometer records are becoming fairly common in the published record, in connection with field research on land subsidence due to ground-water withdrawal. For example, in Japan, Miyabe (1967, p. 2-3) published compaction plots obtained from extensometers in Tokyo and Hirono (1969) showed plots of compaction from extensometers in Niigata. In the United States, extensometers have been operated for more than 20 years in the San Joaquin and Santa Clara Valleys, California. Computer plots of cumulative compaction through 1970 at 30 sites, together with water-level fluctuations, change in applied stress, and subsidence at most of these sites, have been published (Poland, Lofgren, Ireland, and Pugh, 1975, Figures 53-78).

In the case history for subsidence in the Santa Clara Valley, California, Figure 9.14.5 contains time plots of compaction for 15 years for two depth intervals at the San Jose extensometer site. In Figure 9.14.6 the measured compaction is plotted in annual increments that present a more quantitative picture of the annual change in amount of compaction than does the cumulative plot.

If two or more compaction recorders (extensometers) are installed in adjacent wells of different depths, the record from the multiple-depth installation will indicate the magnitude and rate of compaction (or expansion), not only for total depths of individual extensometers but also for the depth intervals between well bottoms. Figure 9.13.8, discussed in the case history of the San Joaquin Valley, California, is a good example of the record from a multiple-depth installation, and is one of six multiple-depth sites in the valley.

2.2.4 Other techniques of subsurface measurement

2.2.4.1 General

In addition to the pipe-type (double pipe) and anchored-cable extensometers described earlier in this chapter, a number of instruments utilizing similar principles but differing in measurement techniques are being manufactured commercially. O’Rourke and Ranson (1979) have made a summary

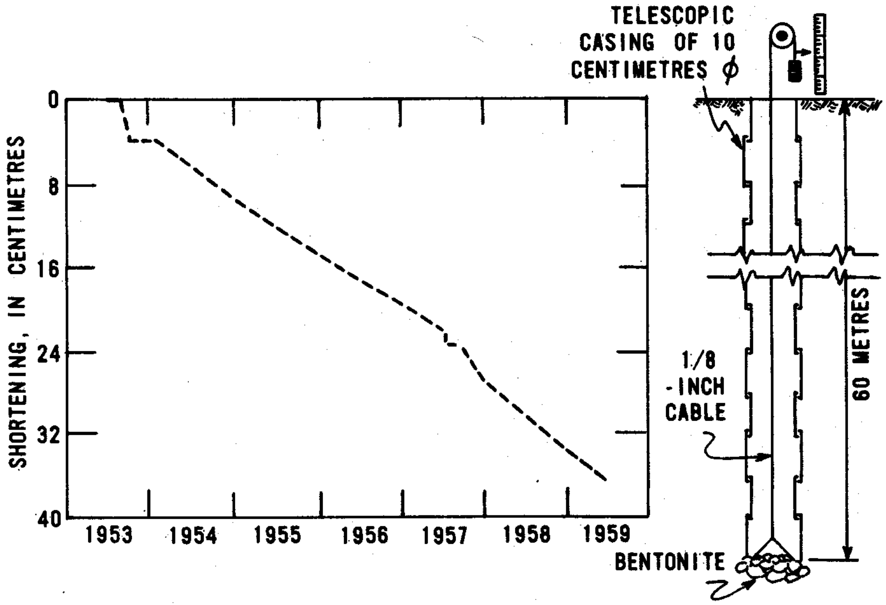


Figure 2.8 Sketch of telescopic extensometer and 6-year record of shortening (compaction of deposits). Redrawn from the Comisión Hydrologica de la Cuenca del Valle de Mexico, 1961, Boletin de Mecanica de Suelos, no. 3, p. 55.

appraisal of the capabilities of existing instruments for monitoring subsurface vertical displacement, examined with respect to availability, performance characteristics, and installation and operating requirements. The summary, reproduced as Appendix B of this guidebook, describes capabilities of 6 wire-type and 6 rod-type extensometers; 1 pipe-type extensometer (the USGS type); 2 multiple base length extensometers with sensors and anchors or magnet markers; 1 chain type extensometer with anchored sensor case; and 6 sonde-type extensometers, including the casing-collar locator and the gamma-ray logger. For details on the various wire-type and rod type extensometers for measuring subsurface vertical displacement, the reader is referred to Appendix B.

The techniques of casing-collar logging and gamma-ray logging with radioactive bullet markers require the use of specialized and expensive equipment. Normally this service would be provided by oil well service companies. In subsidence studies of most ground-water basins, however, the cost of utilizing such expensive equipment on a repeat basis probably would not be economically justified in most cases, when costs were compared with other study techniques. However, because such repeat logging has the decided advantage of indicating the depth range, rate, and magnitude of compaction or expansion of the sediments, a brief statement of the two techniques follows.

### 2.2.4.2 Casing-collar logging

At Long Beach, California, in the Wilmington oil field, changes in thickness of compacting zones have been measured successfully by running a magnetic collar locator periodically in the same well to determine the change in the distance between casing collars between surveys. According to Allen (1969), the first "collar counting" was in 1949 and more than 200 multiple traverse runs have been made to depths of as much as 1,800 m. These collar logs can be used to measure change in length of individual joints compared to joint length when placed in the well or since a prior logging. They also indicate the depth range, rate, and magnitude of compaction of the sediments if it is assumed that the casing or cement at every point moves in exact accord with contiguous sediments as a result of skin friction produced by lateral stresses. The field evidence at Wilmington from various sources generally supports this assumption for depths greater than 600 m. Collar surveys run five times from 1949 to 1960 in an individual well (Figure 2.9) graphically indicate the depth range, rate, and magnitude of compaction of three

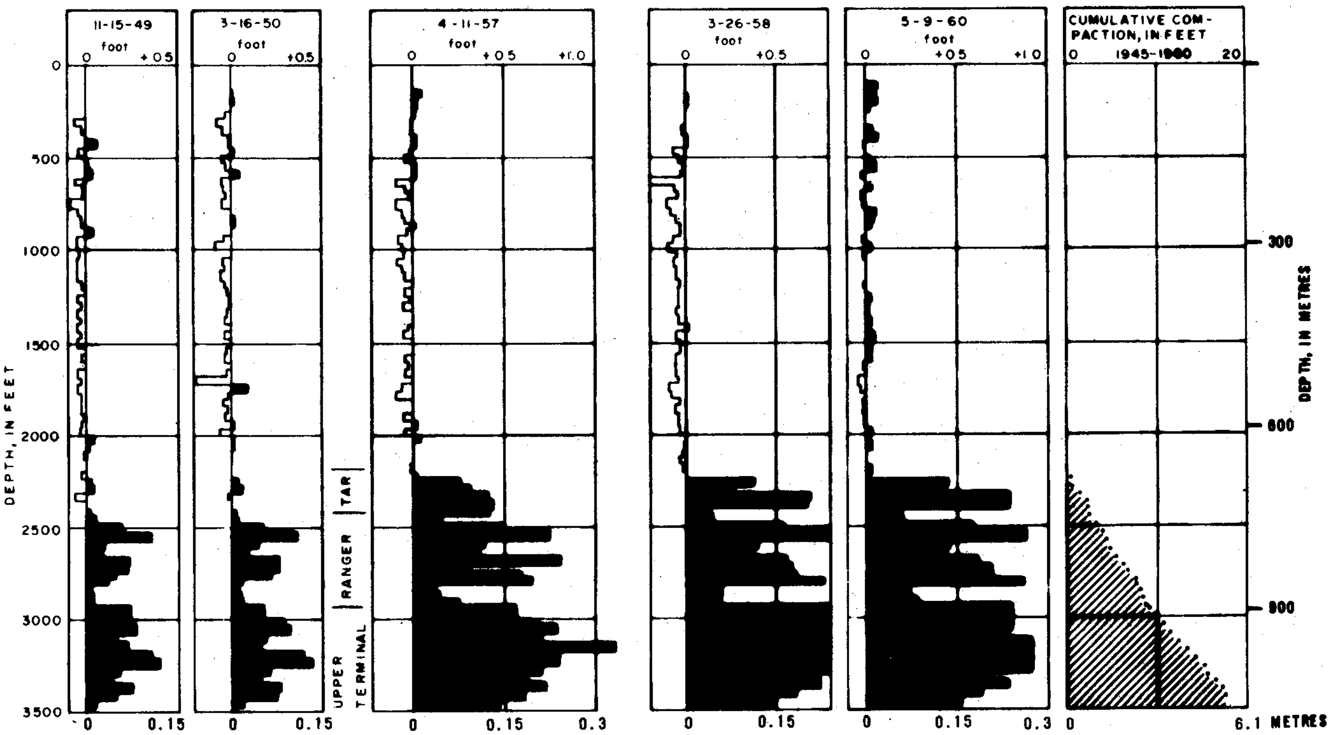


Figure 2.9 Casing collar surveys of a typical well in the Wilmington oil field. Survey on date indicated compared to casing tally of 9-26-45; elongation due to tension shown to left of zero reference, shortening due to compression shown to right (shaded); length of casing joints 12.5 to 13.4 m., in general (data courtesy of Long Beach Harbor Dept.).

oil zones--the Tar, Ranger, and Upper Terminal. The cumulative compaction of these three zones from 1945 to 1960 was 17.6 feet (5.4 m) as summed from the shortening of the casing joints by 1960 compared to their measured length in 1945. Allen and Mayuga (1969, Figure 13) also showed that collar logs can be used to measure oil-zone expansion in an area of rebound by plotting collar-log surveys of wells producing from oil zones that are receiving injection water. According to Allen (oral commun., 1977), recent developments in casing-collar logging at Wilmington provided an accuracy of 9 mm 88.5 per cent of the time for joint lengths of 12.5 to 13.4 m, measured three times. The maximum degree of instrument error is estimated to be 30 mm for each joint length.

Casing-collar logs also have been made in the oil fields on the eastern shore of Lake Maracaibo in Venezuela where maximum subsidence has been about 4 m (Nuñez and Escojido, 1977).

### 2.2.4.3 Radioactive-bullet logging

At Wilmington, California, at the Lake Maracaibo oil fields in Venezuela, at the methane gas and brine reservoirs of Niigata, Japan, and at the Groningen gas field in The Netherlands, radioactive bullets have been shot into the formation at known depths, and their positions resurveyed later by gamma-ray detectors to measure compaction or expansion. The accuracy of the radioactive-bullet logging equipment used at Wilmington is reported by Allen to be about 3 cm per distance between bullets (at Wilmington 6.1 m) when logging at 7.6 m per minute.

Schoenbeek (1977) reports improvement in the accuracy of measurement at the Groningen gas field. The sandstone reservoir depth is about 2900 m, and the average thickness about 150 m. Radioactive bullets were shot into the formation at 10-m intervals; relative displacement was measured with a gamma-ray sonde containing three detectors. After considerable improvement of technique, the mean error of measurements determined by statistical analysis was reported to be

1 cm in 100 m of measured interval. To achieve this accuracy, however, the logging time had to be slowed to about 20 m per hour. DeLoos (1973) has described in detail the development and testing of logging equipment.

At Niigata, Japan, the radioactive bullet technique was refined by experiments in 1959-60 and the construction of two observation wells (Figure 2.10). According to Sano (1969), the first observation well (Yamanoshita) was completed in 1960 to a depth of 650 m. Four sizes of casing were used, each stage from bottom to top being of larger diameter than the preceding one. The base of each stage was grouted to the contiguous strata and overlapped the head of the stage below it. Sano (1969) states that it was intended that the increase in the overlapped length of each stage should represent the shrinkage between the strata to which the casing was grouted. The system was unsuccessful because the casing contracted with the shrinkage of the formation.

The second well (Uchino) was completed in 1961 to a depth of 950 m. It was constructed with a conductor pipe 100 m long cemented to the surrounding strata through its full length. The main casing 5-1/2 inches in diameter was suspended in the conductor pipe, In effect, this observation well was the single pipe type.

In both observation wells, radioactive bullets were shot into the formation every 40 m and radioactive reference pellets were attached to the casing every 20 m (Figure 2.10).  Special logging equipment was designed to improve accuracy. Logging at about 1-year intervals from 1961 to 1966, when the deeper well failed, apparently was reasonably successful in determining location and general magnitude of compaction.

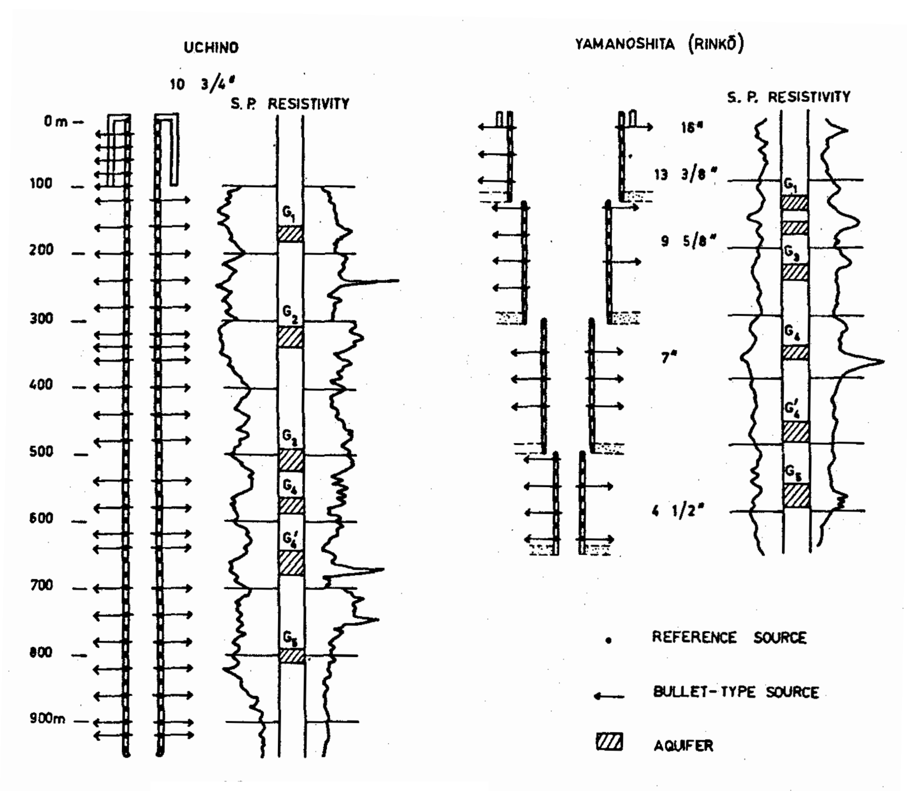


Figure 2.10 Structure of the observation wells in Niigata, Japan (after Sano and Kayana, 1966, Figure 2).

## 2.3 HORIZONTAL DISPLACEMENT

### 2.3.1 Land-surface displacement

In areas of subsidence due to fluid withdrawal, horizontal displacement of the land surface has been measured at only a few places. One of those is the Wilmington oil field in Los Angeles County, California, which has experienced as much as nine metres of subsidence. The vertical subsidence has been accompanied by horizontal movement directed inward toward the center of subsidence. This horizontal movement has been measured by surveys of a triangulation network of the Los Angeles County Engineer’s office. In 1951, when subsidence at the center was 4.9 m, horizontal movement since 1937 had been as much as 1.9 m (Grant, 1954, Figure 1). By 1962, some points on the east end of Terminal Island had moved as much as 2.7 m, according to the Long Beach Harbor Department.

At Wairakei, New Zealand, Bixley reports that both horizontal and vertical movements have occurred along the steam mains route (see case history 9.9). Maximum movement is near bench mark A97 (Figure 9.9.5), where horizontal movement is about 75 mm/year and vertical movement 130 mm/year.

Until recently, short distances were measured by steel tape and longer distances by triangulation. Triangulation involves the measurement of the angles of a triangle, careful measurement of the length of one side, called the base line, and calculation of the lengths of the other two sides. The process can be extended through angular measurement of many additional triangles.

Within the last decade, however, extremely accurate means have been developed for measuring horizontal distances between points. Electronic Distance Measurement (EDM) equipment permits line-of-sight distance measurement, both rapidly and precisely. Thus, the location of points can now be determined by trilateration, whereby a network of triangles is constructed from one or more known points, with the length of all sides determined directly by use of the EDM equipment. Distance measurements by trilateration have largely replaced measurements by triangulation, especially where extreme accuracy is needed.

The general distance capabilities and accuracy of three types of EDM equipment are as follows:

1. Geodolite, capable of 1 unit in 107 units (laser), 30 km;
2. Electronic EDM, capable of 2 units in 106 (laser), 12 km;
3. Distance meter, capable of 1 unit in 105 (infrared), 3 km.

More information on EDM instruments and other types of equipment to monitor horizontal displacements at land surface are summarized by Van Til (1979, table D-1). Van Til’s summary, reproduced in this guidebook as Appendix A, includes a listing of instrument capabilities of steel tapes, EDM instruments, and horizontal extensometers to measure ground strain or crack movement. The appraisal was made with respect to availability, performance characteristics, and installation and operation requirements.

### 2.3.2 Subsurface displacement

Instruments currently available for the measurement of horizontal displacement at depth are sonde-type borehole inclinometers. Oil-well service companies have equipment to measure both the drift angle (angle of departure from vertical) and the true compass bearing at desired depth intervals to depths as great as 6 km. Most other sonde-type inclinometers have been developed for near-surface geotechnical studies and in general have depth ranges limited to 200-300 m. The availability, operating principles, accuracy, and principal installation and operation features of 10 sonde-type borehole inclinometers and 3 fixed borehole inclinometers are summarized in Appendix B.

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