SUBSIDENCE FROM DECLINING ARTESIAN PRESSURE CAN NO LONGER BE IGNORED IN HOUSTON AREA, TEXAS

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INTRODUCTION

The earth's surface is gradually sinking and tilting in a vital part of metropolitan Houston, Texas. This thus-far orderly disturbance centers in the industrial district concentrated near the inland terminus of the Ship Channel, which connects the Port of Houston with the Gulf of Mexico. Many of the industries responsible for sustaining the phenomenal growth of the Houston region are situated in the affected area. Much of the rapid post-war expansion, especially in the petro-chemical-based group of industries, has been along this deepwater outlet to the sea.

THE AUTHOR'S INTEREST IN THE SUBJECT

Despite the exceptional economic importance of the area, relatively few people know that the land surface is undergoing substantial subsidence. And no one knows very much about the character of this regional subsidence.

The author's interest in and concern over this situation stems from several circumstances.

One is the serious subsidence-induced difficulties encountered in recent years in certain engineering surveys; in particular, the difficulties experienced in maintaining the integrity of leveling bench marks. This has caused all sorts of confusion in the affected area, where large scale new construction, expansion and reconstruction has been going on continually for several years. Much of this confusion probably has been erroneously attributed to other circumstances.

It has been necessary, especially, to reckon with this problem on engineering construction works where interrelated design grades or relationships must be maintained over considerable distances. A good example is lined canals or similar works. For such works are extensive enough in at least one dimension, to traverse the area affected by the surface subsidence and tilting.

The very flat, slowly-rising and nearly featureless topography of the Houston Area, characteristic of the coastal plain, compounds the grade difficulties on such projects.

The engineering significance of this situation will be best illustrated by relating it to a specific project where it has been necessary to cope with the problem. Original levels for Houston's fourteen mile long West Canal were run in 1944, see Figure 1. Six years later, these lines were re-run. This was for the planning of a canal-lining and enlarging program, now under construction for the City's surface water supply from the San Jacinto River. The lines were again re-run in 1953. These latest levels, in particular, revealed the effects of the tilting and subsidence of the earth surface.

In the nine-year period from 1944 to 1953, the ground had sunk about 2.1 feet at the terminus of the Canal, on the north side of the Houston Ship Channel. It is estimated that the subsidence at the beginning end of the Canal at the San Jacinto River, for the same period, was only about 0.4 feet. All three sets of levels were run by the author's firm and under the same supervision. Fortunately, this tilting is in the direction which increases rather than decreases the very flat grade of the Canal.

The water supply implications of this ground water-related subsidence, has materially heightened the author's interest in the subject. There is widespread concern over rapidly declining water levels in the area. Excessive rates of withdrawal from limited areas are responsible for falling water levels. The penalty is, ever increasing costs for pumping, for lowering pumps or for drilling new wells to keep pace with the decline.

The City of Houston is dispersing its newer well fields to some extent in coping with this problem. But industry and commercial concerns are pumping about the same amount of water from private wells far more concentrated in location than the City's wells. As a practical matter, the only realistic means of discouraging the increase in pumpage from these highly concentrated private wells, perhaps, is for the City to provide surface water or ground water from remote areas, at competitive costs. To do this, probably would entail outright subsidization.

Concentrated withdrawal persists, however. And it will continue. Neither the present San Jacinto project nor any other presently planned development will be able to meet the future water demand without continued overpumping of ground water in the area now undergoing the most rapid subsidence. Ample additional flood water is available from the San Jacinto and other nearby rivers. Years of time to design, finance and construct storage, transmission and treatment works, however, will be required for its orderly utilization as a significant replacement for the ground water abuses.

Vast quantities of good water for municipal and industrial purposes can be developed from surface sources at costs considered very favorable in most localities, but not at costs comparable with those for pumping excellent quality general-purpose water from the immense underground reservoir which requires only chlorination for domestic purposes.

The short term economics are in control and probably will be for many years. That is, unless subsidence, which heretofore has not been a factor in these considerations, proves more persuasive in limiting concentrated withdrawals. Progressive subsidence in the heavily pumped areas where enormous industrial values exist conceivably could eventually catalyze mutual and self-imposed controls over ground water withdrawals and bring about a further utilization of river water.

By gathering existing factual information on this areal subsidence, and by reporting on it through the medium of this paper, it is hoped that the subject will begin to receive a degree of attention commensurate with the increasing significance of the phenomenon. And also, that others may be spared the tedious process of investigation and elimination to determine the causes of subsidence and of levelling inconsistencies.

AUTHORITIES FOR SOIL MECHANICS AND GEOLOGY

Compilation and interpretation of available information on this complex regional subsidence required knowledge and experience not possessed by the author, especially in soil mechanics and geology. Accordingly, the services of qualified authorities in these fields were enlisted. H. P. Carothers and Spencer J. Buchanan, Members ASCE, collaborated in the soil mechanics aspects and each gave comprehensive consideration to the whole problem throughout the course of the preparation of this paper. Paul Weaver, Member AAPG and AIME, supplied much of the geological analysis. In large part, technical interpretations and conclusions reported herein are directly based on the work of these outstanding specialists, modified to some extent by critical reviews afforded by other such competent authorities elsewhere acknowledged. This paper would not have been undertaken without this clearly essential technical aid.

EXAMPLES OF EXTREME REGIONAL SUBSIDENCE ELSEWHERE

Mexico City is perhaps the best known example of extreme settlement of buildings due to consolidation of the highly compressible foundation soil of volcanic origin. Moreover, it is now a classic example of regional subsidence due to withdrawal of ground water. The City is being carried steadily downward with the present rate of settlement reported as 11.8 inches per year; reportedly due to continued withdrawal of water from artesian wells. A $115 million rescue operation for a 30 year water supply has been suggested. It will include flood control and dams to augment Mexico City's water supply. Also, recharge wells are proposed to restore some of the water which Mexico City has been withdrawing for centuries from its subsoil.

The Santa Clara Valley of California subsided a maximum of about 5.5 feet from 1912 to 1938, according to the National Research Council. This subsidence was roughly proportional to the decline in water table resulting from withdrawal of ground water. The change in volume in the formerly saturated clay, now drained by pumping, is believed to account for the settlement. The sinking virtually ceased in 1937, three years after the well pumping operations were spread and the water level was raised 50 feet.

The Long Beach Area, California, was reported to have reached a maximum subsidence of about 13 feet, between 1937 and 1952, at the center of subsidence which coincided closely with center of production of an oil field. Ultimate subsidence was estimated at 18 to 23 feet. The Geological Society of America reported very close agreement between the relative subsidence of the various parts of the field and the pressure decline, thickness of sand affected, and mechanical properties of the oil sands.

SUBSIDENCE IN THE HOUSTON AND NEARBY AREAS

Surface subsidence with the greatest depth of depression centered in the industrial region along the Houston Ship Channel, generally known as the Pasadena area, is shown by first order levels of the United States Coast and Geodetic Survey. This subsidence is reflected by the differentials between two lines of levels run by the U.S.C.&G.S. in 1943 and re-run in 1951. These show a maximum subsidence of about 1.5 feet during the eight year period. See location of Section A-A in Figure 1 and profile of subsidence in Figure 2.

The same general tilting of the ground surface has been closely verified by levels run along Houston's aforementioned West Canal. As has been indicated, these show that the south end of the Canal, near the Houston Ship Channel, between 1944 and 1953 subsided about 1.7 feet more than the north or beginning end of the Canal at the Lake Houston Dam on the San Jacinto River. See location of Section B-B in Figure 1 and profiles of subsidence in Figure 3.

An extension of the levels for the canal improvement, across the Ship Channel to the Pasadena area, indicates a total accumulated settlement of about 3.25 feet. This compares with the 2.1 feet subsidence determined across the Channel for only a nine year period.

The area around the town of South Houston subsided about 2.1 feet from 1905 to 1951, according to a comparison of older surveys with the 1951 adjusted levels of the U.S.C.&G.S.

In 1944, the author's firm established a precise level circuit for the City of Houston to serve as permanent leveling reference for the part of the City surveyed. Spot checks in 1953 on a few of these bench marks indicates a subsidence of as much as 0.5 feet near the downtown business district of the City. This circuit of bench marks has probably subsided and tilted more or less in relation to the contours of the static water levels in observation wells, which are periodically published by the Texas Board of Water Engineers and the United States Geological Survey.

There are numerous instances of protrusion of water well casings in the area, particularly in the deeper wells.

The subsidence has been accompanied by a more or less definite pattern of faulting, as shown on Figure 1. These faults, ranging from about 6 to 16 inches in displacement, are easily located across the concrete pavements in the area. Generally, most of the movement of displacement of the various faults crossing the pavements has occurred since 1942.

In addition to the very apparent movement of faults at the surface, less apparent differential movements in the order of 3 inches have now appeared in certain building foundations. For instance, the Vocational School Building in Pasadena, Texas which was completed in 1947, has cracked from a differential movement of about 3 inches. Most of this movement occurred in 1950 and 1951. The pattern of this movement cannot be explained by one of the usual theories of consolidation from building load, plastic flow of overloaded foundation, or shrinkage and swell of the soil with seasonal or other moisture changes. It would appear that the only reasonable explanation is that localization of a small differential subsidence has occurred as a part of the greater general subsidence of the area.

The subsidence of the Goose Creek Oil Field, about 1.5 miles southeast of Baytown, Texas, is indicated by changes in the adjacent shoreline and by the following record of a bench mark near the center of the oil field:

Date	Elevation Feet	Total Subsidence
1917	21.2	-
1922	18.9	2.3
1936	17.8	3.4

These elevations furnished by George H. Lacy, Member ASCE, Gulf Refining Company, were tied into U.S.G.S. bench marks on two sides of the field and beyond the limits of the indicated disturbance. The subsidence was bowl shaped around the heaviest oil production, with the large effects within approximately one-half mile of the heavy production. Faults occurred around the edge of greatest movement. The subsidence has been reported to be due to withdrawal of oil, sand and gas.

According to A. P. Pettyjohn, of Carbide and Carbon Chemical Company, the Texas City area, between Houston and Galveston, Texas, has suffered a subsidence of about 4 feet or more to date, due almost entirely to excessive withdrawals of ground water from a limited area. This condition was first noticed in 1944, after an apparent subsidence of about 1.6 feet had occurred.

An industrial plant near Texas City has reported a total differential subsidence within the plant site of about 3 feet. Also, local abrupt cones of subsidence around water wells, of as much as 1.6 feet differential settlement within a horizontal distance of only 1000 feet. This general sinking of the ground was accompanied by surface faults, local irregular settlement causing severe cracking of buildings and broken water and sewer lines.

There are preliminary indications of ground subsidence in the Freeport, Texas area due to decline of artesian pressure. A bench mark established by the U.S.C.&G.S. in Freeport shows a decline of 0.5 foot in the 25 years from 1918 to 1943, and an additional subsidence of 0.5 foot in only 8 years, from 1943 to 1951. The City of Velasco water well No. 1, just across Old Brazos River from the bench mark in Freeport, showed a decline in static pressure of 48 feet from 1941 to 1952. This additional pressure relief due to pumping is quite likely the main cause of the recent and more rapid subsidence of the ground.

POSSIBLE CAUSES OF THE HOUSTON AREA SUBSIDENCE

In seeking explanation of the relatively large scale ground subsidence in the Houston Area, consideration has been given the various possible causes of regional subsidence in general.

The typical settlement of buildings, structures, and fills due to the super-imposed load on soft clay or muck foundations is well known. Geologically, the Beaumont Clay Formation outcrops over most of the area. It has been well demonstrated, both by differential settlement measurements and theoretical analysis, that even the heaviest building in the area have settled an insignificant amount due to building load on the foundation soil.

If the general subsidence were confined to a small area of very concentrated and heavy buildings and fill load, further consideration might be given to this type of consolidation. However, for such a large area of subsidence, including residential and rural areas, the total building and fill loads could not be responsible for more than an infinitesimal part of this regional subsidence.

Various portions of the Texas Coast line show a very slow subsidence relative to mean gulf level. This is reputed to be about one foot per sixty to one hundred years. It is due to sediment load from rivers and littoral drift deposition along the coast. Also, there may be a general rise in sea level. The pattern and relatively rapid rate of subsidence in the Houston Area quite evidently could not be related to such a gentle and gradual subsidence or tilting of the coast line, or to a possible rise in sea level.

The clay surface soils, derived by weathering of the Beaumont Clay, are subject to moderate shrinkage and swell with seasonal changes in moisture content in about the upper seven feet of soil. Very shallow footings or shallow bench marks in the area are subject to seasonal differential vertical movement from this cause in the approximate order of three inches. The continued downward movement of the surface in the magnitude of one to 3.5 feet cannot be caused by this seasonal variation in moisture content of the surface soils.

With the appearance of recent fault movement and development at the surface, consideration should be given to tectonic folding and faulting of the earth's crust which is usually experienced in connection with earthquakes. The region is not subject to earthquakes but the coastal area is underlain, at various depths, by salt domes.

The gentle down-tilting of the coast and/or differential upward movement of the salt domes has created faulted zones. There are large salt domes, with oil field development, near many of the areas of faulting shown on Figure 1. It is believed therefore, that normal geologic movement of old faults could be and probably is involved to a slight degree in the recent and relatively rapid movement of surface faults in the area. However, the definite pattern of relation in location and rate of fault development with rapid reduction of gas and artesian pressure in the oil and water well fields, indicates that this reduction in pressure must be the major cause of the recent movement and/or development of surface faults.

Settlement of the ground surface in general has been caused by or found in connection with withdrawal of oil, gas, water, sulphur and salt from the ground by wells, as has been discussed already and as may be found from many published reports. Great quantities of oil, gas, and water have been withdrawn from the Houston Area and considerable salt has been produced.

Houston for a long time was the largest city in the western hemisphere to secure its entire water supply from the ground. The estimated daily pumpage reported for public and industrial supplies in the Houston and Pasadena areas for 1950, 1951 and 1952 are 156, 167 and 180 mgd respectively. This heavy withdrawal has resulted in a decline of artesian water pressure as indicated by contours of water levels in observation wells on Figure 1 and by profiles on Figures 2 and 3.

The areas of particular interest in this paper are along the West Canal, around the business district of the City, and in the industrial area along the Ship Channel. In these areas, the withdrawal of ground water has greatly exceeded the withdrawal of oil and other minerals. This fact, along with the remarkable relation, reported by the U.S. Geological Survey and Texas State Board of Water Engineers, between ground subsidence and reduction in artesian pressure, has lead to the conclusion that this reduction in pressure is the most logical cause of the major part of the subsidence in these particular areas.

SUBSIDENCE FROM DECLINE OF ARTESIAN PRESSURE

The relation between the ground subsidence and the decline of artesian pressure is shown by Figures 2 and 3. By plotting 1 foot of subsidence to the same scale as 100 feet of decline in pressure head, Figure 3 shows the very close relation of 1 foot of subsidence per 100 feet of decline, between the years 1944 and 1953 along the West Canal. This is the same relation that Allen G. Winslow and W. W. Doyel, Geologists, U. S. Geological Survey, found and reported, in an as yet unpublished bulletin, for the subsidence and decline, between the years 1942 and 1951 along Section A-A between Aldine and Buffalo Bayou.

Total accumulated subsidence and decline with reference to possibly uncertain bench marks and original artesian pressure is shown on Figure 2. This indicates the relation of total subsidence to total decline as less than the 1 foot per 100 feet. This is tentatively attributed to some preconsolidation in the soils, particularly the clays, due to compaction by desiccation. James R. Sims, Associate Member, ASCE, has advised that in foundation studies it is generally found that the shallow clays have been subjected to a preconsolidation load of from 3 to 4 tons per square foot. Geologically these soils, however, are considered to be unconsolidated because there has been no thick deposition and subsequent erosion of soils from above the present ground surface. Consequently, it appears that the first 65 to 100 feet of decline will cause little subsidence. Then, greater decline causes a higher comparative rate of subsidence.

The ground water of the area is produced from a true artesian system. The geological structure shows an arrangement of the soil strata whereby permeable sand and interbedded layers and lenses of relatively impermeable clays dip toward the southeast, beneath the Gulf of Mexico, on a slope considerably greater than the ground slope. That this artesian condition exists, is also demonstrated by the record which shows that originally water wells as shallow as 100 feet were flowing wells. Through the Houston Area, this artesian pressure is reported to have been originally at about elevation +65 to +75, where ground elevations vary from about sea level to about +50. The evidence found to date indicates that the decline of artesian pressure has caused no noticeable lowering of the unconfined water table.

This is a case of subsidence due to consolidation of soils, with the consolidating loads being imposed by the decline in artesian pressure. The stress diagram is quite complex because of varying soil strata, depth and screening of wells, differential and fluctuating artesian pressure heads, and the gradients of seepage caused by unbalanced pressures.

Usually natural soil consolidation, without artesian pressures, is caused by the accumulated weight of soil and water, less the buoyancy effect on the mass below the water table.

With artesian pressure present, there is a reduction of this consolidating load, or effective pressure. With a decline in this artesian pressure, the accumulated consolidating load is increased. This increase, between upper and lower aquicludes, is equivalent to the decline in pressure. The effects reduce to zero at the upper and lower limits of the aquicludes by virtue of the seepage pressure gradients in these strata.

This increase in effective pressures causes permanent consolidation in the soils of the various aquifers, in the interbedded soil layers and in the upper and lower aquicludes. This brings about the permanent ground subsidence.

Most of the ground elevation is irretrievably lost, since there could be little rebound even with complete restoration of artesian pressure.

The influence of this increase in effective pressures is greatest at the general level of the upper aquiclude, and it decreases with depth below that level. Preliminary estimates show some influence to depths exceeding 1500 feet. The rate of consolidation in the relatively pervious soils is rapid, but a considerable portion of the consolidation in the relatively impervious clays is extended over a period of many years, varying as the square of the actual unbroken thickness of the clay layers involved and the time-consolidation characteristics of this soil. The majority of the consolidation probably occurs in the clay layers, with some in the sandy clays and silty sands and little in the producing sands.

FAULTING WITH DIFFERENTIAL SETTLEMENT

Reference has been made to the occurrence of surface faults of 6 to 16 inches, noted by A. C. Kyser, Texas Highway Department, in the concrete pavements in the area. The faults that can be easily located and identified on flat, level pavement grades are shown on Figure 1. The maintenance experience of the Highway Department indicates that the displacement is very slow over a period of years.

Most of the movement recorded in these pavements has been noted since about 1942, the period of rapid decline in the artesian pressure. However, some faulting, such as near the Municipal Airport and on the La Porte Road, were reported as active between 1936 and 1940. Many of the faults are in pairs, forming downblocks or grabens, as they are called by the geologists. Others appear to be single fault lines. The downblocks are said generally to appear to be directly connected with the salt domes and oil fields in the area.

This faulting is also clearly reflected by irregularities in the profile of subsidence to 1951, shown on Figure 2. From the evidence collected to date, it appears that these faults may be largely attributed to differential settlement. This probably has been caused by the superposition of subsidence from declining gas pressure in the oil fields, upon the more general and differential subsidence from declining artesian pressure. No theoretical analysis of the effect of the oil fields has been made to substantiate this assumption, however.

In addition to the very evident and major faults indicated on Figure 1, there is increasing evidence of numerous minor differential settlements. These movements are not as spectacular as the major faults. But they are of about the same magnitude as the usual 3 inch seasonal movement of the ground surface due to variations in moisture content.

In buildings, movements caused by these differential settlements are usually attributed to variations in moisture content of the surface soils. The usual straight line pattern, however, indicates that the general regional subsidence is being accompanied by local differential settlements that can be expected to cause an increase in troubles with cracking buildings, and breaking of sewer and pipe lines. These differential settlements are to be expected because of the local variations in rates and amount of artesian pressure decline; the different depths of the wells from one group to another involving different aquifers; and, also, the differences in consolidation characteristics and elevation and thickness of the various soil strata affected.

CONCLUSIONS

1. The heavy withdrawal of confined ground water for municipal and industrial use in the Houston, Texas Area has caused a cone of pressure relief, or decline in artesian pressure over most of Harris County, due to concentrated pumping. This decline has been accompanied by a remarkably similar conical depression of the ground surface, in the approximate order of one foot per one hundred feet of decline in artesian pressure head.

2. Analysis and interpretation of available information on this complex subsidence, by authorities on soil mechanics and geology, indicates that it is largely due to consolidation of the soil arising from reduction in artesian water pressure. To some extent, however, it probably is due in portions of the area to the superposition of subsidence from declining gas pressure, or related hydrostatic pressure, in the oil fields.

3. The maximum relative subsidence between Lake Houston Dam and the center of the industrial district on the south side of the Ship Channel is about 3.25 feet. The area in the vicinity of the dam probably has sunk, however, about 0.3 to 0.5 feet to date, based on a study of the contours and profiles of the general subsidence and decline of artesian pressure.

Therefore, it is concluded that the total subsidence to date in the Pasadena area is a maximum of from 3.5 to 3.75 feet. This is in the area of maximum pressure decline shown on Figure 4.

4. The artesian pressure in the Pasadena area is declining at the rate of about 100 feet in 8 years. At that rate, the pressure level will have fallen to about minus 450 feet before 1970. That is the approximate elevation of the top of the major aquifer in a representative well in the area. Thus, there is reason to believe that within the next fifteen years the earth's surface in the region of maximum disturbance, will have subsided twice as much or more than it has to date. This estimate of future subsidence compares reasonably well with a theoretical determination made by a rather oversimplified consolidation analysis which necessarily employed assumed values for the mechanical properties of the soils.

5. The ground elevation loss is permanent. There could be little rebound, even with conceivable but wholly improbably restoration of original artesian pressure. Actually, at any given time, the subsidence can be halted only by an increase in artesian pressure.

6. Known or suspected subsidence-induced difficulties in the Houston Area, relatively speaking, have not been very serious to date. Fortunately, the major faults have not occurred in areas occupied by important structures. There has been some minor differential settlements resulting in cracking of building walls. Revision of plans for canals, roads, and drainage systems have been made necessary by the subsidence. The loss of ground elevation in areas of maximum subsidence already has wiped out the normal freeboard allowance for flood and hurricane tides. Much confusion and expense in running and maintaining differential levels is directly due to subsidence. Probably, more often than not, however, the trouble has been attributed erroneously to some other factor.

J. R. Sims points out a curiously interesting coincidence arising from the fact that in the subsiding area under discussion, was situated the starting point used by the U.S. Coast and Geodetic Survey for computing the elevations of all other junction points in the 1927 national level net, and subsequently the 1929 adjustment which included Canada.

After the 1927 Special Adjustment net - to quote from the official report of the U.S.C.&G.S. -

> " . . . had been made entirely consistent within itself by the adjustment, the unadjusted difference of elevation between mean sea level at Galveston, Tex., and the junction bench mark at Houston, Tex., was used to determine the elevation of the junction bench mark at Houston. From that starting point the elevations of all other junction points in the net were computed."

Then in the 1929 Special and General Adjustments -

> " . . . as in the 1927 Special Adjustments, elevations based on Galveston, Tex., were computed for the mean-sea-level planes at the other tide stations."

The value of the key bench mark in Houston is obviously destroyed. Also, it would seem that the important tide gage at Galveston is close enough to the subsiding areas in Houston and Texas City to warrant the most careful consideration of the future validity of the Galveston gage.

7. More serious troubles may be expected in the future is this subsidence continues at the present rate or increases. Up to now, neither uniform nor differential subsidence has received much, if any, detailed consideration by designers and builders. The time has come for responsible management to have its planners, designers and constructors recognize the significance of the subsidence factor in all its important future undertakings in the affected area.

8. More care should be exercised hereafter in placing wells adjacent to concentrated industrial or other high-value developments, buildings, wharves or other structures. Especially, if the wells are of such depth and in soil conditions that might cause abrupt local cones of subsidence.

New buildings either should be located clear of known surface fault lines or be designed for differential settlement. Elevated tanks ought not to be located too close to wells producing from shallow depths. Where differentials or tilting would appear to be in prospect, special care should be taken in the design and routing of surface drainage, sewers, water and other underground utilities.

9. To cope with this subsidence problem, there must be a reduction in the excessive rates of withdrawal of ground water in the critical areas. This would entail dispersion of well fields and much increased use of river water in the future.

10. Ample sources of good water are available for all forseeable future municipal and industrial requirements of the Houston Area. Supplies, entirely satisfactory in quantity and quality, can be developed at reasonable costs from ground and river sources, in such way as to minimize the subsidence pitfalls of the future. The incremental cost of transmission to heavily developed areas, from properly situated well fields and from rivers, might prove to be less in the long run than the unhappy alternate - serious property damages in the subsiding area.

11. What is needed now, is more information, more data, more study and more technical and lay interest in and discussion of this subject. Frequent and complete coverage of the subsiding area by precise levels, is very desirable. The U.S.C.&G.S., which is now releveling along the Houston Ship Channel, and all other agencies public and private, should release significant data bearing on the situation as early as is feasible. In addition to precision leveling records, it would be helpful to have any good detail maps showing traces of identifiable old and new faults in the area.

Consolidation tests should be made, perhaps as a community enterprise, on the typical clays, sandy clays and silty sands of each formation involved in the water wells. Electrical micrologs should be run on typical wells. Reservoir pressure measurements at peak production, and in the various aquifers, should be made. All of this, in order to afford a basis for really dependable estimates of future rates and ultimate amounts of subsidence; and, to assist in forecasting possibilities of abrupt and destructive differentials.

12. Finally, this paper is, and must be recognized as, merely a preliminary report on the subsidence situation of the Houston Area. Of necessity, it is based on technical data too meager and too incomplete for more specific evaluation of the ultimate consequences. Such conclusions as have been reached, were possible only by the most dogged and determined gathering and interpretation of the scattered information on the subject and by the extraordinary professional assistance and friendly cooperation of an unusually large number of engineers and geologists. To recite the polite acknowledgements customarily found in technical writings, would be to miss the main point here. Better, perhaps, to say that the work of these contributors is both a practical application and a heartening manifestation of the spirit of the very first Commandment of the "Canons of Ethics for Engineers" which states that:

> "The engineer will co-operate in extending the effectiveness of the engineering profession by interchanging information and experience with other engineers and students and by contributing to the work of engineering societies, schools, and the scientific and engineering press."

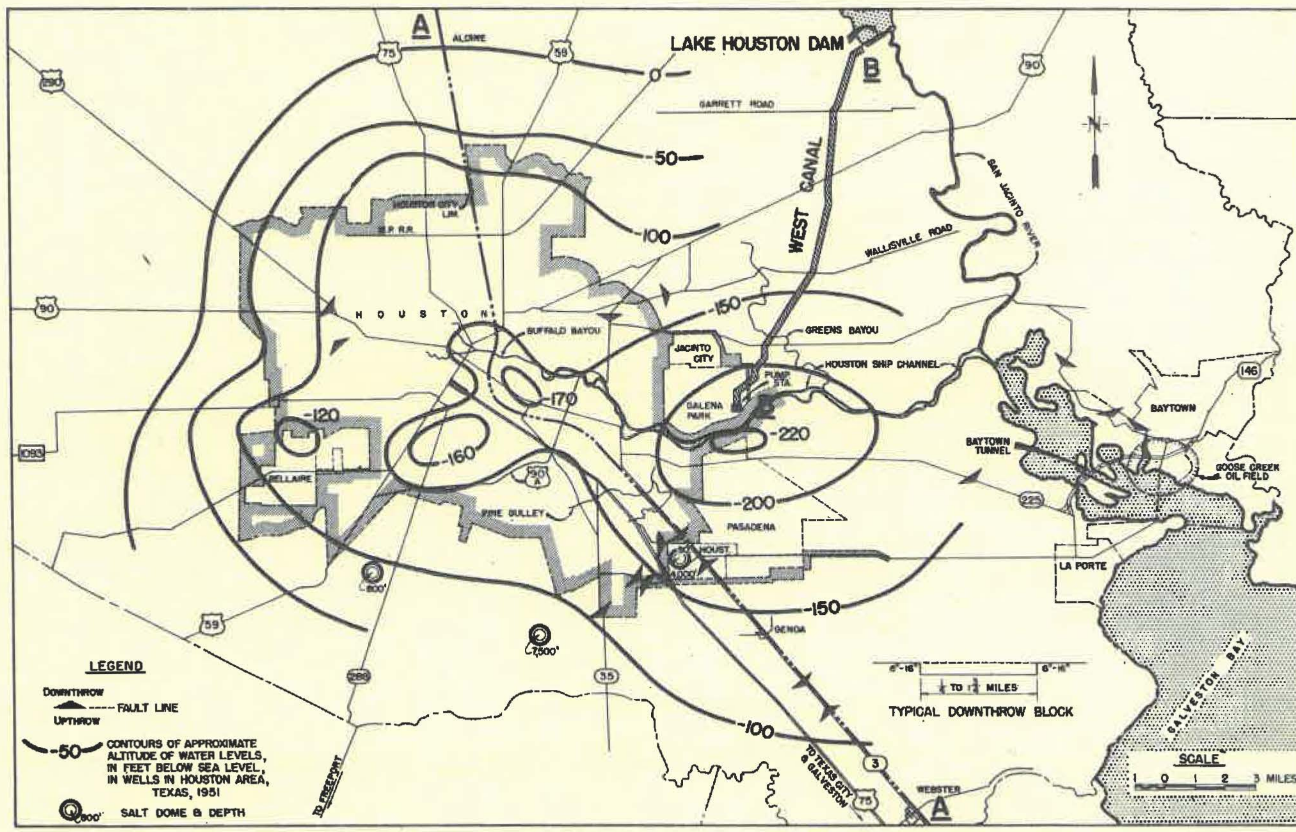

FIG. 1 - WATER LEVELS AND FAULTING - HOUSTON AREA

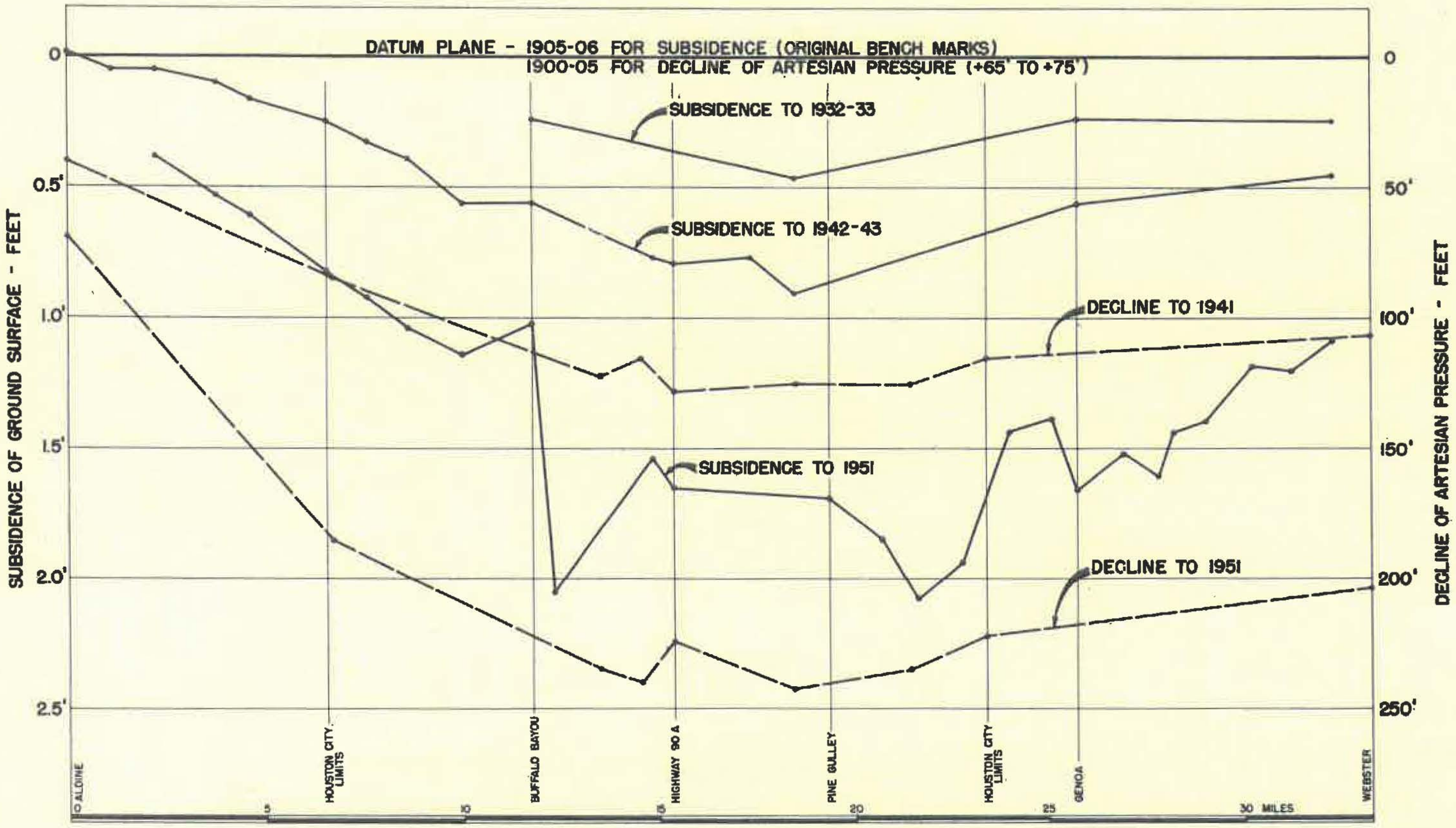

FIG. 2 - CROSS-SECTION A-A THROUGH HOUSTON AREA