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SETTLEMENT STUDIES BY MEANS OF PRECISION LEVELLING

The U.S. Coast and Geodetic Survey is responsible for the first- and second-order vertical control net of the United States. The development of the level net started in 1878 and as of January 1, 1960, there were 177,623 miles of first-order lines and 268,159 miles of second-order lines or a total of 445,782 miles of first- and second-order levelling along which 380,414 bench-marks have been leveled over. In the early development of the net, marks were spaced rather widely, on an average of every six miles. Later the spacing of bench-marks was from three- to five-miles apart, but the present specifications call for a mark at one-mile intervals with a closer spacing in cities and towns.

The levelling instrument is equipped with a level vial with a sensitivity of two seconds of arc per two millimeters graduation. Three-wire readings to the nearest millimeter are taken on standardized invar rods which are graduated in centimeters. Paraffin-impregnated wooden rods were used prior to 1916 but since that date invar rods have been used. Since the invar is considered much superior to the wooden rod, the relevelling program has been planned so that all lines established prior to 1916 would be releveled first. The majority of the level lines established prior to 1916 have now been releveled and many lines established since 1916 have also been releveled, especially in areas of known vertical change.

The areas of known vertical change in which the Coast and Geodetic Survey has undertaken concentrated relevelings are shown on figure 1 and are as follows :

1. San Jose, California,
2. Delta Area, California,
3. Dixie Valley, Nevada,
4. San Joaquin Valley, California,
5. Eight Crossings of Fault Lines, California,
6. Long Beach and Terminal Island, California,
7. El Centro, California,
8. Hoover Dam, Arizona and Nevada,
9. Hebgen Lake Earthquake, Montana,
10. Galveston-Houston, Texas.

1. In the vicinity of San Jose in the Santa Clara Valley of California, the original levelling was done in 1912 with a concentrated net of about 240 miles of lines first established in the spring of 1934 for future settlement study. San Jose is in an area of heavy removal of underground water for irrigation. The decline in the underground water

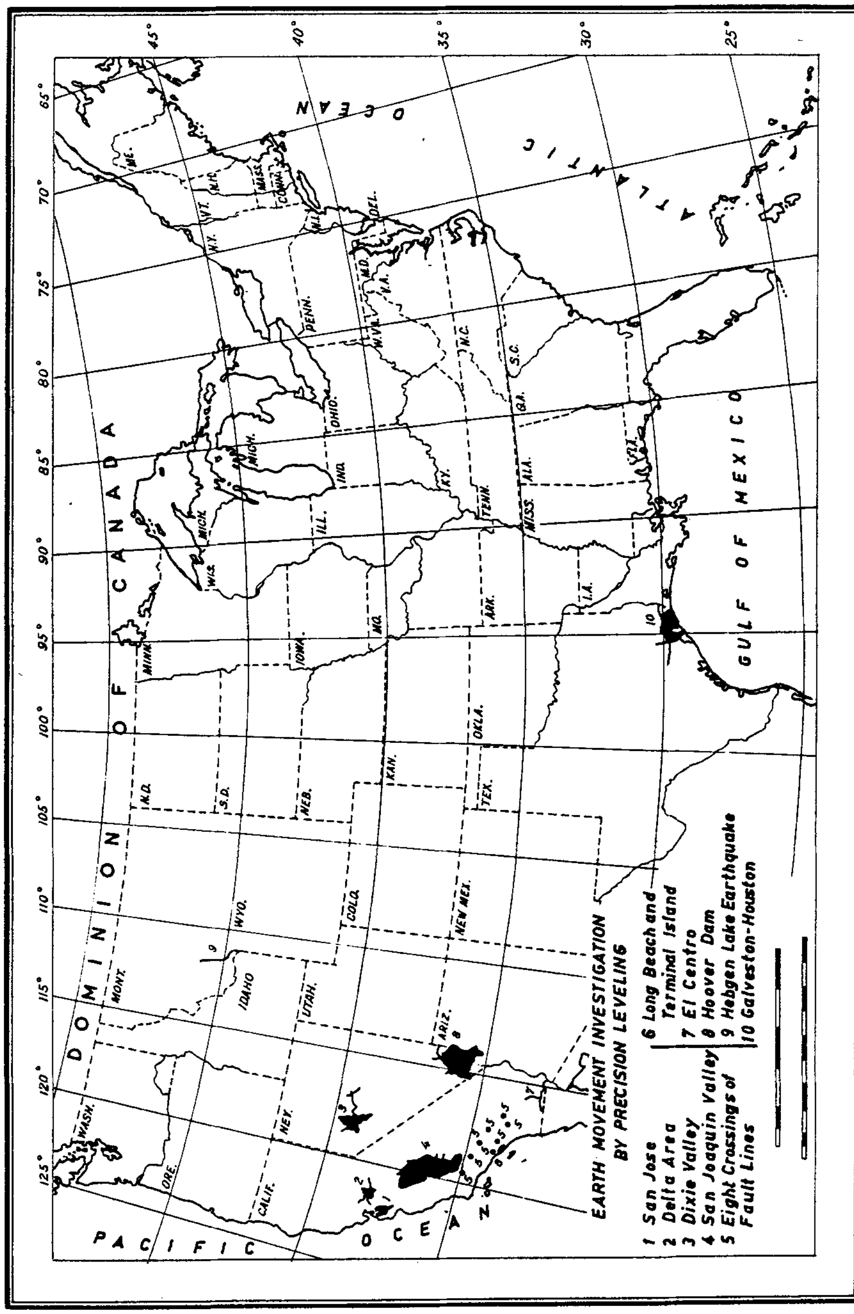

EARTH MOVEMENT INVESTIGATION
BY PRECISION LEVELING
1 San Jose
2 Delta Area
3 Dixie Valley
4 San Joaquin Valley
5 Eight Crossings of Fault Lines
6 Long Beach and Terminal Island
7 El Centro
8 Hoover Dam
9 Hebgen Lake Earthquake
10 Galveston-Houston
DOMINION OF CANADA
PACIFIC OCEAN
ATLANTIC OCEAN
GULF OF MEXICO

Fig. 1

table has caused compaction in the underground clays with a resulting settlement of the earth's surface.

The Coast and Geodetic Survey has undertaken 14 relevellings at various times of high and low underground water. There is a good correlation between the settlement and the decline in underground water. The last complete relevelling was in 1954 with a complete relevelling scheduled for the winter of 1960-61. There was a partial relevelling of this net in 1956 in connection with a Corps of Engineers' request for relevelling surrounding the San Francisco Bay Area and a small amount of relevelling in 1959 in connection with levelling to the San Jose Airport.

The maximum settlement is 9.04 feet from 1912 to 1959 at the Hall of Records Building in San Jose. Fortunately, there are stable bedrock marks located about 5 miles southeast of San Jose established in jurassic ultra-basic intrusives, which are serving as excellent anchors. A good agreement between relevellings has been obtained from these bedrock marks to tidal marks at The Presidio, San Francisco. The San Jose net has been expanded to include about 300 miles of levelling.

2. The Delta Area levelling is mainly in the lowland region of the confluence of the Sacramento and San Joaquin Rivers. Levellings were undertaken in 1934-35, 1938-39, 1946-47, 1951, 1953, 1957, and 1958 with a relevelling sheduled during June and July 1960 comprising about 210 miles of first-order levelling. In 1957, a basic net was established which tied to anchors set in bedrock about 3 miles south of Clayton in the Coast Range and near San Andreas in the Sierra Nevadas. Prior to 1957, the levelling was rather piecemeal and was not developed as a net tied to rock anchors. During the 1951 levelling, marks were set on piling driven to a considerable depth through the peat, but subsequent levelling shows many of these marks also to be settling slightly. During the 1957 levelling, 26 "Copperweld" rods were driven at five-mile intervals to depths of 15 to 126 feet. Use of these rods will be discussed more fully later.

The maximum settlement in the Delta Area is 2.109 feet from 1939 to 1957. The factors contributing to change are removal of gas and the compaction of the peat. Levelling in the Delta Area is important in connection with the study on a Salinity Control Barrier. Some of the islands are 15 to 20 feet below sea level and the continuation of settlement requires altering dikes.

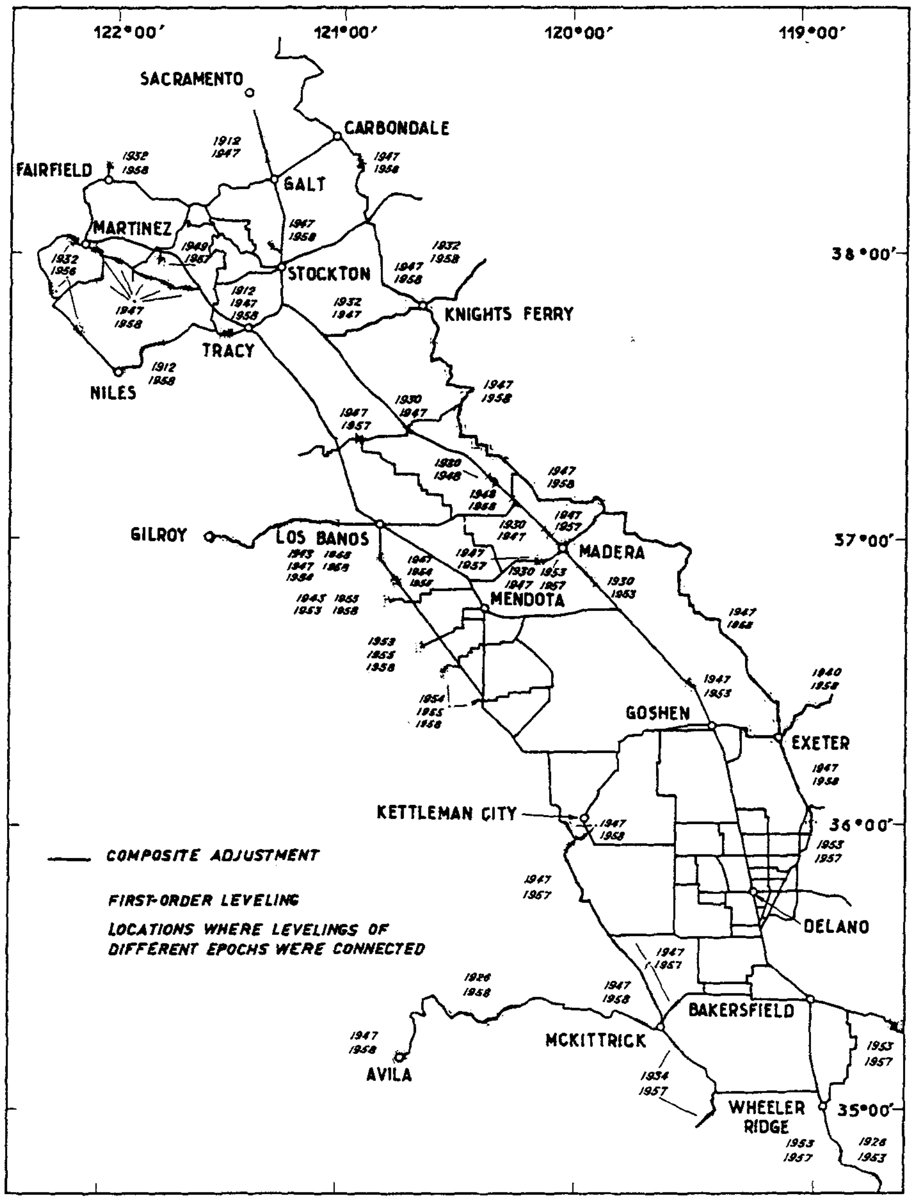
3. In the spring of 1955, relevelling of 517 miles of first-order lines was undertaken to determine the vertical changes resulting from the Dixie Valley, Nevada, earthquake of December 16, 1954, (39° 19 N. 118° 12' W. magnitude 7.0), and to bring bench-mark data up-to-date in this region. Third-order levelling by the U.S. Geological Survey in 1908 was nearest the epicenter. A comparison with this levelling shows the maximum bench-mark settlement to be 7.307 feet. At the fault, vertical displacement was estimated to be 23 feet; however, no old bench-marks were located in this area of greatest change.

4. In 1947, the Coast and Geodetic Survey established about 1,000 miles of first-order levelling in the San Joaquin Valley, California, for future settlement studies. The north-south lines were placed as near the foothills as possible and there were several east-west lines across

the valley. In planning a field program for settlement investigation, geology maps are consulted to determine where the best available rock is located where bench-marks can be installed for use as anchors. In the study for the San Joaquin Valley, there are many anchors in the Sierra Nevadas and the Coast Range as well as connections to tidal observations. The main factor contributing to settlement in this area is the removal of underground water for irrigation. The study is required to obtain knowledge regarding areas of relative stability in order to plan canal routes to carry water from northern to southern California. The canals are built with such small gradients that the carrying capacity is affected by settlement. In two of the areas of greatest settlement, a relevelling program at two-year intervals has been scheduled. These two areas are known as the Los Banos-Kettleman City area and the Tulare-Wasco or Delano area. In the Los Banos-Kettleman City area, relevellings were undertaken in 1953, 1955, 1957, and 1959-60. The rate of settlement has been 1-3/4 feet per year as a maximum, with a maximum bench-mark settlement of 14.481 feet from 1935 to 1957 at a location about six miles west of Mendota. The latest levelling is not yet adjusted. In the Tulare-Wasco area, relevellings were undertaken in 1948, 1954, 1957, and 1959. The maximum bench-mark settlement in this region has been 9.291 feet from 1930 to 1959. After the Tehachapi earthquake of July 21, 1952, (epicenter 35° 00' N. 119° 02' W. magnitude 7.7), there were certain lines releveled south of Bakersfield and through Tehachapi. The total vertical change was approximately four feet, some areas having risen about two feet and others settling about two feet. The present net of lines in the San Joaquin Valley and vicinity form an excellent area for future generations to study the settlement in the valley and, by the periodic relevelling from the anchor marks to primary tide stations at San Francisco and Avila, results will be available on changes taking place in the Sierra Nevadas and Coast Range which are classed as geologically young and still growing. During our life-span, there probably will be very small changes, if any, in the granite of the Sierra Nevadas or Coast Range in California unless there is a severe earthquake.

Figure 2 is a sketch of the routes of lines comprising a composite adjustment of all of the levellings in central California. The darkened portions are locations where levellings of different epochs were connected and the dates are shown for which stability was indicated through comparison of the levellings. The composite adjustment of all of the original levelling and relevellings consisted of 6,500 miles of lines and a solution of 175 equations. However, the main effort in an adjustment of this type is deciding where the levellings of different epochs can be tied together. At widespread points where the deviations between successive levellings are less than the probable errors of the levelling involved, such deviations may represent accumulations of small errors inherent in all physical measurements; it may represent actual small earth movement, or it may represent a combination of the two.

5. In 1935, eight lines of levelling were established at right angles to known fault lines in southern California. The lines averaged about 10 miles in length with about 200 bench-marks on each line. The marks were established approximately 100 feet apart for the first mile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KNIGHTS FERRY
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NILES
GILROY
LOS BANOS
MADERA
MENDOTA
GOSHEN
EXETER
KETTLEMAN CITY
DELANO
BAKERSFIELD
MCKITTRICK
AVILA
WHEELER RIDGE
COMPOSITE ADJUSTMENT
FIRST-ORDER LEVELING
LOCATIONS WHERE LEVELINGS OF DIFFERENT EPOCHS WERE CONNECTED

Fig. 2

each way from the fault line, 200 feet apart for the second mile, 300 feet apart for the third mile, 400 feet apart for the fourth mile, and 500 feet apart for the fifth mile. The locations at which these lines were established, the fault crossed, and the dates of the levellings are as follows :

Location	Fault	Dates of Levellings
1. Vicinity of Inglewood	Inglewood	1935, 1945-6
2. Vicinity of Brea	Whittier	1935, 1945-6 (Part), 1949
3. Vicinity of Cajon Pass	San Andreas	1935, 1943-4 (Part, 1956
4. Vicinity of Palmdale	San Andreas	1935, 1938, 1947, 1955
5. Vicinity of Moreno	San Jacinto	1935, 1949
6. Vicinity of Gorman	San Andreas	1935, 1938, 1953
7. Vicinity of Whitewater	San Andreas	1935, 1949
8. Vicinity of Maricopa	San Andreas	1935, 1938, 1948 (Part), 1953, 1956, 1959

The relevellings of these earthquake cross lines have not shown changes of any large magnitude as yet. The maximum divergence between levellings is 3 to 4 centimeters. It is planned to continue relevelling the cross lines to provide data for long-time geophysical studies.

6. In the Long Beach - Terminal Island area, levellings were undertaken by the Coast and Geodetic Survey in 1931-32, 1933-34, 1941, 1945, 1946, 1949, and 1954. The settlement is 19.6 feet as a maximum from 1932 to 1954 caused by removal of underground gas and oil. More recent levelling by local organizations shows the settlement to have reached 25 feet. Fortunately, there are rock marks nearby at San Pedro which have remained stable. Their stability has been shown not only through levelling but also through tidal observations.

7. The original levelling in the vicinity of El Centro, California, was run in 1926-27 and 1928. The first relevelling of 226 miles was done in 1931 to determine the changes resulting from the El Centro earthquake of March 1, 1930 (epicenter west of Brawley). A fault line crosses the levelling at two locations. The maximum vertical movement noted by the 1931 relevelling was 0.12 foot settlement and 0.05 foot rise where the levelling crosses the fault north of El Centro. A second El Centro earthquake occurred on May 18, 1940, (epicenter 32° 44' N. 115° 27' W.). Relevelling was undertaken in 1941 along 270 miles of lines. When compared with the 1931 levelling, the 1941 relevelling shows a settlement of 0.70 foot and a heaving of 0.09 foot on opposite sides of the fault at the same location referred to above.

8. At the request of the Bureau of Reclamation, the Coast and Geodetic Survey established a net of first-order levelling in 1935 in Arizona and Nevada, surrounding Hoover Dam. The purpose of this levelling was to establish bench-marks which could later be releveled to determine possible settlement due to the superimposed load of Lake Mead. The original levelling was established before the water was impounded. The net was releveled in 1940-41 during a period of highest water after the reservoir had filled to near capacity.

The two levellings, therefore, were done at a time of minimum and near maximum load. Both levellings of this net were done under the criterion of 3.0 mm. $\sqrt{K}$ though our usual criterion in first-order levelling is 4.0 mm. $\sqrt{K}$ for checks between forward and backward runnings where K is the length of the section in kilometers. The total length of the net of lines was approximately 700 miles. At the time of the relevelling in 1940-41, levelling was carried across the lake with automatic tide gages stationed at four locations. Three months of simultaneous observations were obtained for determining two differences in elevation across the lake. The maximum settlement as shown by the 1940-41 relevelling was 12 centimeters or 0.4 foot.

9. Second-order levelling was established in 1934 in the region of the Hebgen Lake, Montana, earthquake of August 17, 1959, (epicenter 44° 50' N. 111° 05' W. magnitude 7.1). First-order relevelling was undertaken along 115 miles of lines from West Yellowstone to Sappington, Montana, during September and October 1959. The maximum bench-mark settlement was 18.8 feet and is shown on the profile in figure 3. This is the largest vertical change resulting from earthquake activity measured through geodetic levelling in the United States. Additional relevelling is planned for the summer of 1960 and it has been estimated there are some vertical changes of about 30 feet. It very seldom happens, however, that previously established bench-marks are at the location of greatest change.

10. In the Galveston-Houston area of Texas, the Coast and Geodetic Survey has done rather extensive relevelling to determine subsidence. There is no rock in this region on which to establish anchor bench-marks. Local checks are obtained with previous levelling for at least three bench-marks at the extremities of the relevelling, then by ascertaining if checks are obtained from one extremity to another through previous levelling, one can be fairly certain of being outside the region of settlement. The maximum settlement has been about three and one-half feet at Texas City Junction from 1943 to 1959.

In 1958-59, a rather extensive net was developed for future settlement studies and 24 bench-marks were placed on abandoned well casings that extend to depths from 535 feet to 10,496 feet. It will be interesting to study the results of future relevellings over these marks. It is hoped they may prove hepful as anchors in adjusting future relevellings. However, the factors contributing to change in this area are so deep-seated that even these marks may show some settlement.

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There are many factors contributing to vertical changes, some of which are : frost action, varying moisture content of the soil, removal of underground water for irrigation and municipalities, removal of oil and gas, mining activities, fault lines, earthquakes, tectonic or deep-seated changes, and so-called "secular" changes which are gradual and widespread.

Those who make studies of subsidence are interested in having surface marks that depict the actual ground changes, yet one can readily see that a most important item in precision levelling from an adjustment standpoint is to try to establish some fundamental or basic marks that

DIVERGENCE BETWEEN LEVELINGS OF 1934 & 1959

WEST YELLOWSTONE TO 12 MILES SOUTH OF CAMERON

NEW MINUS OLD
(1959-1934)

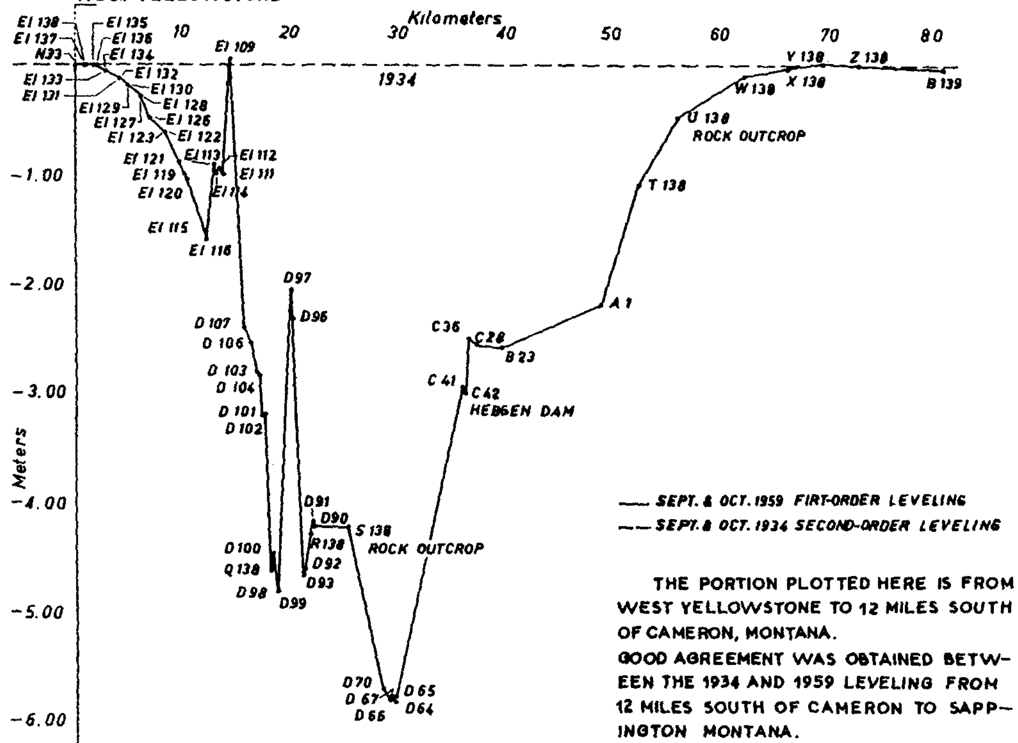

Fig. 3

will remain stable. The first choice for the installation of a fundamental mark would be bedrock, preferably granite. In the absence of bedrock, the next best choice would be in some substantial structure.

For the past four years, the field parties of the Coast and Geodetic Survey have been establishing a basic mark at five-mile intervals along the routes of our levelling lines which consists of a copper-coated steel rod 5/8-inch in diameter which is driven to refusal with a 90-pound gasoline hammer. The rods now used are in 8-foot sections, joined together with a brass coupling. The field parties are equipped with a tripod which has legs that can be extended to 16 feet. A block and tackle is mounted on the tripod which hoists the gasoline hammer. The hammer is started and drawn to the top of the tripod. It is then placed on a 8-foot section of rod which is driven to the ground surface. Another section is coupled to the driven rod and the gasoline hammer hoisted and set on the second section. This process continues until refusal is reached, whereupon the rod is cut off and a disk compressed on the top of the rod. A tile four or six inches in diameter and two feet long is set about 18 inches in the ground and extending about six inches above the ground for protection and to aid in recovery. The tile is set around the mark but not cemented to the disk or rod. It refusal is not reached when the rods are driven to a depth of 50 feet, but the driving is difficult, the mark is considered adequate. Some of these rods have been driven to depths of over 100 feet. Relevelling has been done over some marks of this type which were set in an alluvial area west of Memphis, Tennessee, near the Mississippi River. Although the original levelling and relevellings were only one and one-half years apart, the indication is that these marks are remaining stable.

Brass tubing with an inner diameter of 5/8 inch and one and one-fourth inches long is silver soldered to the back of a standard survey disk. The tubing is compressed to the rod with a nicopress tool. In pull tests undertaken by the U.S. Bureau of Standards, it required 4,000 pounds pull to remove a disk compressed to the rod.

In the near future, it is planned to relevel certain selected lines which will comprise a net of about 20,000 miles of first-order levelling in order to determine regional changes. This relevelling will consist of three east-west transcontinental lines and about eight north-south lines. It is anticipated that this relevelling will be completed in about seven years. It is also planned to obtain gravity observations along the route of this 20,000 miles of basic relevelling in order that geopotential heights as well as orthometric elevations can be computed for each bench-mark.

This 20,000 miles of relevelling will, no doubt, reveal settlement that we are unaware of, and enable us to bring elevations up-to-date. Settlement can be expected in cities that obtain their municipal water supply from underground sources or have heavy underground withdrawal of oil or gas. There is usually a good correlation between settlement and underground withdrawal.