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DISCUSSION

Intervention of Dr. Sakuro Muraya (Japan)

Questiob:

This morning, Dr. Miyabe mentioned acute subsidence due to the earthquake in Tokyo. I think there were some earthquakes in Long Beach. Do you have any experience about influence of earthquake on the movement of surface?

Answer of Mr. Yerkes:

There has been earthquakes during oil production in Long Beach but the relations are complex and I do not clearly understand.

Intervention of Dr. Jose G. Mendez (Venezuela)

Question:

I think there have to be room for certain legal aspects. Who is respensible for the damage?

Answer of Mr. Yerkes:

I am not in the position to answer that.

SUBSIDENCE IN THE WILMINGTON OIL FIELD, LONG BEACH, CALIFORNIA, U.S.A.

M. N. MAYUGA[1] and D. R. ALLEN[2]

Abstract

The subsidence area is in the shape of an elliptical bowl superimposed on top of California's largest oil giant, the Wilmington Oil Field. The center of the bowl has subsided over 9 meters (29 feet) since 1926. Horizontal and vertical movements have caused extensive damage to wharves, pipelines, buildings, streets, bridges and oil wells necessitating costly repairs and remedial work, including the raising of land surface areas to prevent inundation by the sea. Remedial costs have already exceeded US$100 million. Most investigators

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(1) Assistant Director and
(2) Subsidence Control Engineer, Department of Oil Properties, City of Long Beach, California, U.S.A.

agreed that the withdrawal of fluids and gas and the consequent reduction of subsurface pressures in the reservoirs caused compaction in the oil zones. A massive repressurization program, by injection of salt water into the oil reservoirs, has reduced the subsidence area from approximately 50 sq. kilometers to 8 sq. kilometers. The rate of subsidence at the historic center of the bowl has been reduced from a maximum of 75 cm (28 inches) per year in 1952 to 0.0 cm (0.0 inch) in 1968. A small surface rebound has occurred in areas of heaviest water injection.

RÉSUMÉ

La région subsidente a la forme d'une cuvette elliptique qui se superpose au top du plus grand champ pétrolier de Californie, le gisement de Wilmington. Au centre de la cuvette la subsidence a dépassé 9 mètres (29 pieds) depuis 1926. Les mouvements horizontaux et verticaux ont causé des dégats importants aux jetées, pipelines, immeubles, rues, ponts et puits de pétrole, nécessitant des réparations coûteuses et des travaux de protection, tels que l'élévation du niveau du sol pour empêcher les inondations par la mer. Les travaux de protection ont déjà coûté plus de $100 millions. La plupart des spécialistes sont d'accord que le soutirage de production d'huile et de gaz, et la réduction conséquente de pression dans les réservoirs a causé la compaction des zones productrices. Un programme de recompression massive, par injection d'eau salée dans les réservoirs, a réduit la région subsidente de 50 à 8 km^2, environ. Le taux de subsidence au centre de la cuvette a été réduit d'un maximum de 75 cm (28 inches) pa ran en 1952, à 0.0 cm (zéro inch) en 1968. Un léger gonflement de surface s'est produit dans les régions où l'injection d'eau a été la plus forte.

1. INTRODUCTION

Ranking high among the many causes of land subsidence are those related to man's exploitation of the earth's natural resources. One of the most widely known cases of induced subsidence occurred in Long Beach, California, USA. The subsidence in the Long Beach area has been related directly by most investigators to the production of oil and gas from the huge Wilmington Oil Field. The subsidence here has attracted world-wide attention because of its location and magnitude. Situated within the bowl of subsidence is one of California's most highly industrialized areas, including the Port of Long Beach and one of the United States Navy's most important shipyards. Figure 1 shows an airphoto of the area with contours of total subsidence as of October, 1968. Total vertical movement is about 9 meters (29 ft.) at the center of the bowl of subsidence. Horizontal movements of nearly 3 meters (10 ft) also have been measured within the area. There appears to be a definite relationship between the shape and location of the axis of the bowl of subsidence and that of the underlying Wilmington oil structure.

2. GEOLOGIC FEATURES

The Wilmington Oil Field, located near the southwestern margin of the Los Angeles Basin in Southern California was discovered in 1936. The geologic structure is a broad, assymetrical anticline broken by a series of transverse normal faults (fig. 1). The structure was "buried" or covered by approximately 550 to 600 meters of late Pliocene, Pleistocene and Recent sediments deposited almost horizontally over a Lower Pliocene-Upper Pliocene unconformity. The sediments above the unconformity contain no commercial oil and gas. Below the unconformity are seven major producing zones which range in age from Lower Pliocene to Upper Miocene (fig. 2). These productive zones span a vertical section of about 1 500 meters. Oil and gas are produced primarily from sands of varying thickness and consolidation which are interbedded with layers of shale or siltstone. The degree of consolidation of sediments is generally related to depth of burial. The sands at shallow depths are loosely consolidated and the shales become progressively softer and grade to claystones and mudstones toward the surface. Oil bearing sands are generally poorly sorted with a high percentage of fine materials. Porosities vary from 25 percent in the deep zones to approximately 35 to 40 percent in shallower zones. The "shales" at shallow depths are more accurately described as siltstones due to the high percentage of silt materials which they contain. The beds are either flat or dip gently near the crest of the structure. The primary production mechanism essentially has been a solution-gas drive. Due to a very limited water encroachment the pressure decline in the oil and gas reservoirs was relatively rapid. The substantial reduction of reservoir pressures and the compactability of rocks within the oil producing zones are considered by most investigators to be the primary causes of subsidence in the area.

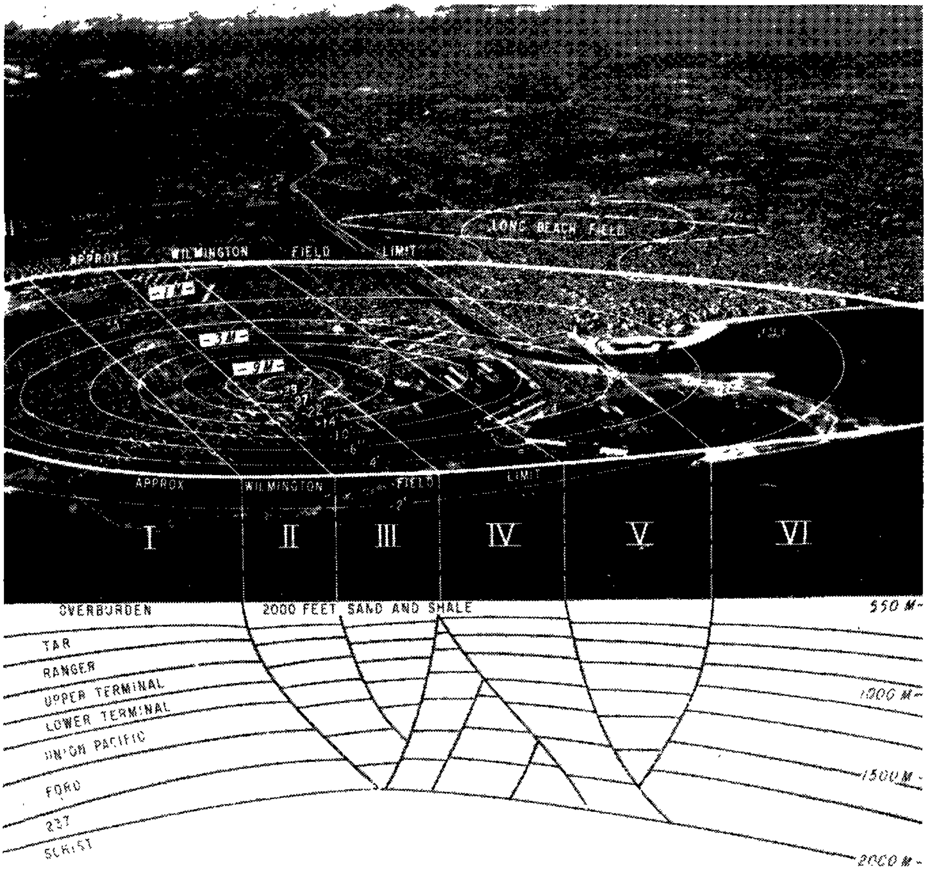


FIGURE 1. *Subsidence and Geologic Cross Section Wilmington Oil Field*

The oil reservoirs were developed by zones and fault blocks. From November 1936 to July 1, 1969 the oil field has produced approximately 203, 360, 000 cubic meters (1.279 billion barrels) of oil.

3. SUBSIDENCE HISTORY

Small amounts of regional subsidence had been detected in the Long Beach-Wilmington-San Pedro area at various times prior to 1940, but little attention was given because the amount was very small. A noticeable amount of subsidence did not occur until after the major oil field development began in 1939-1940. By coincidence, the first major elevation changes were recorded in 1940 and 1941, when 40 centimeters (cm) (1.3 ft.) of land subsidence was observed at the easterly end of Terminal Island, apparently due to shallow dewatering operations in a nearby area for a large US Navy graving dock. It was assumed that the land subsidence would cease when the dewatering operations stopped. In July 1945, long after the dewatering operations had ceased, a survey by the US Coast and Geodetic Survey showed a surface subsidence of more than 122 cm (4 ft.) at the easterly end of Terminal Island. The rate of subsidence and the size of the affected area continued to increase during the following years. Continuing damage to surface and subsurface structures and the threat of inundation of the surface area caused serious concern. The average ground elevation of the harbor area prior to subsidence was only a few meters above the extreme high tides of the bay. As the ground subsided, the tidewater backed up through the storm drain systems at high tide and flooded the streets (fig. 5). By 1963, over 1 300 hectares of natural and artifically created industrial land which had been above high tide level before subsidence, had settled well below that level. Extensive diking, filling and land raising operations were undertaken throughout the harbor area. Remedial operations

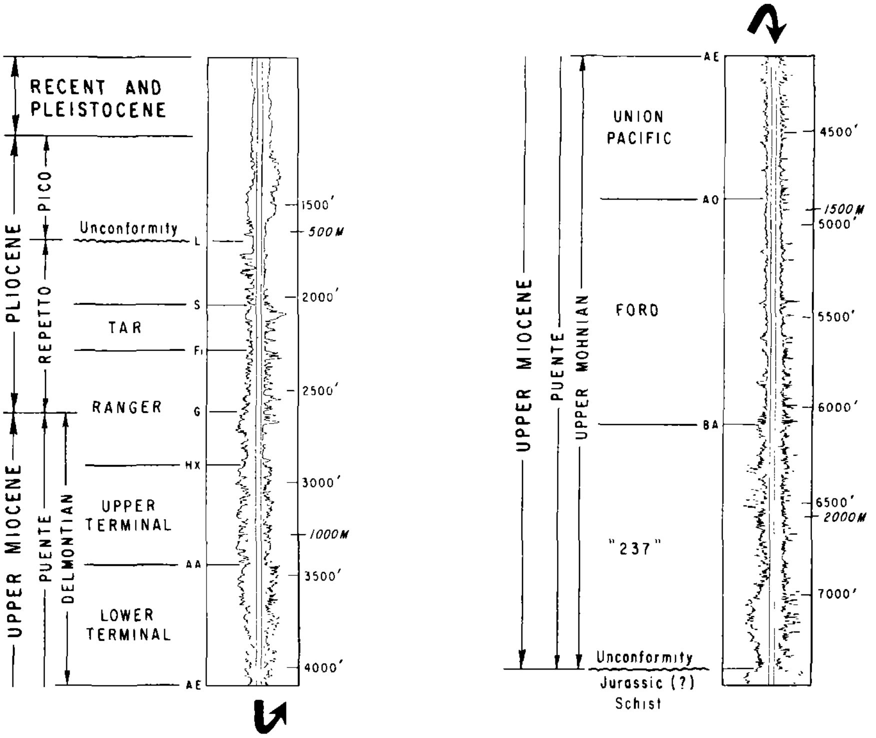


FIGURE 2. *Wilmington Oil Field—Composite log and Stratigraphic Units*

included raising and replacement of wharves, transit sheds, warehouses, oil wells, pipelines, and buildings of all types. The deepest part of the subsidence bowl, which is located over the crest of the oil structure, sank about 9 meters (29 ft.) between 1926 and 1968 (fig. 1). The maximum subsidence rate of 71 cm (28 in.) per year at the center of the bowl

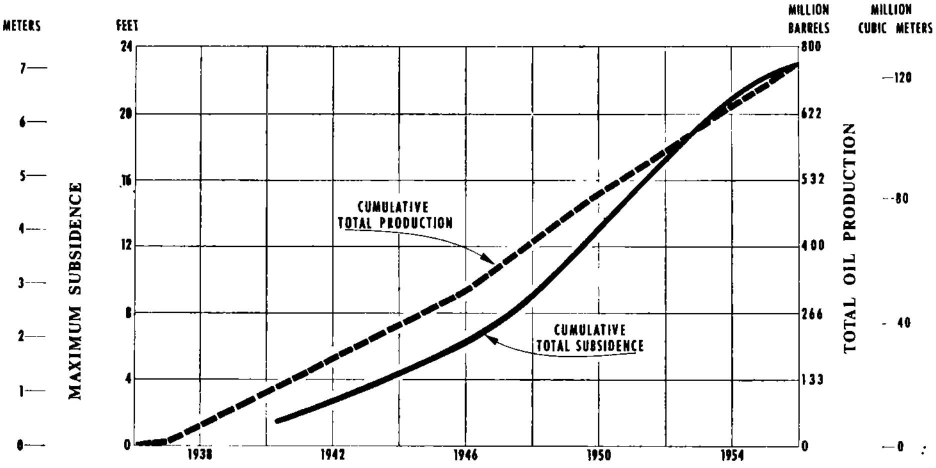


FIGURE 3. *Wilmington Oil Field—Relation of oil production to subsidence*

was reached in 1952 (fig. 4). The horizontal movements which accompanied the vertical land subsidence have caused extensive damage to many surface and subsurface structures necessitating costly repairs and replacements. Many oil wells have been damaged or destroyed by subsurface shearing associated with subsidence.

In order assist the harbor engineers in planning new construction and remedial work, various experts were engaged to predict the amount of ultimate subsidence in the area.

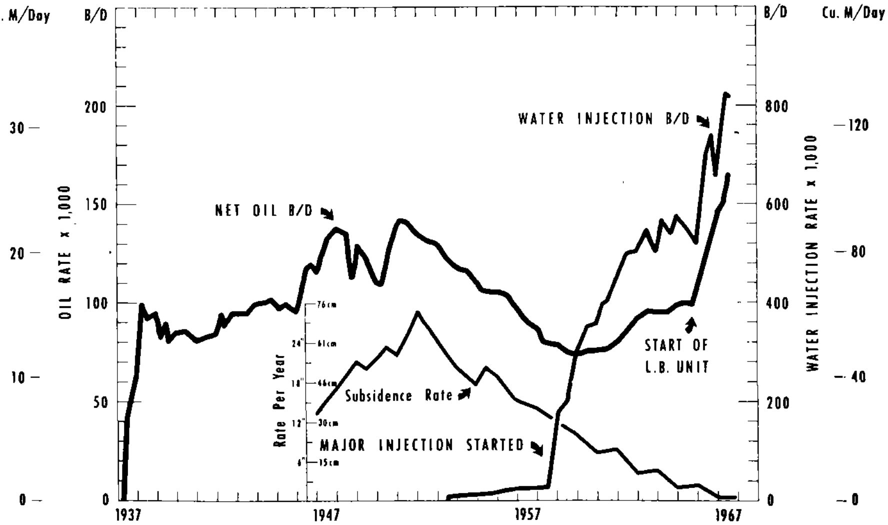


FIGURE 4. *Wilmington field Oil production rate VS. Subsidence & Water injection rates*

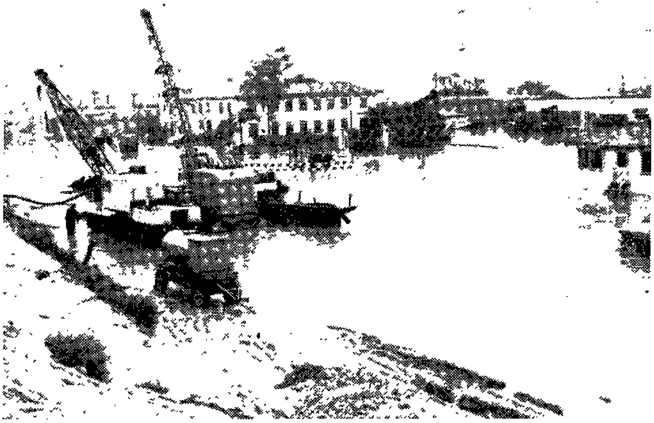


FIGURE 5. *Flooded Area Due to Subsidence*

FIGURE 6. *Buckled Pipelines*

Some early predictions ranged from 2.1 meters (7 ft.) to 3.6 meters (12 ft.) at the center of the bowl, but these were soon exceeded. Later estimates ranged as high as 22 meters with most investigators predicting between 9 to 13,5 meters (30 to 45 ft.).These predictions were made before it was known that repressurization of the oil reservoirs by water injection would stop subsidence.

A massive repressurization program, which started in 1958, has succesfully reduced the surface area and vertical rate of subsidence. The rate of vertical movement at the historic center of the bowl was reduced from a maximum of 71 cm (28 in.) in 1951 to 0.0 cm per year by 1968 (fig. 4).

4. EXTENT OF DAMAGE

The horizontal movements associated with the land subsidence built up great stresses in the surface and near-surface structures. The elastic limit of ordinary construction materials was easily exceeded. Evidence of horizontal movements was manifested on the surface by buckling of asphalt paving and railroad tracks. Buried pipelines often buckled when the overburden was removed, (fig. 6) showing the great stress imposed by the horizontal movements. Large buildings were among the most seriously affected structures due to the shortening of the ground, which pulled the foundation system with it, while the more rigid roof system successfully resisted the movement. The result was shear failures in the gunite walls and cracking of columns (fig. 7). A transit shed built with concrete walls and steel frames showed buckling of side trusses which caused compression failure of the concrete lintel in the exterior wall (fig. 8).

The Commodore Heim Bridge, a lift bridge which connects Terminal Island with the mainland to the north, suffered considerable damage (fig. 9). This bridge and its elevated approach roadways, about 1 220 meters (4 000 ft.) long, underwent approximately 2.3 meters (7.5 ft.) of shortening due to horizontal movements. The heavily reinforced concrete columns within the pier structure of the bridge were sheared off by the horizontal movements (fig. 10). The supporting towers moved horizontally and were tilted out of position making it impossible to operate the bridge.

Severe shear forces were imposed on the oil well casings by the earth movements and caused widespread casing damage. These subsurface stresses were relieved several times by sudden earthquake generating horizontal movements along claystone and soft shale beds between 450 and 600 meters below the surface. As a result of these movements, steel casings of several hundred oil wells were sheared or severely damaged along the planes of movement. Five such earthquakes were recorded between November 1949 and April 1961. A movement of 23 cm (9 in.) was observed along one subsurface horizon at about 470 meters (1 550 ft.) after one of the earthquakes. A slow continuing or "creeping" horizontal movement was also evident between the periods of earthquakes as many oil wells were continually being damaged along suspected of movements. Evidence of well damage was manifested by protrusions of tubing and casing at well heads, constriction of casing diameters, corkscrewing of pulled pipe and failure of liner hangers (fig. 15).

5. REMEDIAL WORK

(*a*) SURFACE STRUCTURES

As early as 1940, some remedial work was initiated at the waterfront area. As previously stated, it was imperative that the land area and the surface structures be protected from inundation by the sea. This protection took the form of nearly every type of engineering

FIGURE 7. *Shear Cracks on Wall*

construction work, including the raising of land areas with earth fills, raising of wharves and buildings, a complete replacement of badly damaged structures and facilities, construction of earth dikes, raising of bridges and approaches, increasing the height of bulkheads and rebuilding of railroad tracks and streets to provide access to the facilities. An interesting example of surface remedial work is shown in figure 13, a transit shed damaged by horizontal movements. To remedy the conditions, contraction-expansion joints were cut entirely though the width of the building approximately 60 meters (200 ft.) apart. As

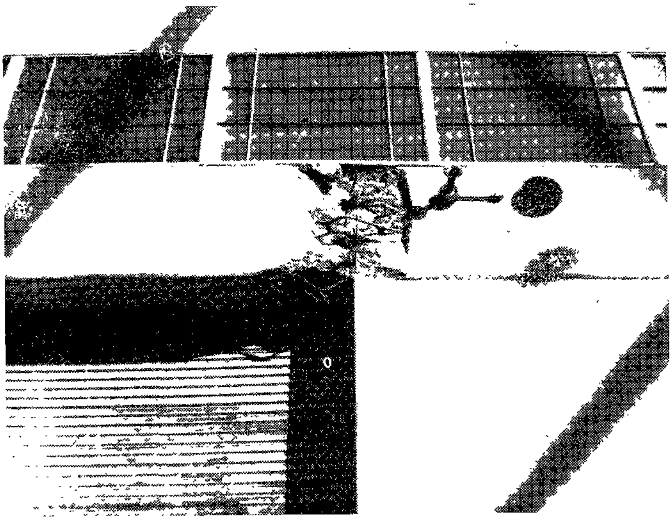


FIGURE 8. *Crushed Concrete Lintel*

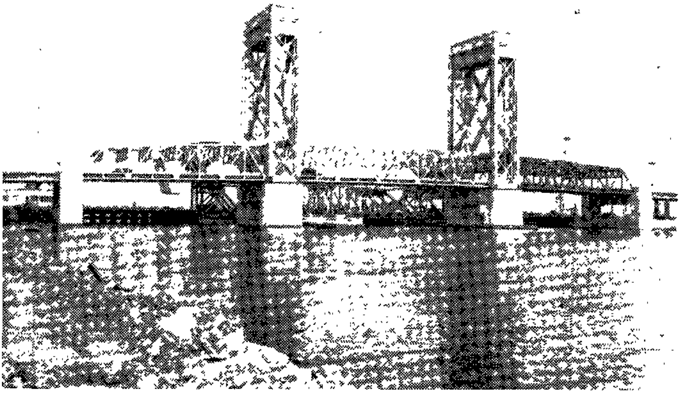


FIGURE 9. *Commodore Heim Bridge*

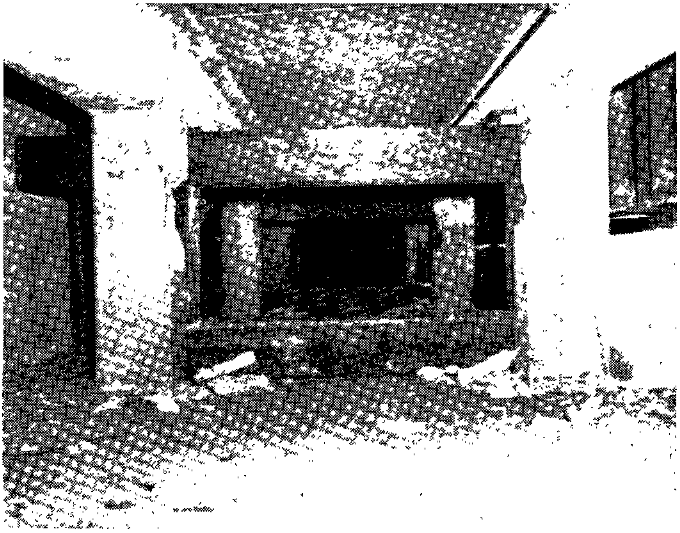


FIGURE 10. *Sheared Bridge Columns*

the threat of inundation of the area increased, however, it was physically lifted, underfilled around and lowered on new foundations at higher elevation. It has been estimated that over one hundred million dollars have been spent for surface remedial work due to subsidence.

(*b*) OIL WELLS

To prevent inundation of oil wells in seriously affected areas, a large number of wellheads were raised during land fill operations (figs. 11 and 12). Oil wells which were damaged

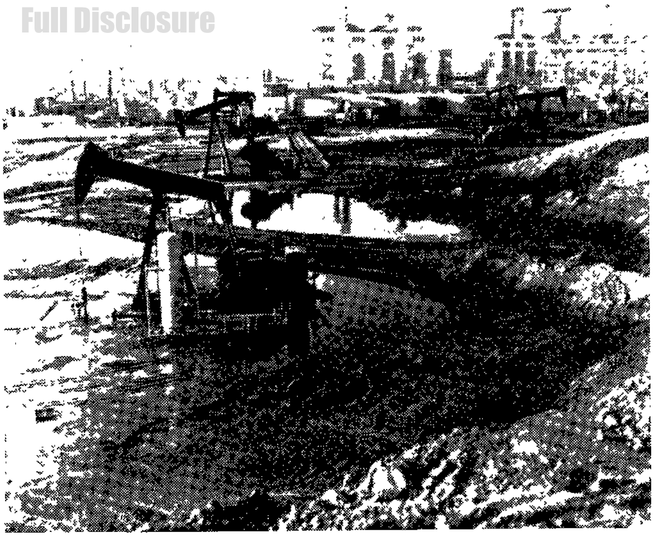


FIGURE 11. *Oil Wells Before Raising*

beyond repair by subsurface horizontal movement were abandoned, but many were replaced by new ones. Partially damaged wells were repaired by installing smaller diameter casing opposite the damaged section. In order to protect new oil wells being drilled within the area where subsurface horizontal movement was anticipated, a unique oil well completion technique was designed which allowed a small amount of subsurface horizontal movement to occur without shearing the well casing (fig. 16). The design provided for

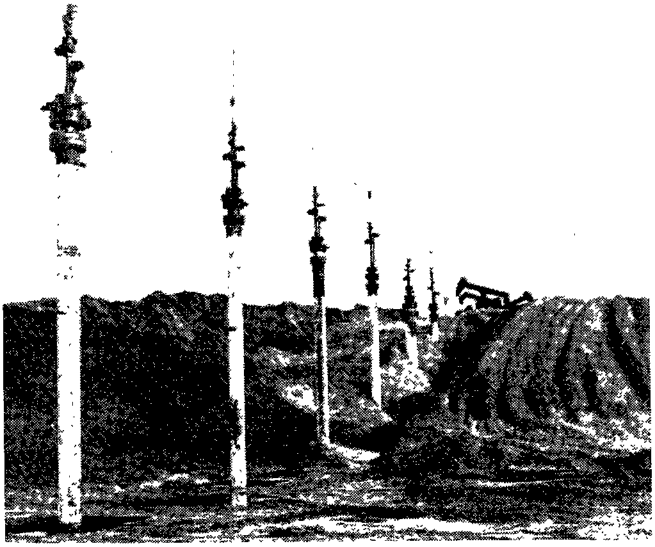


FIGURE 12. *Raising Oil Wells During Land Fill*

enlarging the usual 30 cm (12-1/4 in.) hole to 76 cm (30 in.) hole straddling the suspected interval between 425 meters (1 400 ft.) and 600 meters (2 000 ft.). Normal size casing was run inside the hole and the 76 cm (30 in.) cavity known as the "bell hole", was filled with high gel oil-base compound resembling asphaltic mastic. The technique was so successful that it became the standard completion method for many years in areas where subsurface movements were anticipated. It was discontinued during recent years due to the success in abating subsidence. It is estimated that the cost of damage to oil facilities due to subsidence has exceeded twenty million dollars.

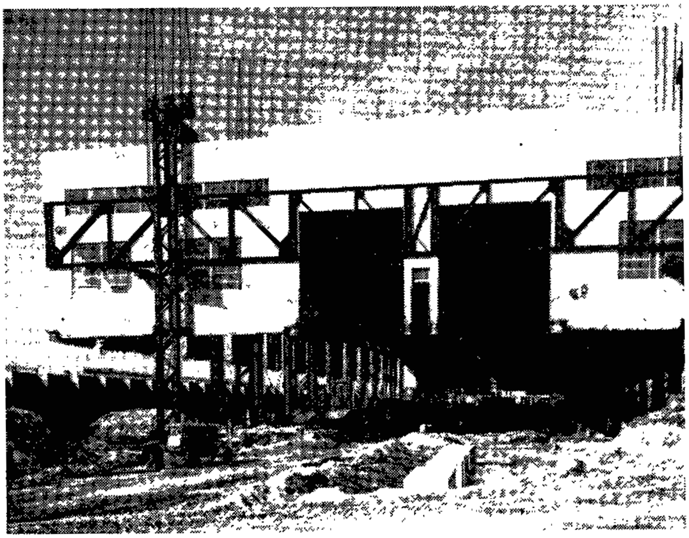


FIGURE 13. *Raising of Transit Shed*

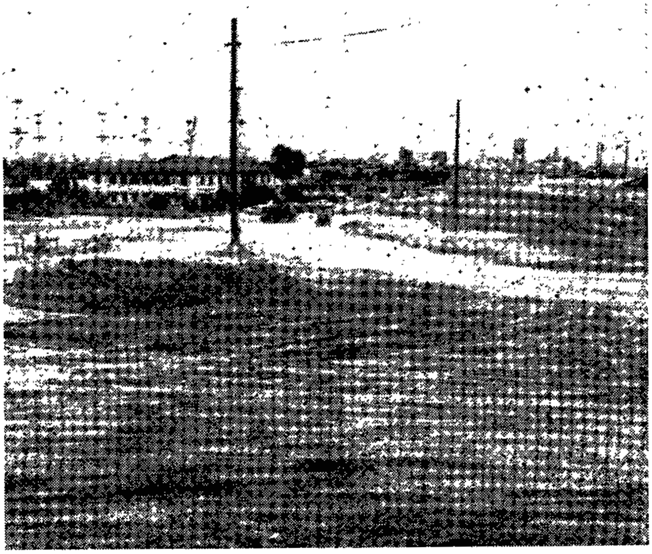
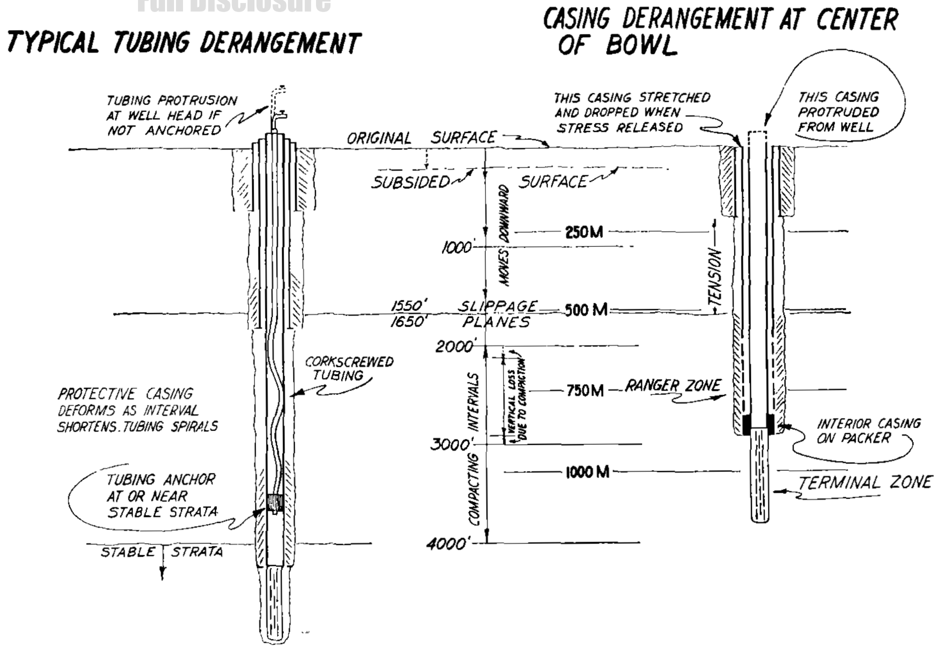


FIGURE 14. *Raising of Land Surface*


TYPICAL TUBING DERANGEMENT

CASING DERANGEMENT AT CENTER OF BOWL

Figure 15. *Effect of Vertical Movement on Well Casing and Tubing*

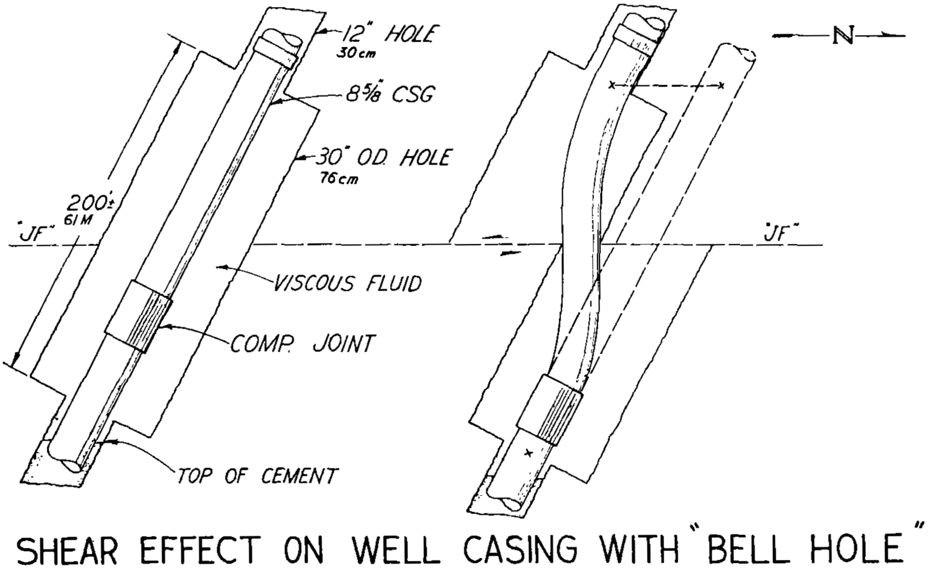

SHEAR EFFECT ON WELL CASING WITH "BELL HOLE"

Figure 16. *"Bell Hole" Protection of Well Against Horizontal Movement*

6. CAUSE OF SUBSIDENCE

The cause of subsidence and the mechanics of compaction of subsurface rocks in the Wilmington Field are discussed in greater detail in the companion paper prepared for this Symposium (Allen and Mayuga, 1969). Several possible causes of subsidence were investigated by many authorities including geologists, engineers, soil mechanics experts, and mathematicians. Among the possible causes investigated were:

1. Lowering of hydraulic head due to ground water withdrawal;
2. Oil reservoir compaction due to gas and fluid withdrawal;
3. Compaction of shales and siltstones interbedded with the oil sands;
4. Surface loading by land fill and building facilities;
5. Vibrations due to land usage;
6. Regional tectonic movements and local movement along known faults in the field;
7. Lack of structural rigidity of the anticlinal structure and overlying sediments;
8. Lack of preconsolidation in sediments.

Regional tectonic movement, ground water withdrawals, surface loading and vibrations due to land usage may have all contributed to the land subsidence but the magnitude of vertical movement that has taken place is far greater than could be attributed to these causes. Most investigators agreed that the withdrawal of fluids and gas from the oil zones and the consequent lowering of subsurface pressure caused compaction in the oil sands and interfingered silts and shales. The relative amount contributed to subsidence by the shales and the sands has been a controversial issue. An interesting correlation of rate of subsidence with rate of oil production is shown in figure 4. The maximum subsidence rate of 75 cm (28 in.) per year was reached in 1952, only eight to nine months after the primary peak production of oil was reached in the area. Figure 1 also shows an interesting relationship between the deepest part of the subsidence bowl and the crest of the subsurface oil structure where the largest gross oil production per unit surface area had been obtained. Figure 3 shows a relationship between cumulative primary oil production and cumulative subsidence.

To determine the location and magnitude of compaction of the subsurface formations, a casing joint measuring method, using a magnetic collar detecting device, was developed. Results of these collar locating surveys are described in another paper dealing with mechanics of compaction (Allen and Mayuga, 1969). In general, most of the compaction apparently took place in the oil zones between 600 and 1 200 meters.

7. REPRESSURIZATION PROGRAM

Although surface remedial work which was previously described kept the area in operation, it was obvious to most observers the ultimate answer had to be the abatement of subsidence. The apparent solution to the problem, based on several studies, was to repressure the oil reservoirs by water injection. By 1961, after resolving the complex legal, engineering and economic problems involved, a full scale water injection operation was in progress in the Long Beach harbor area. Approximately 174,900 cubic meters (1.1 million barrels) of water per day are currently being injected into the field. It is estimated that a total of 366 million cubic meters (2,3 billion barrels) have been injected since the expansion of the waterflood operations in 1958. Subsidence has now been stopped over a large portion of the field and the area has been reduced from 50 square kilometers (20 sq. miles) to 8 square kilometers (3 sq. miles). A small rebound has occurred in areas of heaviest water injection. (Allen and Mayuga, 1969).

In addition to ameliorating subsidence, the water injection program has also been a great economic success, as shown by the increase in daily oil production since 1959 (fig. 4). Approximately 75 percent of the present daily production rate in the Long Beach harbor area is credited to water injection stimulation. Water currently being used for injection is sea water produced from shallow beds directly connected with the ocean. Produced oil field water is also being injected into the formations. Before the end of 1969, the largest operator in the field will commence the injection of "renovated" sewage water which will help reduce the use of high sulfate-bearing sea water and produced brine.

8. SUBSIDENCE SURVEILLANCE PROGRAM

As a subsidence surveillance program, the City of Long Beach establishes the elevation of approximately 900 bench marks within the affected area on a quarterly basis. Reservoirs are also being closely monitored by periodic subsurface pressure surveys in selected wells. Tidal gauges have been installed on the drilling islands off Long Beach as a means of detecting subsidence. Several strategically located wells are also surveyed periodically by the "collar counting" technique to detect any changes in casing joint lengths which would be an indication of subsurface compaction.

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DISCUSSION

Intervebtion of Dr. J.F. ENSLIN (Republic of South Africa)

Question:

What machinery, if any, exists in the U.S.A. whereby property owners may legally be entitled to claim compensation in the event of damage to their properties as a result of surface subsidence due to extraction of oil?

Answer of Dr. MAYUGA:

As you may have heard, we did have a lawsuit in Long Beach. The U.S. Navy, with their naval shipyard in the area and who has no interest at all in the oil, sued the City of Long Beach, the State of California, who is our partner in this oil production, and all the oil operators in the area for damage to their installations allegedly due to subsidence. That case was never actually adjudicated, because a compromise of financial settlement was made. So the responsibility was not actually established by the courts.

Most people who have been damaged in the Long Beach area are themselves involved in oil operation and received benefits from the oil production. I do not know yet what the responsibility would be or who would be liable, if someone files a claim. I think, this is a good case for lawyers. This will be argued for some time. We thought the U.S. Navy's case against the oil operators, including the City of Long Beach, would establish liability but it did not. The case was not adjudicated.