SUBSIDENCE CONTROL AND URBAN OIL PRODUCTION - A
CASE HISTORY BEVERLY HILLS (EAST) OIL FIELD, CALIFORNIA

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Abstract
The City of Los Angeles has permitted Urban oil producing operations
for the past 20 years in the belief that the risk of significant oilfield
subsidence is negligible and in the knowledge that should slight negative
changes in the surface elevations be noted at or near the outset of pro­
duction measures can be taken to abate the condition before damage to
surface improvements could occur. Soon after the Beverly Hills (East)
Oilfield had been discovered in December 1964, it became apparent that a
major hydrocarbon reserve had been found in an urban area. Early in the
life of the field it was determined that pressure maintenance operations
would prove economically attractive and water injection was begun in
December 1969. A cooperative venture to monitor precisely the ground ele­
vations over the field area was initiated in 1966 by establishing a net­
work of benchmarks to add detail to those benchmarks previously established
by the City of Los Angeles. Because a history of ground movement existed
in the Beverly Hills area prior to first production and so little rock
physics or reservoir data were available, the operators constructed an
empirical model to aid in the prediction of the potential for surface sub­
sidence. By gathering the essential data to apply in the model, the oper­
ators concluded that the potential for surface subsidence from oilfield
operations would be negligible. The operators also developed a procedure
for evaluating the survey records in order to separate oilfield related
ground movements from other possible causes.

Introduction
The City of Los Angeles, situated on top of one of the great petroleum
provinces of the world, has been dealing with oilfield subsidence since 1945.
So dramatic was the classic case at Wilmington that oil production in urban
areas is no longer permitted without reasonable assurance that similar
events will not occur. In 1964, after the Beverly Hills (East) Oilfield
had been discovered in two separate core holes drilled by the Standard Oil
Company and the Occidental Petroleum Company, both operators and the City
Government recognized a potential problem. Working together under the
existing city oil ordinance, a workable solution was devised for monitoring
for oilfield subsidence which permitted oil development to move ahead in a
densely populated urban area.

Oilfield History
The Beverly Hills (East) Oilfield is located within an East-West
trending elongate complexly folded and faulted anticline situated on the
Northwesterly rim of the Los Angeles Basin at the common boundaries between
the Cities of Beverly Hills and Los Angeles (Figure 1). Productive limits
eventually encompassed approximately 843 acres within which 6,200 indi­
viduals are currently receiving royalty payments. Depth of the productive
formations ranges from 3,200 feet below the surface at the structural
crest to over 3,000 feet in the deepest zones. A simplified structure
contour map drawn at the top of the main zone is represented by Figure 2.
Table 1. Beverly Hills (East) Reservoir Data.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Repetto</th>
<th>Miocene Main</th>
<th>Miocene Deep</th>
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<tr>
<td>Year of First Production</td>
<td>1967</td>
<td>1966</td>
<td>1967</td>
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<tr>
<td>Reservoir Area (Acres)</td>
<td></td>
<td>840</td>
<td></td>
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<tr>
<td>Depth to Top of Zone (ft.)</td>
<td>3200</td>
<td>5350</td>
<td>6750</td>
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<tr>
<td>Maximum Width (ft.)</td>
<td>2000</td>
<td>3300</td>
<td>2300</td>
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<tr>
<td>Ratio of Depth/Width*</td>
<td>1.6</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Net Sand Thickness at Crest (ft.)</td>
<td>535</td>
<td>455</td>
<td>425</td>
</tr>
<tr>
<td>Average Porosity (% bulk volume)</td>
<td>28.6</td>
<td>23.1</td>
<td>20.3</td>
</tr>
<tr>
<td>Average Permeability (millidarcies)</td>
<td>265.0</td>
<td>108.0</td>
<td>22.0</td>
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<tr>
<td>Interstitial Water (% pore space)</td>
<td>22.0</td>
<td>22.7</td>
<td>26.0</td>
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<tr>
<td>Original Oil in Place (barrels/acre-feet)</td>
<td>1349</td>
<td>990</td>
<td>710</td>
</tr>
<tr>
<td>Original Solution Gas—Oil Ratio (standard cubic feet/barrel)</td>
<td>500</td>
<td>665</td>
<td>1040</td>
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<tr>
<td>Initial Formation Volume Factor (volume/volume)</td>
<td>1.283</td>
<td>1.40</td>
<td>1.64</td>
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<tr>
<td>Original Reservoir Pressure (psig)</td>
<td>2200</td>
<td>2850–2920</td>
<td>3300</td>
</tr>
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<td>Saturation Pressure (psig)</td>
<td>2200</td>
<td>2680–2975</td>
<td>3300</td>
</tr>
<tr>
<td>Datum (feet subsa)</td>
<td>4700</td>
<td>5700</td>
<td>7000</td>
</tr>
<tr>
<td>Reservoir Temperature (°F)</td>
<td>170</td>
<td>200</td>
<td>215</td>
</tr>
<tr>
<td>A. P. I. Gravity of Oil (°)</td>
<td>30–35</td>
<td>22–30</td>
<td>40–45</td>
</tr>
</tbody>
</table>

*Ratio of Depth/Width at Wilmington Ranger Zone 2300:15000.

Fig. 1. Oilfield Location and Survey Traverse Line Map.
This structure is noteworthy in that the Southerly flank is vertical to overturned and is characterized by an active natural water drive within the field. Cross Section A-A', (Figure 3) is drawn North-South from the Santa Monica Mountains to the Inglewood Fault and passes through the middle of the Beverly Hills (East) Field. The Santa Monica Fault is on the North end of the cross section and separates the intrusives and metamorphic rocks from the basinal rocks to the South. The Southerly acting crustal pressure has also generated a complex series of en echelon folds, some of which have ruptured due to the intensity of folding and have developed thrustal faults similar to the Santa Monica Fault. As is indicated on the cross section, these faults are not major faults as they become obscure higher in the section and are apparently limited to the Miocene formations. The field has produced a net voidage of oil, water and gas from all reservoirs through December 1975 of approximately 234,000,000 barrels. Maximum daily production reached 34,000 barrels of oil per day during September of 1963 from 62 producing wells.

History of Earth Movements

Southern California has long been known as a tectonically restless province. In connection with oil production from an urban area, it is therefore essential that the history of earth movements be reviewed and understood before substantial production is permitted. Fortunately, the record of such movements is both extensive and has been thoroughly investigated (Grant 1939). Since 1934, the City and the County of Los Angeles have leveled over an extensive network of precise level lines (Figure 1). These survey records were used as part of the earth movement evaluation by Occidental and Standard for the Beverly Hills (East) Field. Although the available leveling records in the area of study go back to the 1920's, their erratic coverage did not allow for the construction of good regional ground movement maps; but by 1949, the density of these traverse lines in this area was such that one could begin to construct regional maps using the 1949 data. Figure 4 shows the annual rate and distribution of ground movement that was occurring in the area for the period 1949 to 1963. This is prior to any fluid extraction from the Beverly Hills (East) Oilfield. In addition to reviewing this information, Occidental and Standard decided to establish their own leveling network over the area of indicated oil accumulation prior to any fluid extraction. With this background in hand, Occidental and Standard set about analyzing and describing the various possible causes of pre-production ground movement that are apparent in Figure 4.

Possible Causes of Ground Movement

Standard and Occidental have used an empirical approach for predicting potential subsidence wherein each of the possible contributing factors have been considered, weighed and, as necessary, received further evaluation. Many of the factors causing earth movement are not perfectly known. With sufficient data, however, it has become possible to isolate certain components and determine which may be contributing to the movement. Whenever there are multiple causes, difficulty naturally arises in estimating the quantitative effect of each. Those variables which the author considered important in the evaluation of earth movements -- particularly oilfield related -- have been organized into the following empirical model and were applied to the Beverly Hills (East) Field prior to production in order to estimate the oilfield subsidence potential.

1. Tectonic Activity.
2. Compaction of Sediments Due to Earth Surface Loading or Wetting.
Fig. 2. Beverly Hills (East) Oilfield, structure contour map on top Miocene Main Zone.

Fig. 3. Inglewood to Santa Monica mountains cross section.
3. Compaction and Consolidation Due to Vibration.
4. Subsurface Solution or Cavitation.
5. Subsurface Pore Pressure Reduction.
      (Note: These may be applied to all of the foregoing items.)
      (1) Regional Structural Conditions.
         (a) Geological Structure.
         (b) Depth of Production.
         (c) Breadth and Length of Accumulation.
         (d) Thickness of Productive Zones.
      (2) Physical Properties of Producing Zones.
         (a) Porosity.
         (b) Lithology.
         (c) Preconsolidation and Cementation.
      (3) Formation Temperature Changes or Thermal Properties.

In the Beverly Hills (East) Area, variations in recorded ground movement were too great and too complex to be explained by only one or two causes listed above. By analyzing these recorded ground movements in light of each of the possible causes, it can be shown that in this area the movements were resulting from the combined effects of tectonism, near-surface fresh-water fluid withdrawals and, to a slight extent, the recently deeper oilfield fluid withdrawals. For this empirical approach to be effective, it has become necessary to rely on correlation techniques wherein the survey records are used as the base to which all other factors are compared on a time-of-occurrence basis (i.e., formation pressure decline, earthquake instance, the lowering of fresh water tables, etc.). Figure 5, a graphic display of surface changes in elevation at a benchmark near the center of the Beverly Hills (East) Oilfield and fluid level changes in a shallow water well located nearby should be referred to for the history of ground movements in the Beverly Hills Area since 1935.

Tectonic Activity
That the Beverly Hills-Hollywood area is, and has been, tectonically active is readily apparent from the existing, folding, faulting and sedimentary patterns. Also, recorded seismic activity (Figure 6), surface physiographic features and the fault displacements of quaternary sediments testifies to the restlessness of the region. How much, where and at what rate the earth has moved as a result of this activity has been revealed by the recourse to proper monitoring systems. For example, surface movements have been measured by precise surveying techniques and the seismic activity has been recorded by the seismographs.

Compaction of Sediments Due to Either Surface Loading or Wetting
There are no indications that any significant part of the present-day earth movements in the immediate area of the Beverly Hills (East) Field have resulted from surface loading or wetting. The fact that the water table was, at one time, at or near the present surface precludes shallow compaction from surface wetting in the area (Mendenhall, 1905, and Ebert, 1921).

Compaction and Consolidation Due to Vibration
The only events capable of causing subsidence by vibration are earthquakes, although some very minor local movements may be occurring as a result of surface traffic. Recent leveling traverses East of the Beverly Hills (East) Oilfield and along Pico Boulevard showed a marked acceleration and subsidence between level runs in October 1970 and March 1971. It is
Fig. 4. Annual rate of earth movement for the period 1949 to 1963.

Fig. 5. Graph of surface change in elevation at B.M. 120 and hydrograph of fluid levels at B.H. City water well No. 4.
believed that this acceleration resulted from vibratory subsidence set up within the shallow fresh water aquifers by the February 9, 1971, magnitude 6.4 San Fernando Earthquake.

Subsurface Solution or Cavitation

There is no evidence that any of the subsidence in the Beverly Hills Area has resulted from subsurface solution or cavitation.

Subsurface Pore Pressure Reduction (Fluid Withdrawal)

One of the most important criteria related to oilfield subsidence is the reduction or change in pore pressure within the subsurface formations undergoing depletion. When the formation pressure is either reduced or increased deformation within the particular reservoir will occur. Such a change in formation pressure will result in a load transfer from the fluid phase to the solid matrix, or the reverse. The magnitude of the resulting deformation is dependent upon several other variables which interact with each other. Because of the difficulty in adequately defining each of these variables at the time of first hydrocarbon discovery, a rigorous mathematical analysis of the eventual magnitude of deformation is impossible. An early assessment of the potential compaction can, however, be made by using the empirical approach mentioned earlier.

Studies discussed earlier have revealed the fact that some of the subsidence in the area is related to shallow fresh water withdrawals. The same controlling geologic characteristics discussed in considerable detail under Oilfield Related Subsidence can also be applied to shallow fresh water aquifers. To determine the extent to which shallow groundwater withdrawals were contributing to subsidence in the area, the distribution and thickness of the aquifers were mapped (Figure 7). The changes in the water table elevations within this aquifer system were then compared to the overlying ground movement measurements (Figures 3, 5 and 3).

Subsidence which might be attributed to oilfield production is depicted on Figures 5, 9 and 10. To further evaluate this ground movement, a bench mark within the survey system but removed from the influence of fluid withdrawals was selected as a constant datum. In this case, Bench Mark No. 32 at the corner of Western Avenue and Wilshire Boulevard was selected because of its historical stability.

Figure 11 shows the amount of movement based on mean sea level datum that have occurred in the area of Bench Mark No. 32 between 1967 and 1973, as the possible result of tectonic movement, surveying error, and minor local building or traffic disturbances. All of the elevation changes shown in Figure 10 were adjusted based on Bench Mark 32 as a datum to produce Figure 12. This new map (Figure 12) probably represents the rate and areal distribution of subsidence related to oilfield fluid withdrawals during this period. A rate and amount too small to be considered serious. Figure 13, an annual rate of earth movement map based on Bench Mark 32 as datum for the period October, 1972 to October, 1973, shows the arresting affect of both the water injection project and the declining production, on the rates of subsidence in the oilfield area. The total field production history can be seen on Figures 9 and 14.

Controlling Geologic Characteristics of Beverly Hills (East) Oilfield Subsidence

Each of the controlling geologic characteristics listed in the empirical model were set forth prior to oilfield production and reviewed again during the progress of field development and production. Numerical values for some of these characteristics are set out in Table 1. It can be seen on analyzing the amount of subsidence that occurred that there were some very definite reasons why the amount of subsidence was not large. First, the regional structural conditions for the Beverly Hills
Fig. 6. Earthquake epicenter map for the period 1934 to 1974, data from California Institute of Technology and USC Geophysical Lab.

Fig. 7. Isochore map of fresh water aquifers. Refer to Fig. 3 for stratigraphic position.
Fig. 8. Graph of surface movement at B.M. USGS 118 and hydrograph of water wells located in Section 3-T2S/R14W.

Fig. 9. Graph of surface movement at B.M. 120 and daily production rates from the Beverly Hills (East) Oilfield.
Fig. 10. Annual rate of earth movement for the period March 1967 to March 1971, based on a mean sea level datum.

Fig. 11. Adjustment of B.M. No. 82 to a constant datum as of March 1967.
Fig. 12. Annual rate of earth movement for the period March 1967 to March 1971, based on B.M. No. 82 as datum.

Fig. 13. Annual rate of earth movement for the period October 1972 to October 1973, based on B.M. No. 82 as datum.
Fig. 14. Beverly Hills (East) Oilfield, total barrels of reservoir voidage and injection.

(East) Field vary from a tight asymmetrical fold within deep Miocene sediments to a broad gentle fold in the shallower lower Pliocene rocks. The significant oil accumulation occurs within the deep, tightly folded section which reflects, along with the associated thrust faulting, strong north-south compression. This configuration should furnish arch support within both the producing intervals and the overlying capping rock (Figure 3).

The ratios of the breadth of accumulation to depth for each significant zone are listed in Table 1. Thickness of the oil productive main section is impressive on the south flank, where the beds are standing nearly vertical. Oil productive thickness on this flank ranges up to 1,000 feet, whereas, on the north flank, which is more gently dipping, the productive section averages about 650 feet in thickness. There is also the strong likelihood that these deeper Miocene reservoirs are more resistive to consolidation due to retained tectonic prestressing.

Second, the physical properties of the producing zones have a bearing on the degree of consolidation which may occur when and if a sizeable load transfer from the fluid phase to the rock matrix occurs. Of the rock characteristics that exert some control in the Beverly Hills (East) Field, the lithology and preconsolidation and cementation probably are the most effective. From ditch samples, cores and sidewall samples, it was determined that the reservoir rock is a firm clastic with intergranular porosity. The porosity in the main producing horizon and shallow zones is quite good, ranging from 20 to 30%.

The third property, formation temperature changes that may result in contraction or expansion of the reservoir rock, does not appear to apply in this instance.
Conclusions

1. Regulations of the City of Los Angeles have been effective in controlling oil well drilling and production within the city.

2. The Beverly Hills (East) oilfield is situated in an area undergoing regional subsidence as a consequence of tectonic forces. Imprinted upon this regional downwarping are subsidence components arising from shallow water production and deeper oilfield fluid withdrawals. Singly or in combination, these forces produce subsidence measurable in no more than a few hundredths of a foot per year.

3. Precise leveling surveys conducted by Standard Oil Company of California and Occidental Petroleum Corporation have been effective in detecting and monitoring surface elevation changes over the Beverly Hills (East) oilfield. Similarly, these surveys have demonstrated that subsidence attributable to oilfield operations is being arrested by subsurface reservoir pressure maintenance based on water injection.

4. Oilfield subsidence, which in rare cases has been extremely damaging, can be detected at an early date following the advent of production by precise leveling surveys. Corrective measures can be instituted to arrest subsidence before damage to surface structures or wells occur.

5. Oilfield subsidence may be due to a wide assortment of causes, chiefly geologic in nature, and, therefore, its prediction may not be quantitatively accomplished. From a qualitative point of view, however, the construction of a model using empirical components may be extremely helpful in forecasting subsidence prospects and estimating their magnitude. Subsurface geologic data, coupled with other related information, are indispensable in the accuracy of such forecasts.

Acknowledgements

The author wishes to express his appreciation to the Standard Oil Company of California for permission to prepare and publish this paper, and to Messrs. A. O. Spaulding and I. I. Dagan for their valuable suggestions and discussion.

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