NOAA Technical Report NOS 131 NGS 44

Subsidence at Houston, Texas 1973-87

Sandford R. Holdahl
Joseph C. Holzschuh
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Rockville, MD
August 1989

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
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ABSTRACT. Models of vertical deformation are needed for calculation of vertical motion corrections to leveling data in areas like Houston, TX, where significant subsidence results from withdrawal of groundwater. The repeated levelings at Houston have been used as test data to refine and evaluate modeling techniques. For the last 10 years, surface-fitting methods have been used in scientific studies to quantify and interpolate crustal motion and subsidence. Now the same modeling procedures are used to create a data base of coefficients that are the basis for correcting old leveling measurements forward in time, to allow simultaneous adjustment with recent measurements.

The regional subsidence pattern at Houston, TX, has been derived from repeated levelings and extensometer data. The leveling surveys were performed in distinct epochs: 1973, 1978, 1983, and 1987. The earliest extensometer records date from 1973. The Houston region was divided into two zones according to whether water levels in artesian wells had recently risen (east zone) or fallen (west zone). The west zone shows mildly nonlinear and increasing subsidence rates ranging up to -72 mm/yr in 1987, just 7 miles west of downtown Houston. The east zone was characterized by rates of up to -70 mm/yr from 1973 to 1978, followed by 60-90 percent decreases in these rates by 1987. The sharp decrease has been caused by regulated declines (44-84 percent) in pumping of groundwater, as well as importation of surface water from Lake Houston. The subsidence model for Houston was derived at the same time its level network was adjusted, using multiquadric (MQ) analysis for spatial interpolation of subsidence velocities. A quadratic height function was used for west Houston, with one set of unknown coefficients to describe regional variation of subsidence velocity and another to describe acceleration. Subsidence in east Houston was modeled as a sequence of regionally variable velocities; one set of MQ coefficients describes the velocity pattern between 1973 and 1978, and a second set describes the subsidence from 1978 to 1987. The coefficients that define the Houston subsidence model were placed in a data base, and then accessed to successfully calculate corrections for old leveling data.

INTRODUCTION

The National Geodetic Survey is presently developing improved methods for modeling vertical motion. This development must precede readjustment of the national level network which extends into many areas of crustal motion and subsidence. The geodetic objective of these models is to allow old leveling data in vertically deforming areas to be corrected to the rough equivalent of recent measurements. This improves the reliability of the leveling and allows use of the traditional static adjustment model in the adjustment of the national net. The nonlinear subsidence at Houston is a good example to illustrate some of the new techniques that may be applied in the national project.

The phenomenon of land surface subsidence has long been recognized as a serious problem in the area near Houston. (See fig. 1.) As early as 1926, a meter of subsidence was reported at Goose Creek oil field at the north end of Galveston Bay. The subsidence at Goose Creek was due to the withdrawal of oil from shallow reservoirs and was confined to the small area of the oil field itself.

Since that time, the nearby cities of Houston and Galveston, as well as a large petrochemical industry, have all seen dramatic growth. This growth was supported exclusively by large withdrawals of groundwater from vast aquifers which underlie most of this Gulf Coast region. These withdrawals lowered water pressures in the aquifers allowing the many clay beds to compress, resulting in the lowering of the land surface (subsidence) up to 3 m in some areas. Thousands of acres of valuable land have been submerged due to subsidence and even larger areas are now subject to flooding from hurricane storm surge or overflow of freshwater streams and bayous during periods of heavy rainfall.

Land subsidence continues to the present at Houston and is being studied intensively by the Harris-Galveston Coastal Subsidence District, an organization whose task is to balance the sometimes conflicting requirements for water resources and stable land surface.

Between 1963 and 1978, all of the region within 20 miles of Houston had subsided at least 3 dm. A maximum change, exceeding 1.5 m for that time interval, was centered east of Houston about halfway to Baytown (Balazs, 1980). This is the area in which the heaviest groundwater withdrawals were occurring for Houston's growing petrochemical industry.

Balazs (1980) compared level survey results from 1963, 1973, 1976, and 1978. A significant conclusion in that report was that subsidence rates between 1973 and 1978 had slowed by 25 percent on the east side of Houston where maximum change had occurred for the prior period 1963-73. The lowering of subsidence rates in that region was attributed to reduced withdrawal of water for industrial use. Increasing amounts of surface water brought in by newly constructed canal systems have continued to replace water previously taken from underground.

During the period from 1978 to present, groundwater withdrawals continued to decrease on the east side of Houston due to the continued regulation of groundwater and the availability of surface water to replace it. The area to the west of Houston, however, was continuing a period of rapid growth which was supported solely by groundwater withdrawals. The means to supply surface water to west Houston have not yet been implemented. After a partial releveling of the Houston network in 1983, Zilkoski (1984) also calculated a decrease in subsidence east of

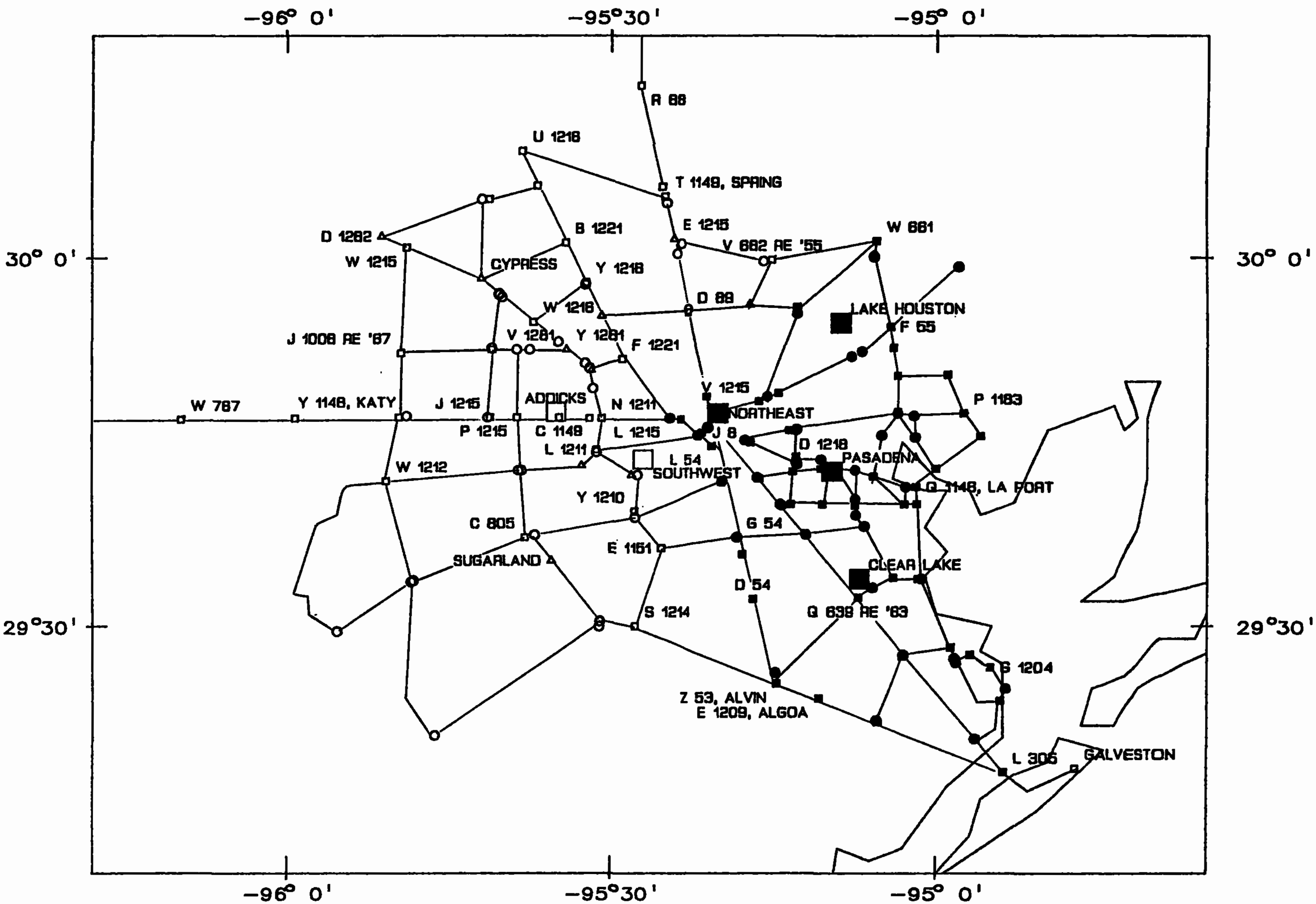


Figure 1.--Locations of level lines and extensometers - Houston, TX. Solid symbols are used to distinguish east Houston modeling district.

Houston and noted continued rapid subsidence on the west side of Houston (328.6 mm between Houston and Addicks) since 1978. This result seemed to conform well with the pumping patterns.

The present analysis of the 1987 leveling survey is aimed at determining the most recent subsidence velocities as well as to quantify and document how the subsidence pattern has shifted during the period from 1973 to 1987. The leveling measurements made in 1973, 1978, 1983, and 1987 were the basis of the investigation. The 1973 and 1978 surveys were undoubtedly biased by magnetic errors that were not known to exist in 1978. All of the Zeiss Ni-1 leveling measurements used in the present analysis have been corrected for magnetic error using a procedure based on empirical calibrations (Holdahl et al., 1987).

The computation of Houston's elevations has become complicated because subsidence rates are changing with time. Most computer programs for calculating motion utilize simple models which assume that motion is constant in time. In this study, more advanced techniques are used to model accelerations in the subsidence rates. This report documents significant aspects of this mathematical model, and gives the results of the investigation to determine the recent character of subsidence at Houston. The model established for Houston can be used to interpolate subsidence rates to points where no repeat leveling data exist, and allows short term predictions of future subsidence. The Subsidence District has used a geotechnical model to predict subsidence with good results, but data are available for only 20 widely spaced locations in the area. The model described herein can be used to fill in the "holes" between those locations, and together, both models should yield better results.

MATHEMATICAL DEVELOPMENT

In the usual adjustment of a static level network, where the land surface is assumed to be stable, it is only necessary to solve for heights considered constant in time. All historical level measurements in the network are collected and a least squares adjustment is performed to remove any inconsistencies caused by random errors or small residual systematic errors. This is not done at Houston because subsidence causes large inconsistencies, and such an adjustment would only result in average heights that would be difficult to associate with any particular date.

The Quadratic Height Function

Furthermore, acceleration of Houston's subsidence with time must be allowed by the selected mathematical model for height. One acceptable height function is given below:

$$H_i = H_o + H' \ (t_i - t_o) + H'' \ (t_i - t_o)^2. \quad (1)$$

The height H_i corresponds to time t_i. H_o is the height at a specified reference time t_o. H' is the velocity at time t_o, and H'' is half the acceleration. Modeling of the subsidence is a surface fitting exercise in which

$$H' = \sum_{j=1}^{n_v} v_j \, [(x - x_j)^2 + (y - y_j)^2]^{1/2}, \text{ and} \qquad (2)$$

$$H'' = \sum_{k=1}^{n_a} a_k \, [(x - x_k)^2 + (y - y_k)^2]^{1/2}. \qquad (3)$$

The (x_j,y_j) and (x_k,y_k) are coordinates of "nodal points," in the terminology of multiquadric (MQ) analysis. The nodal points are located at bench marks which, after review of profiles, are known to indicate maximums and minimums of motion or are otherwise critical to the description of the movement pattern. Expressions (2) and (3) are used to calculate the velocity and acceleration at location (x,y). The coefficients v_j (corresponding to velocity) and a_j (corresponding to acceleration) are unknowns to be solved for in the adjustment of a mixed-age network of repeated levelings. The reference-time heights for all stations, H_o, are also unknowns.

Expression (2) gives the velocity at the reference time, t_o. The more general expression for velocity, for any time t_i is

$$\text{velocity} = H' + 2H'' \, (t_i - t_o), \qquad (4)$$

and the expression for acceleration is

$$\text{acceleration} = 2H''. \qquad (5)$$

Leveling measures differences in height between two points, for example P_1 and P_2. In our model, this measurement is expressed mathematically as

$$\Delta H_{2\text{-}1} = H_{2,0} - H_{1,0} + (H_2' - H_1') \, (t_i - t_o) + (H_2'' - H_1'') \, (t_i - t_o)^2 \, . \qquad (6)$$

In expression (6), $H_{1,0}$ denotes the height at P_1 at time t_o, and H_1' denotes the velocity at P_1 at time t_o, etc. West Houston can be reliably modeled with the quadratic height function, i.e., expression (1).

Extensometer records show that subsidence east of Houston has slowed to almost zero in some locations. The Pasadena extensometer record indicates a sharp decrease in 1978, at about the time when significant amounts of imported surface water from Lake Houston allowed pressure in aquifers to be maintained or rise. The sharp change in subsidence velocity in 1978 motivated the use of a different modeling technique for east Houston.

Time Districting

East Houston is defined to be the zone that encompasses the solid symbols in figure 1. The part of this boundary separating east and west Houston corresponds to the line of zero net change in the Chico and Evangeline aquifer levels. Within the east zone, water levels have rebounded or remained unchanged. In the west zone, water levels continue to be lowered.

This spatial districting of the region allows distinct coefficients to describe the subsidence east of Houston, and allows use of a different height function for the east zone. However, the east zone data also required a modeling strategy we will call "time districting," which is similar to the technique used by Vanicek et al. (1979), to model vertical motions in southern California. The motion in the east zone was assumed to be rapid and linear prior to 1978, followed by slower linear motion after 1978. Separate sets of MQ coefficients were used to describe the vertical motion before and after 1978.

The expression for height, when using time districting, is as follows:

$$H_i = H_o + \sum_{k=1}^{n_t} H_k' T_k \qquad (7)$$

where each T_k is some fraction of the time interval $t_{k+1}-t_k$. For simplicity, assume $t_o = t_n$, and $t_i < t_n$, where t_n is the latest time boundary, then

$$T_k = \begin{cases} o, & \text{if } t_i > t_{k+1} \\ t_i - t_{k+1}, & \text{if } t_k < t_i < t_{k+1} \\ t_k - t_{k+1}, & \text{if } t_i < t_k \end{cases} \qquad (8)$$

For east Houston, the two time districts (intervals) are defined to be 1972-1978, and 1978-1987.3. The reference time, t_o, was taken to be 1987.3.

APPLICATION TO THE HOUSTON LEVEL NETWORK

Figure 1 shows the Houston level network that was leveled all or in part in 1973, 1978, 1983, and 1987. An initial height for the network is obtained from the tide gauge at Galveston. Mean sea level (MSL) is equated with zero height and MSL is related to the nearby tide gauge bench mark by leveling. An initial velocity is obtained by fitting a straight line through the plot of mean sea level with time. (See fig. 2.) This plot shows that annual mean sea level has been rising at Galveston by an average rate of 6.3 mm/yr. The eustatic (global) rise of sea level can account for 1.0 mm/yr; therefore, the remainder is attributed to coastal subsidence of the land. Thus, an initial estimate for velocity of -5.3 ± 0.3 mm/yr and an acceleration of 0.0 ± 0.1 mm/yr^2 were assigned to the tide gauge at Galveston.

Well outside of Houston, bench marks K 87 (RIVERSIDE) and Z 6 (SEALY) were constrained to be stable (zero velocity and acceleration). These two points, too far to the north and west of Houston to be shown in figure 1, were concluded to be outside the zone of significant subsidence. This conclusion was arrived at after reviewing profiles of relative elevation change made from comparisons of the unadjusted repeated levelings. Closer in, bench marks U 1216, and D 1282 in the northwest sector of figure 1 were also constrained to have zero velocity in 1987.

Compaction data from six extensometer locations (see large square symbols in fig. 1) were also used to control the adjustment to determine the reference-time heights and motion coefficients which constitute the subsidence model. A conceptual example of an extensometer (compaction recorder) installation is

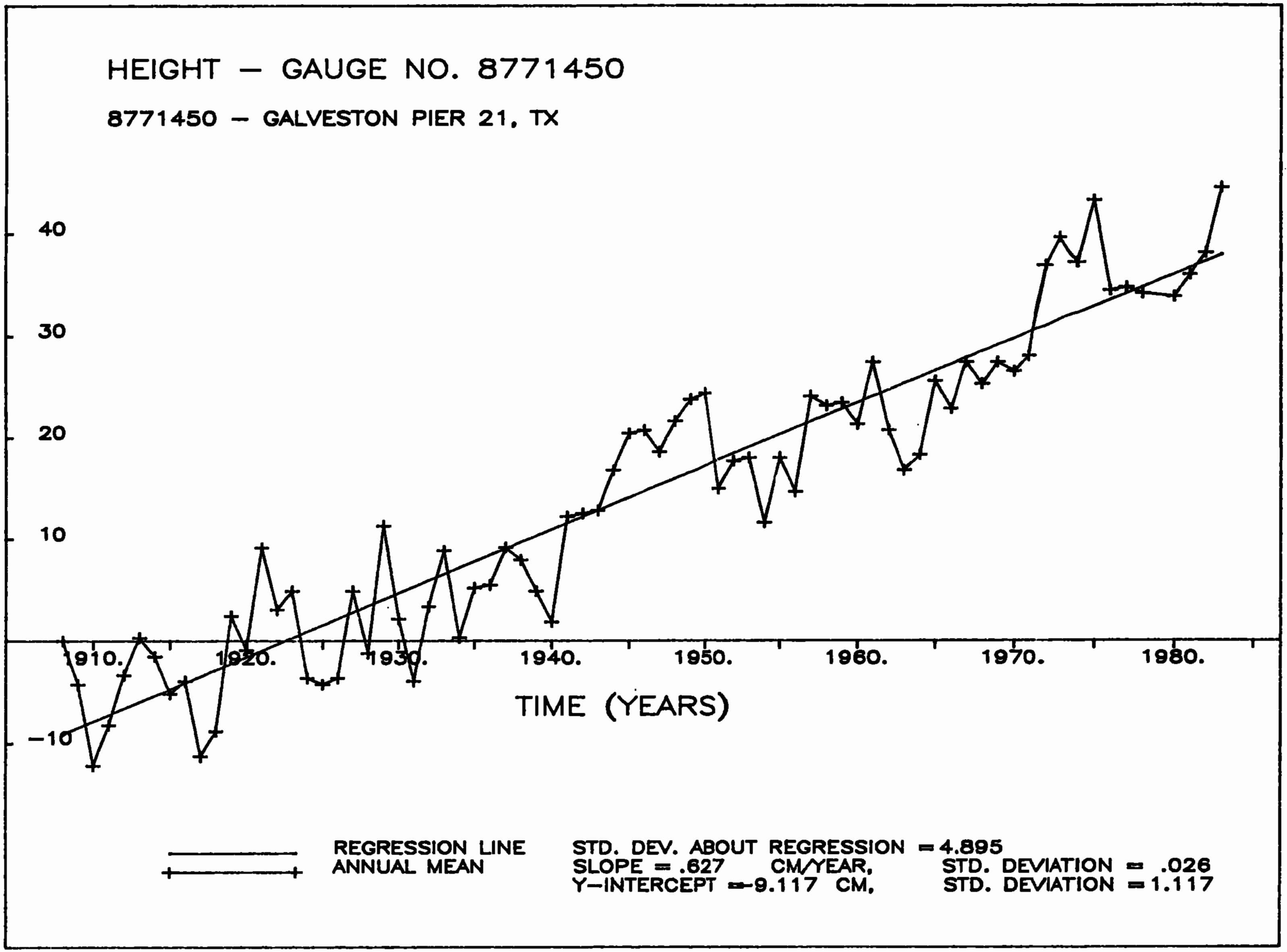


Figure 2.--Sea level record at Galveston, TX. Fitted straight line corresponds to rate at which the vertical relationship between sea and land is changing. After correction for eustatic rise of sea level (1.0mm/yr), land is shown to be subsiding (5.3 mm/yr) at Galveston.

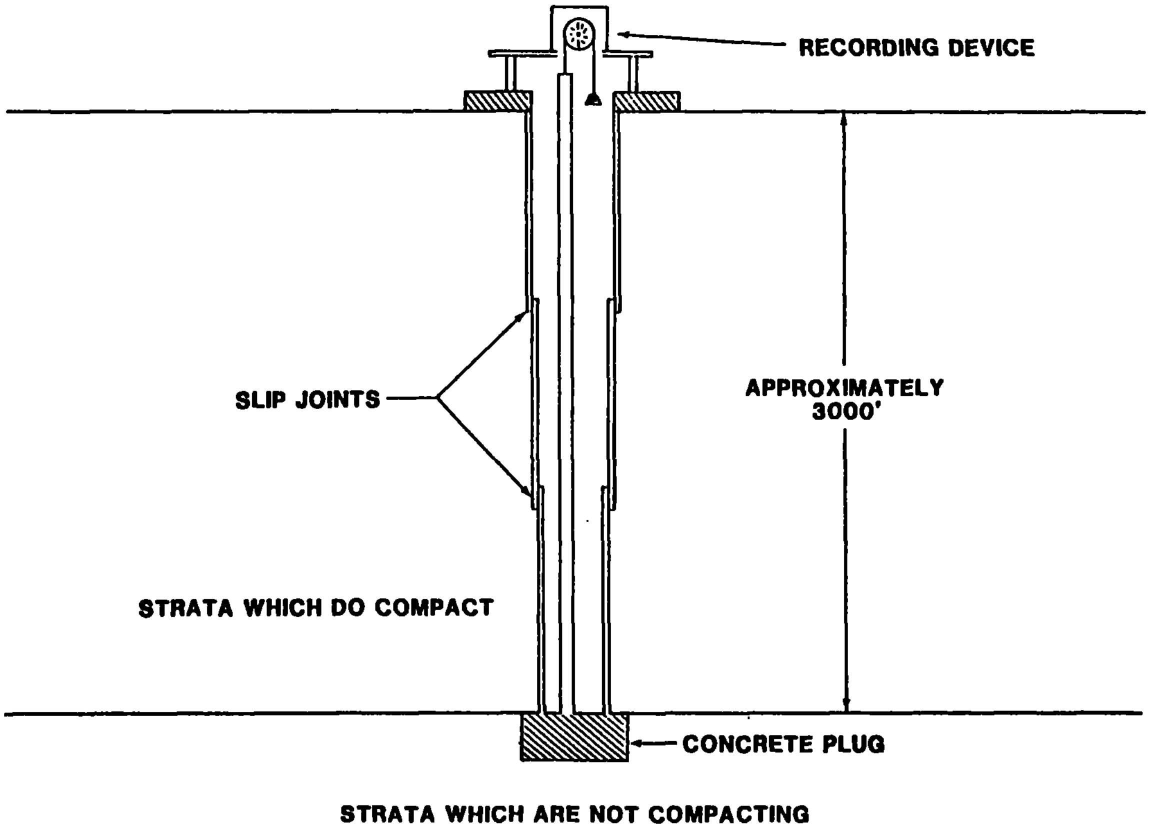


Figure 3.--Typical borehole extensometer.

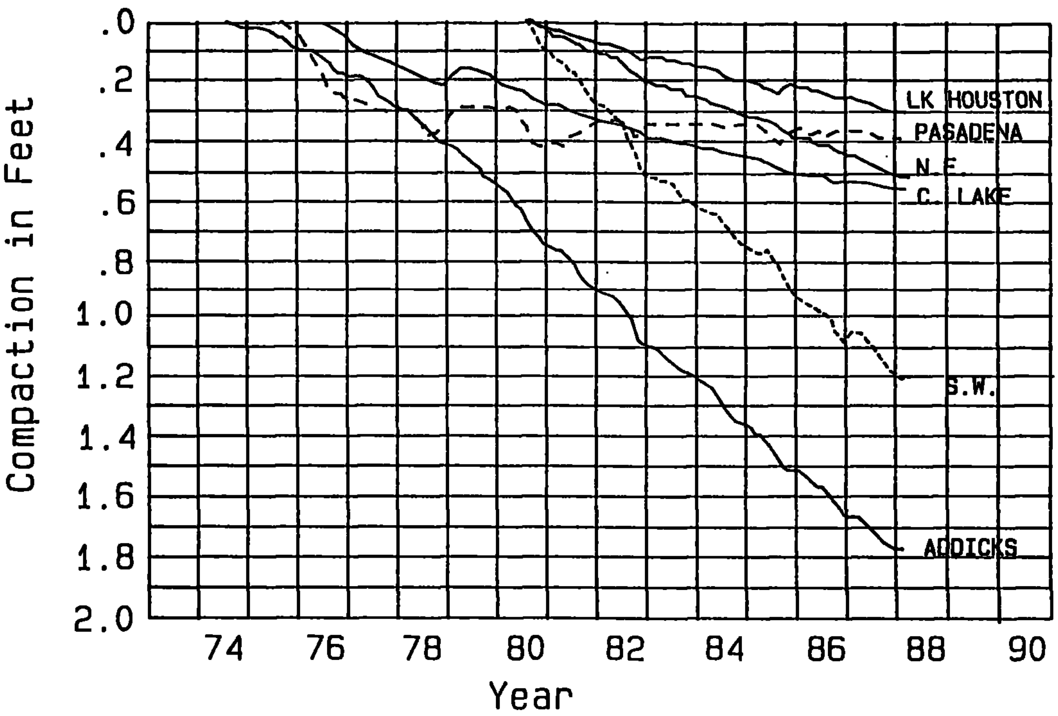


Figure 4.--Records from deep extensometers located in Houston region.

illustrated in figure 3. Figure 4 shows the records of compaction from the six contributing installations. Each installation consists of a rigid central pipe, surrounded by a segmented pipe casing. As the ground layers compact, the surface installation is lowered with respect to the base of the inner pipe. The amount of shortening is measured by means of a wire/tape rolling over a drum. One end of the wire is attached to the bottom of the well and the other end is heavily weighted to keep it taut. The measured compaction is attributable to the layers of soil above the base of the well. The compaction records from the Clear Lake, Addicks, Pasadena, Northeast, Southwest, and Lake Houston installations were considered deep enough to provide good estimates of subsidence, meaning that no compaction is believed to occur below the base of the well. The Clear Lake, Pasadena, and Addicks installations have been in existence for several relevelings and are known to provide accurate indications of subsidence. The Northeast, Southwest, and Lake Houston installations were more recently constructed to the same standards, and their reliability is still being investigated.

The compaction data from the Clear Lake, Addicks, and Pasadena recorders showed nonlinear subsidence, and accordingly were input to the level net adjustment as a sequence of monthly observed heights. But first, a free adjustment of only the 1987 leveling survey provided heights for the inner pipes at these gauges. The compaction data then were used to compute heights of a second point (at the same location) which is moving vertically by the amount of the compaction, but has the identical 1987.3 height as the top of the non-moving inner pipe. The inner pipe should not move because it presumably extends below the lowest compacting layers. However, the ground around the site is subsiding because of compaction. The observed heights correspond to the subsiding ground surface.

The compaction records at Northeast, Southwest, and Lake Houston show linear subsidence, and accordingly, were input to the Houston level net adjustment as velocities with zero accelerations. The velocities and weights were derived from a straight line fit to those compaction records. Compaction recorders at Baytown, East End, NASA, Seabrook, and Texas City (not shown in fig. 1) all show nonlinear and decreasing rates of compaction, but these installations are not considered deep enough to reveal total subsidence.

The above-described boundary and interior controls, together with the leveling data, were used to determine the subsidence model.

RESULTS AND MODEL VALIDATION

The velocity surfaces for 1973 and 1987.3 are shown in figures 5a and 5b. Figure 5b shows more rapid subsidence west of Houston for 1987, while at the same time subsidence has slowed or terminated for areas to the east. The eastern locality that showed the greatest reduction is near La Porte. Between 1973 and 1978, this area was subsiding at a rate of 65 mm/yr or more. By 1987, these rates had been reduced by at least 90 percent near the coast and lesser percentages near central Houston. To the west of Houston, the 1973 velocities for bench marks Y 1281, C 1149, and C 805 were respectively -52, -32, and 4 mm/yr. By 1987, these same velocities had increased to -76, -61, and -31 mm/yr. The dramatic reduction of subsidence east of Houston and the significant increase of subsidence west of Houston become graphically evident by comparing figures 5a and 5b, as well as 5c and 5d. Table 1 contains the subsidence velocities and standard deviations for specific points shown in figure 1.

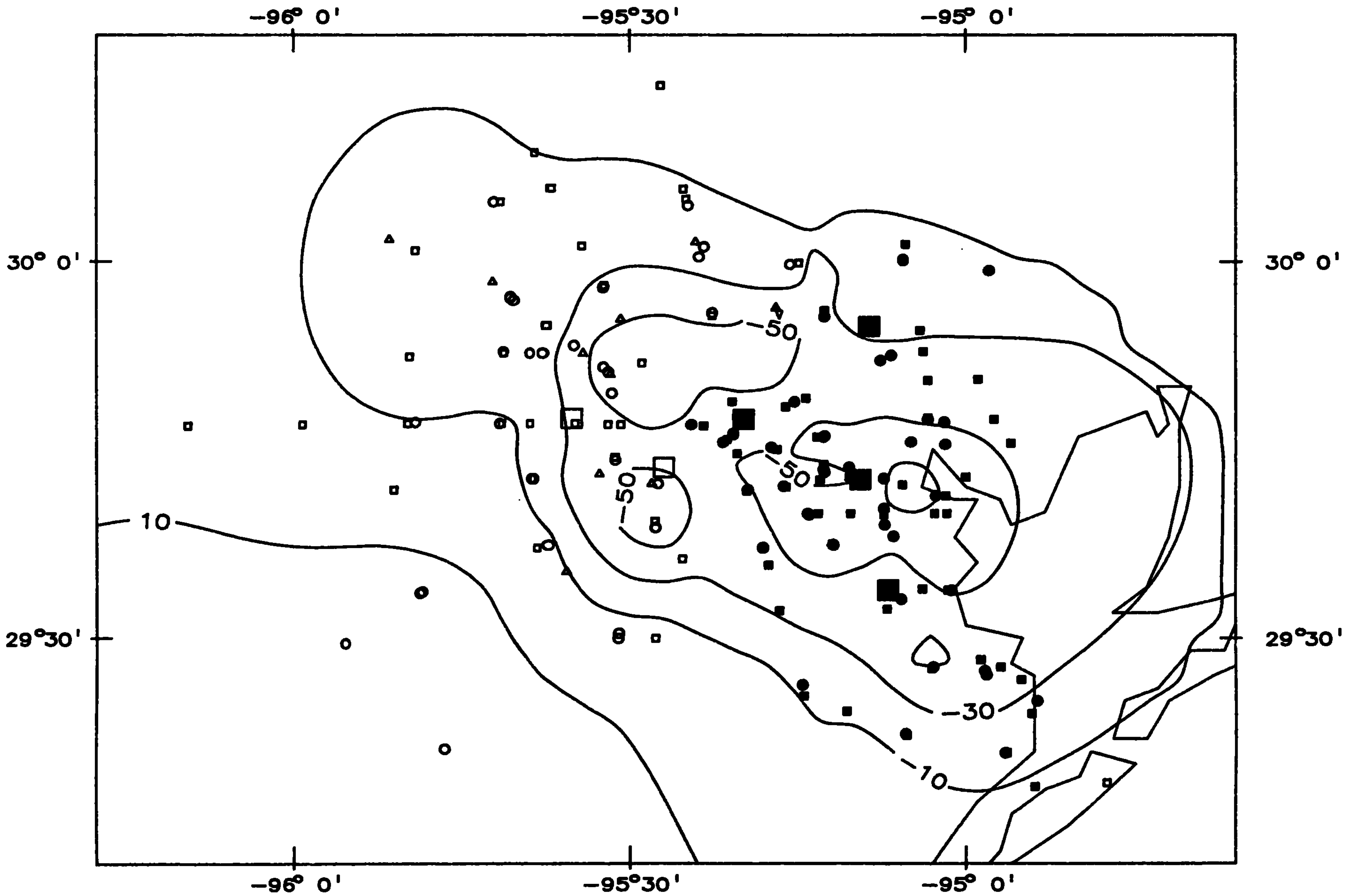


Figure 5a.--1973 Subsidence Velocities (mm/yr) - Houston, TX. Solution derived from 1973, 1978, 1983, and 1987 leveling data.

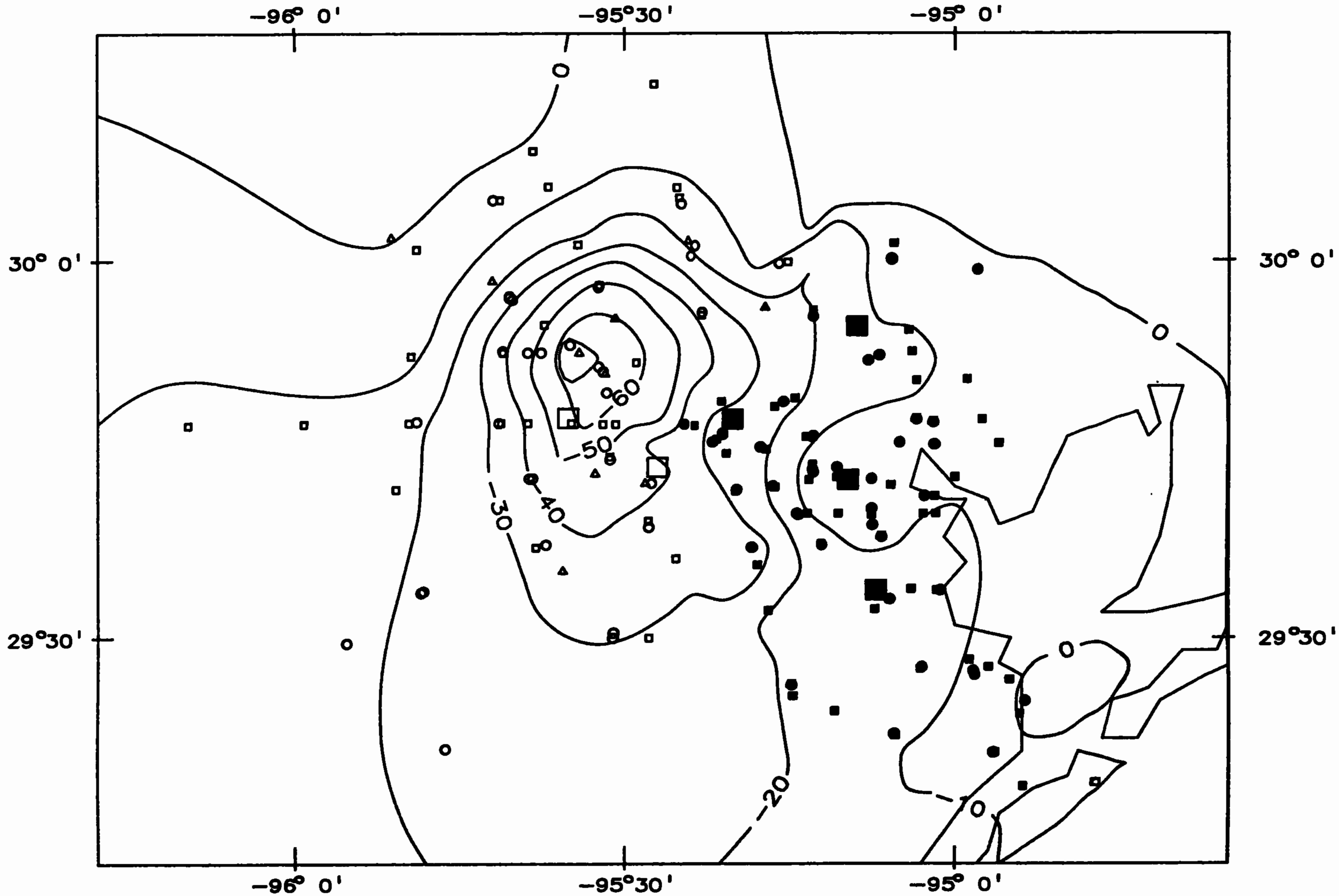


Figure 5b.--1987 Subsidence Velocities (mm/yr) - Houston, TX. Solution derived from 1973, 1978, 1983, and 1987 leveling data.

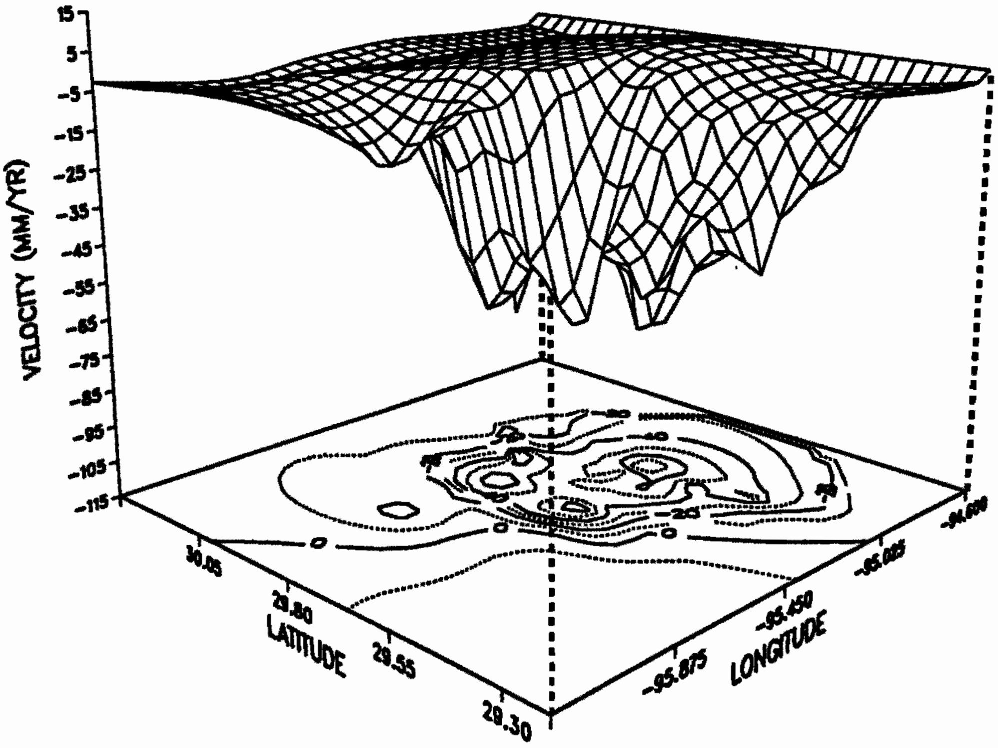


Figure 5c.--Velocity surface corresponding to subsidence in 1973.

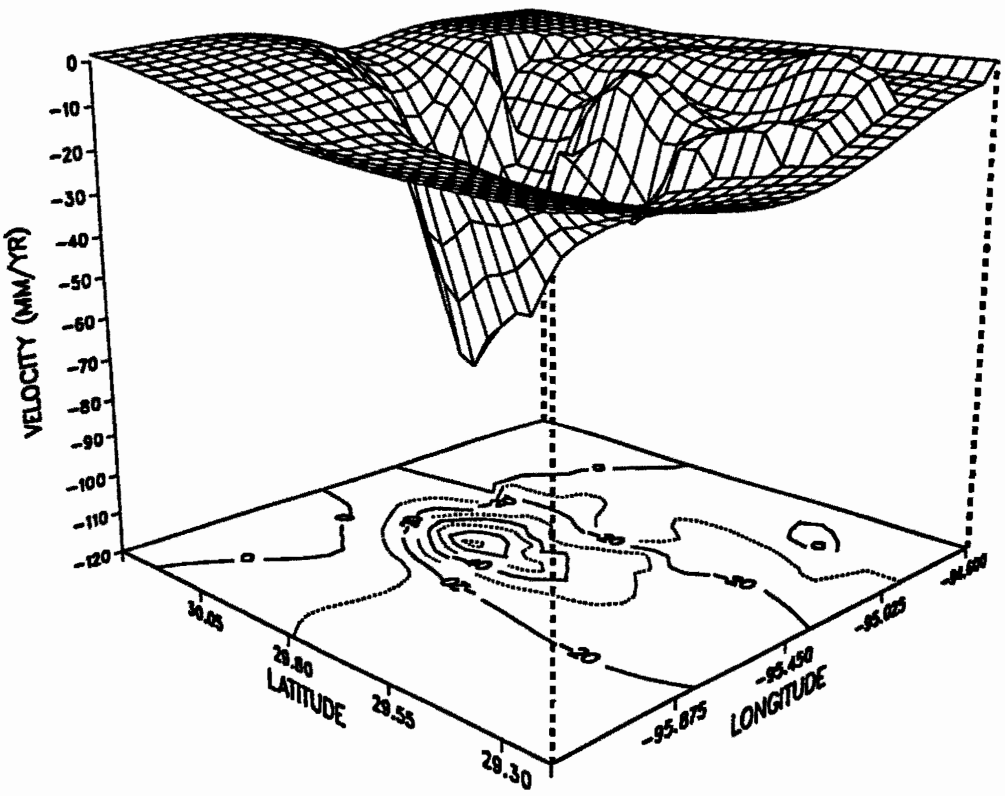


Figure 5d.--Velocity surface corresponding to subsidence in 1987.

Table 1.--Subsidence Velocities, Houston, TX
(See fig. 1 for locations of bench marks.)

WEST ZONE

BM NAME	VELOCITY (mm/yr)		ACCELERATION (mm/yr^2)	
Tidal 19, Galveston	- 5.5	± 0.4*	0.02	± 0.14*
S 1214	-29.6	4.9	-2.14	0.83
C 805	-31.1	4.2	-1.88	0.71
W 1212	-16.6	4.6	-1.43	0.75
Y 1148	-19.2	3.6	-0.67	0.60
Y 1210	-29.8	4.2	3.30	0.69
E 1151	-32.5	4.5	0.55	0.75
SOUTHWEST **	-47.2	0.8	-0.01	0.16
ADDICKS **	-54.6	1.2	-1.65	0.18
N 1211	-51.4	3.0	-0.53	0.52
J 1215	-31.5	3.7	-1.78	0.63
W 767	-12.7	3.8	-1.40	0.89
B 1221	-18.8	3.5	-0.06	0.62
F 1221	-64.8	4.0	0.30	0.66
CYPRESS	-16.5	2.2	-0.37	0.41
Y 1281	-76.1	2.8	-1.73	0.45
T 1149	-17.9	4.1	-0.19	0.67
R 88	- 4.1	5.5	0.05	0.88
V 1281	-53.6	2.8	-2.31	0.47
Y 1216	-58.3	3.8	-1.71	0.64

EAST ZONE

BM NAME	PRE-1978 VELOCITY (mm/yr)		POST-1978 VELOCITY (mm/yr)	
L 305	- 2.5	± 3.7*	- 3.1	± 1.3*
P 1183	-43.0	5.1	- 3.6	2.3
Q 1146	-66.8	5.0	- 7.1	1.6
Z 53	-14.1	4.8	-14.1	1.6
Q 639 RE '63	-41.5	4.6	-15.1	1.5
CLEAR LAKE **	-26.7	4.3	-13.2	0.4
J 8	-34.8	4.3	-24.1	1.4
W 661	- 5.8	5.8	- 5.1	1.9
V 1215	-41.7	5.0	-26.4	1.4
F 55	-19.3	5.5	- 8.0	1.7
D 1218	-50.2	5.3	- 9.8	1.6
PASADENA **	-31.5	2.9	- 2.5	0.5
D 54	-32.2	5.3	-18.1	1.8
NORTHEAST **	-42.0	4.4	-21.0	0.3
G 54	-47.6	4.7	-34.6	1.6
LAKE HOUSTON **	-22.2	5.5	-11.3	0.3

*Standard deviation
**Extensometer

The modeled vertical motions should accurately reflect the observed subsidence along a path. Figure 6a is a subsidence profile which compares 1973, 1976, and 1987 surveys to the 1978 survey between Katy (bench mark Y 1148) and central Houston (bench mark J 8). There is approximately 200 mm of subsidence between 1973 and 1978, and additional subsidence of 500 mm between 1978 and 1987.

It is interesting to see if the subsidence model can be used to remove the motions seen in profiles like figure 6a. After storing the velocity and acceleration coefficients in a proper data structure, along with other pertinent parameters, the coefficients were accessed to evaluate subsidence for any point in the Houston region. The date, t_i, and point position (x,y) were provided to a subroutine which calculated the elevation change since time t_0. Using this procedure for pairs of bench marks, it is possible to formulate subsidence corrections for leveling measurements. For example, the 1973.3 measurements in figure 6a can be reduced to 1978.3. After applying subsidence corrections, a new profile can be made where all levelings are reduced to the same point in time. In Figure 6b, the 1973, 1976, and 1987 levelings have all been reduced to t_0 = 1978. The regional trend of motion is removed from the profile. Notice, however, that only the regional trend of motion is removed. It would be possible to remove all minor localized motion by adding more MQ nodal points, but this is not done in order to keep the model compact and meaningful. In the region surrounding Houston, there is motion at the 1-3 cm level caused by alternate wetting (rain) and drying of clay beds near the surface. The rms (root mean square) scatter of heights reduced to 1978, relative to the observed heights of 1978, are 2.4, 1.0, and 3.8 cm for the 1973, 1976, and 1987 surveys, respectively.

Figures 7a and 7b are the "before corrections" and "after corrections" profiles for the level line from Algoa via Alvin and Houston to Spring. Before subsidence corrections, there is approximately 600 mm of movement between 1973 and 1987. The regional trend of motion is removed well by the addition of corrections as shown in figure 7b. The rms about the horizontal axis, which corresponds to the 1978 survey, is 3.2, and 3.4 cm for the two corrected 1973 surveys, and 2.8 cm for the corrected 1987 survey.

After application of subsidence corrections, which removes the 50-60 cm of subsidence seen in the "before-corrections" profiles (figs. 6a and 7a) it is still likely that corrected height differences between adjacent bench marks will be in error at the 1-3 cm level in the Houston region because of the small random local motion associated with seasonal rainfall. As seen in figures 6b and 7b, discrepancies may occasionally be as large as 10 cm. Consequently, the modeling process cannot completely restore old levelings to their original precision of 1 mm per kilometer. In Houston, any leveling which is several years old and between adjacent bench marks about 1 km apart should have an assigned uncertainty of 1-3 cm, even if water is not being pumped nearby.

Figure 8 shows how east Houston's 1978 time boundary permits a sequence of velocities that fit the data at the Pasadena extensometer. The later velocity value should be good for predicting height changes into the near future. A previous solution using a parabolic fit for the same locality did not predict well. The first of the two velocities in figure 8 underpredicts slightly, but this slight misfit may occur because other monitored points in the vicinity of the Pasadena extensometer were experiencing somewhat less subsidence prior to 1978.

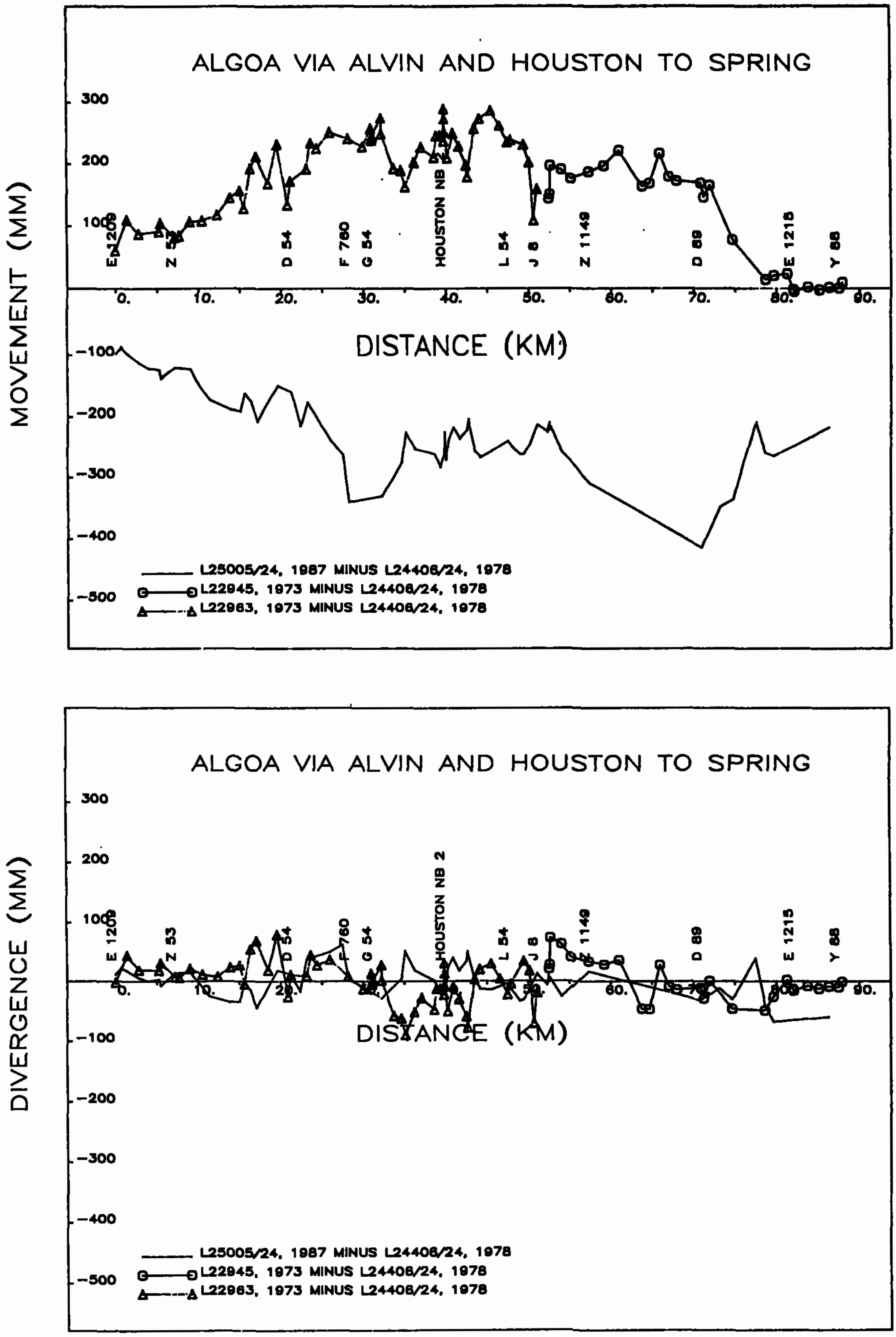
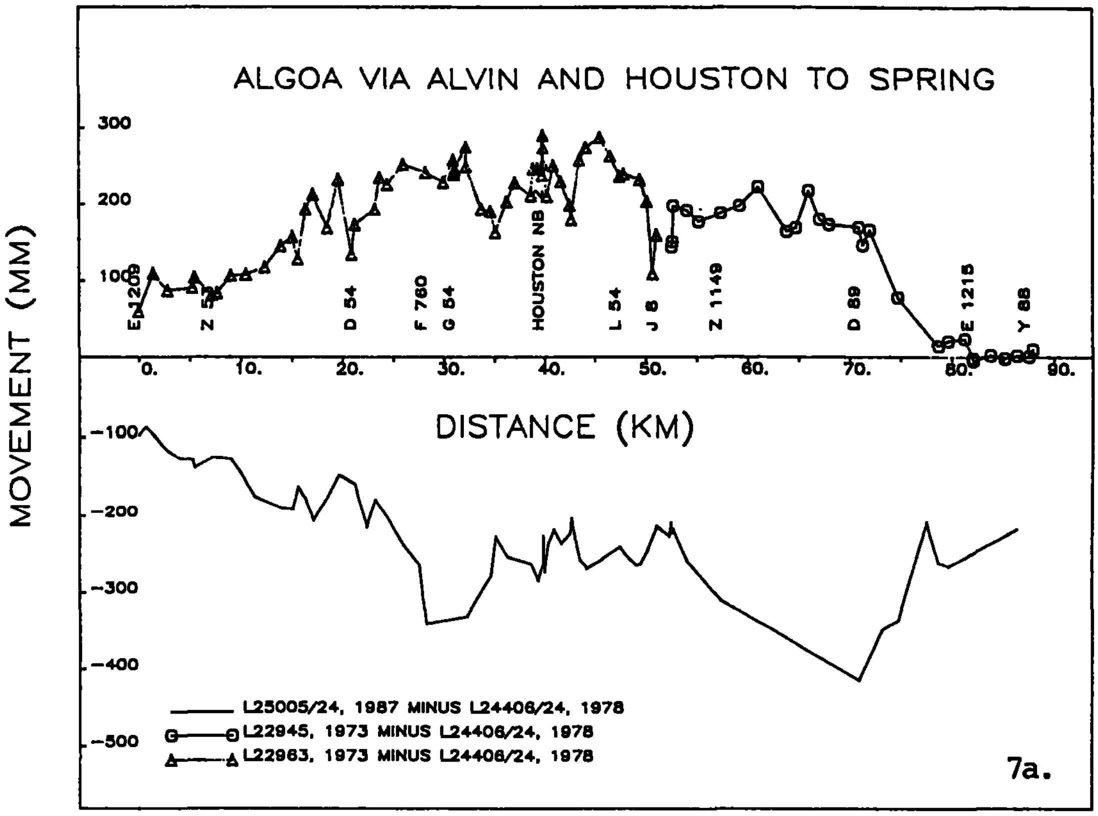


Figure 6a.--a) Profile of subsidence along a route of leveling between Katy and Houston, TX. b) Same profile as 6a, but plotted after application of subsidence corrections.



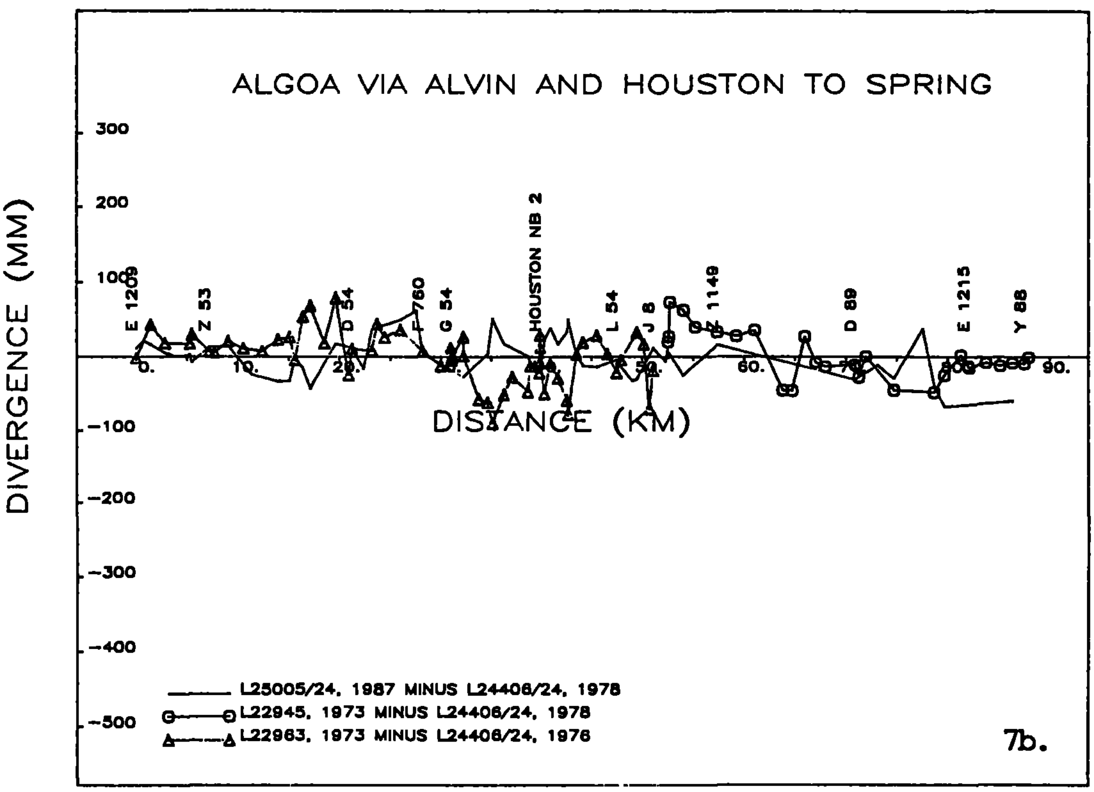


Figure 7.--a) Profile of subsidence along a route of leveling from Algoa via Alvin and Houston to Spring, TX; b) Same profile as 7a, but plotted after application of subsidence corrections.

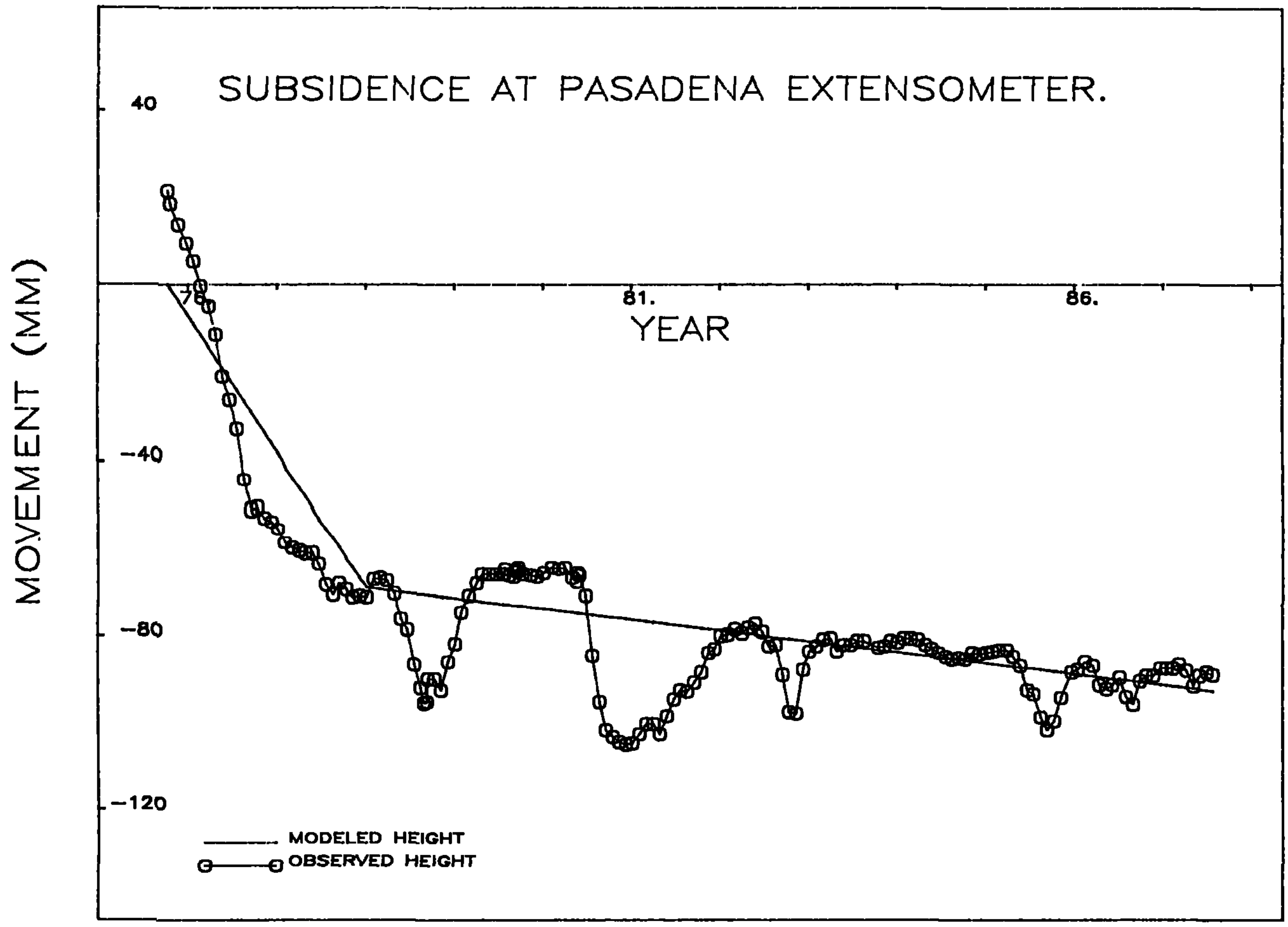


Figure 8.--Extensometer record showing subsidence at Pasadena, TX. Slopes of straight line segments correspond to modeled rates of motion before and after 1978.

SUMMARY

The techniques for modeling nonlinear vertical motion described here adapt well to the subsidence problem in Houston. Houston's subsidence model enables the production of a variety of computer generated graphics such as the subsidence contour maps shown in figures 5a and 5b. Predictions of subsidence into the near future can be accomplished using velocities calculated for 1987.

The compaction data from deep extensometer installations were valuable for subsidence modeling. Periodic leveling from a stable point or tide gauge confirms the consistency of these two data types. If leveling data are free of systematic error, and the extensometer installation extends below all compacting layers, both measurement systems should give a similar estimate of subsidence. But the greater frequency of recorded height change at deep extensometers provides better information as to when major changes are occurring. The extensometer results also prevent small systematic leveling errors, accumulated over long distances, from negatively impacting the model derivation.

Regulated reductions of pumping east of Houston are responsible for the dramatic decrease in subsidence there since 1978. The Coastal Water Authority Canal System has provided alternative surface water since 1978. No alternative source of water

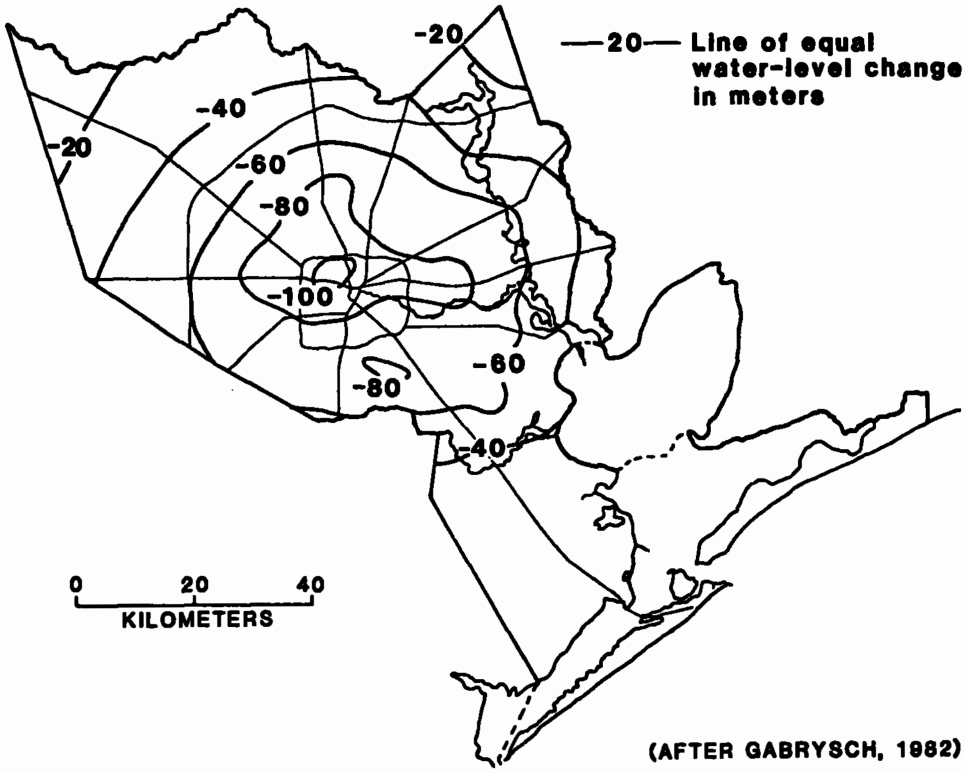


Figure 9a.--Approximate water-level declines in the Evangeline Aquifer, 1943-77.

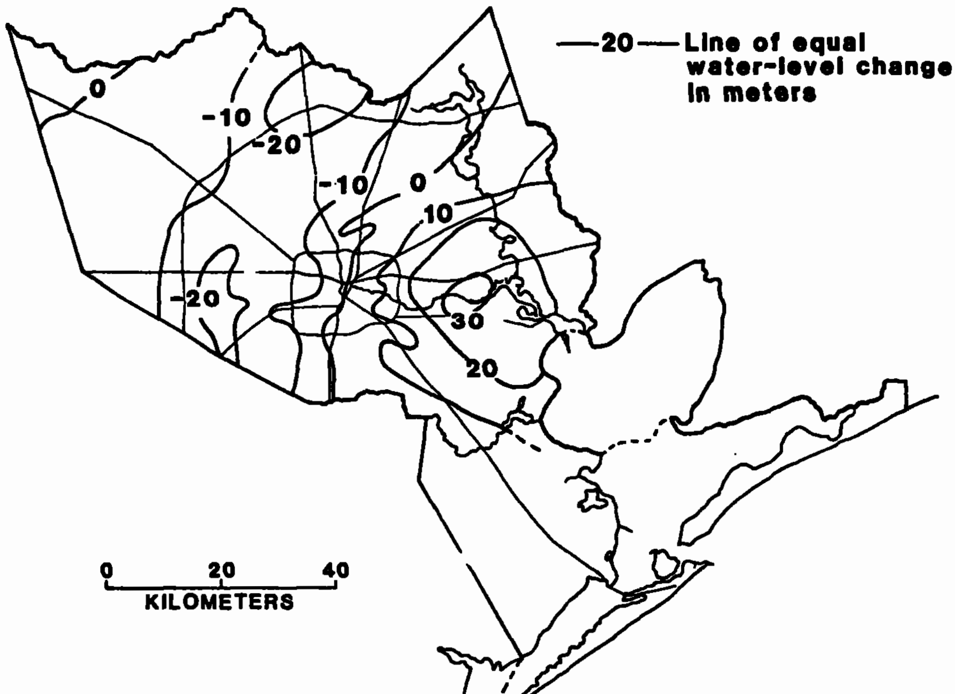


Figure 9b.--Approximate water-level changes in the Evangeline Aquifer, 1977-83.

is available for the area west of Houston, which has experienced rapid residential and commercial growth. All water comes from deep aquifers and pumping has increased significantly due to expansion and growth since 1973. See figures 9a and 9b from Neighbors and Thompson (1984), and Gabrysch (1982), which show lines of water level change for the periods 1943-77 and 1977-83, respectively. Table 1 contrasts velocities calculated for 1973 and 1987 at selected points in Houston. The changes in velocity have a direct correspondence with regional changes in water level. Figure 10 shows accumulated subsidence since 1906.

To monitor the subsidence at Houston, it has been necessary to reobserve a large percentage of the regional level network in periodic intensive campaigns. In each campaign, the measurements were made in a short time interval to preclude bias of the results caused by subsidence. By performing the leveling quickly, it has been possible to use a simple static height model to adjust each individual survey campaign. The set of adjusted heights resulting from each project has traditionally been compared to the preceding set to calculate subsidence. With this approach, subsidence can be calculated along the routes of releveling without a dynamic height model such as described in this report.

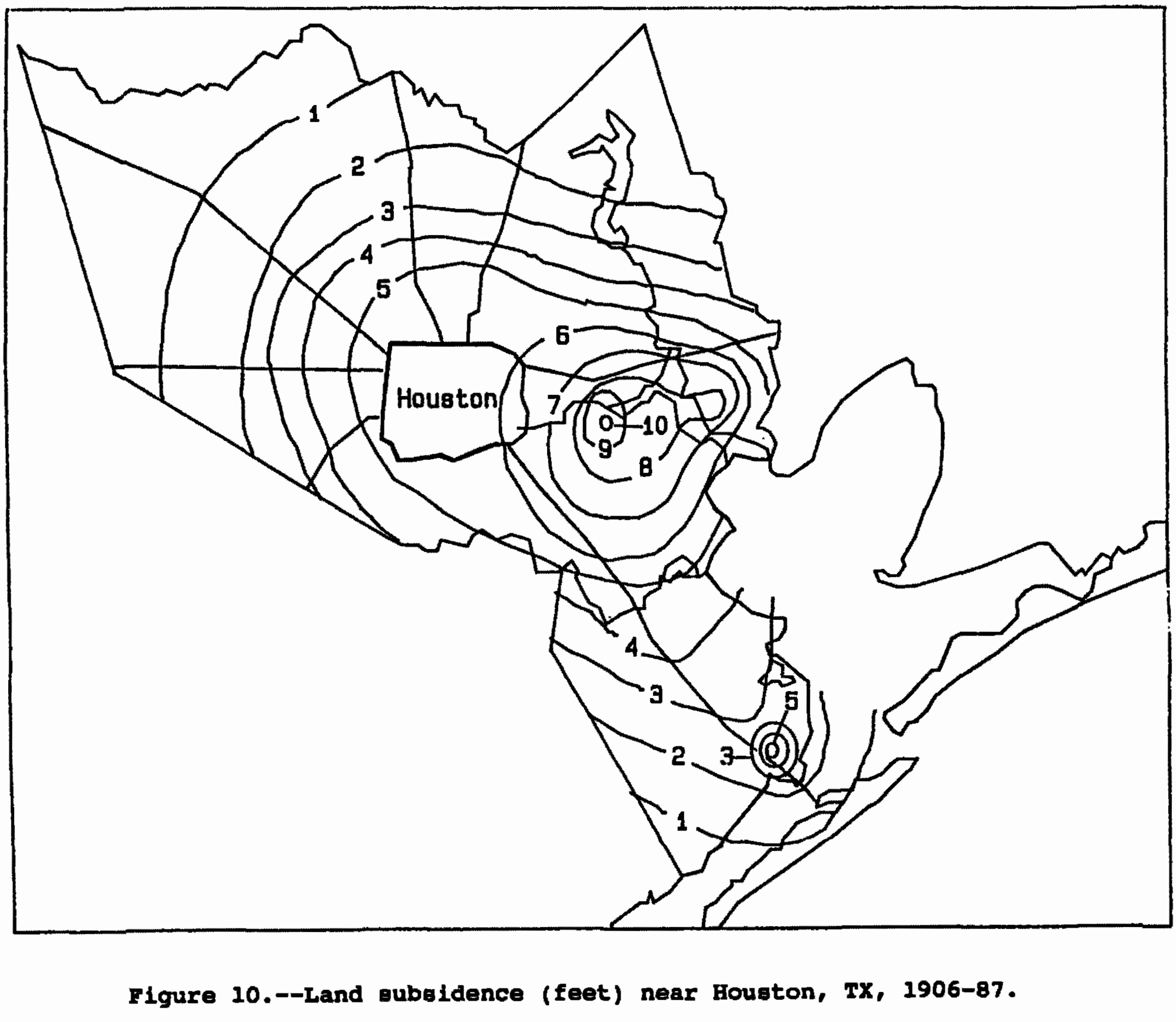


Figure 10.--Land subsidence (feet) near Houston, TX, 1906-87.

However, a good model for height change can be very useful. The Harris-Galveston area is so large that it has become increasingly difficult to organize a rapid survey campaign to relevel the entire subsiding region. Because the dynamic model accounts for height change, it is not necessary to level all parts of the network at exactly the same time. The model determination process permits observations of any dates. This facilitates the management of monitoring activities by allowing more flexibility in planning. Slow-moving areas or zones of low economic importance can be measured less frequently.

The model can be used to interpolate or predict height at locations which are not on a line of releveling, while recognizing that interpolation reliability decreases as distance from surrounding levelings increases. Such information may be necessary to resolve legal or engineering problems. The calculations can be made economically for any desired time.

From the geodetic point of view, it is necessary that a first- and second-order level network be useful for control of large engineering projects, mapping, and related survey activities. But in a subsiding area, most levelings may be biased by motion soon after the adjusted heights are determined. Consequently, a mechanism such as Houston's subsidence model must be available to correct for motion so old measurements can be made useful. Figures 6 and 7 show that corrected old measurements in the Houston area can be incorporated in a national or broad regional adjustment of the area without biasing newer survey results, provided the corrected measurements are given a realistic weight.

To properly serve geodetic purposes, the subsidence velocity surface should be made to taper down to zero velocity near a well defined outer boundary of the region. Outside that boundary, terrain height can be considered unchanging. The outer boundary for Houston is adequately defined on the east by Galveston Bay, and to the north it can pass through bench mark R 88. But to the southwest, it is unclear where the line of zero velocity should be placed. Further study is required. For completeness, the model should also be extended backward in time to account for motion prior to 1973.

Future subsidence computations at Houston will utilize the Global Positioning System (GPS) data. Simultaneous with the 1987 leveling project, many points in Houston were positioned three-dimensionally by GPS measurements. Further monitoring of those points is anticipated, and planned combinations of leveling and GPS measurements will allow subsidence to be monitored even more efficiently.

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John Chase and Janice Bengston of NGS assisted with organization and profiling of the leveling data.

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