Publication n°121 of the International Association of Hydrological Sciences
Proceedings of the Anaheim Symposium, December 1976

CALCULATED HORIZONTAL MOVEMENTS AT BALDWIN HILLS, CALIFORNIA

Kenneth L. Lee
Professor, School of Engineering and Applied Science
University of California, Los Angeles, California

Abstract

The paper demonstrates that a linear elastic finite element calculation can provide a good indication of the ground surface subsidence and horizontal movements caused by fluid removal from an oil field. The case history used for comparison purposes was the Inglewood Oil Field, Los Angeles, California, which included the site of the Baldwin Hills dam failure in 1963, believed by many to be related to the oil field induced ground movements.

Sommaire

L'article démontre comment l'utilisation des éléments finis en élasticité linéaire peut donner une bonne indication des tassements en surface et des déplacements horizontaux provoques par l'extraction de fluide dans un champ de pétrole. Le cas considéré pour illustration est le champ de pétrole Inglewood à Los Angelès, California qui englobe le site du barrage de Baldwin Hills, dont la rupture en 1963 est considérée par beaucoup comme lieé aux mouvements de surface causés par le champ de pétrole.

Introduction: This paper reports the results of a study to check the validity of using a linear elastic finite element approach for calculating the nature and magnitude of horizontal ground movements to be expected from subsidence due to fluid withdrawal from a confined oil field. Geotechnical engineering abounds with examples of horizontal ground surface movements which develop in association with vertical subsidence. The best known examples involve mining operations, but other examples include soil consolidation and pumping of fluids (oil and water) from underground reservoirs. Many methods have been proposed for quantifying the amount of vertical and horizontal movements that will develop under various natural and man imposed conditions, of which the finite element method is thought to be the newest and most versatile. It has been shown to give reasonably good checks against field case history data for some model tests and dam settlement (Lee and Shen, 1969), salt mine collapse (Lee and Strauss, 1969) and subsidence due to oil pumping at Long Beach, California (Lee, 1975).

An additional case history comparison between observed and computed ground movements caused by oil pumping from an underground reservoir is presented herein. This case history is particularly significant because of the failure of an important earth dam which was located in the subsidence bowl. Although many detailed engineering investigations have been conducted and expert opinions expressed on factors pertaining to this dam failure, there still appears to be no consensus of opinion as to whether or not the failure was caused predominantly by the oil field operations (Casagrande et al, 1972; Castle and Youd, 1972; Hudson and Scott, 1965; Investigation, 1964; Jansen et al, 1967; Leps, 1972). This paper does not intend to indicate blame for the dam failure, but rather to investigate the ability of the calculation technique to reproduce the observed ground movements. The dam failure merely adds an interesting and perhaps instructive aspect to the discussion.

Case History Description: Details of the Baldwin Hills area, the underlying Inglewood Oil Field and the dam are readily available so that only a brief summary need be repeated here. The Baldwin Hills area lies within the city of Los Angeles, midway between the International Airport and Downtown. Oil was discovered in 1924 and significant oil production has continued from that time to the present.

A water storage reservoir was constructed during the years 1948 to 1951 by excavating into a hilltop and building an earth dam across a small valley with the excavated soil. On Dec. 14, 1963, the dam failed by eroding a V-notch through the embankment. The ensuing flood damaged a large portion of the city to the north below the reservoir to the extent of about 15 million dollars and killed 5 people.

The ground conditions at Baldwin Hills consist of interbedded shales and sandstones which extend to a depth in excess of 20,000 ft. This sedimentary rock material is similar to that at Long Beach, where some engineering property data are available (7). These Long Beach data were also used in this study because the sedimentary rock was believed to be similar.

The major oil producing zones at Baldwin Hills occur within a depth range of about 1000 to 1500 ft below the surface, but some smaller amounts of oil are produced at depths ranging up to 10,000 ft. Good records of oil reservoir pressures are unavailable (Castle and Yerkes, 1969), but such data as exist suggest that prior to any oil production, the initial pore fluid pressure, u_o, in Southern California oil fields increases hydrostatically with depth, D, below the surface according to the equation, $u_o = \gamma_w D$, where $\gamma_w = 64$ lb per cu ft, the unit weight of sea water. It is further estimated (Investigation, 1964) that the reservoir pressure in the zone of major production reduced to about 30 psi (4.3 ksf) as the oil was removed.

The exact magnitudes of ground subsidence and horizontal movements in the Baldwin Hills area are somewhat uncertain. Two original surveys were conducted in 1911 and 1917 respectively, before oil was discovered. The next surveys were not until after oil production began and considerable movements had developed causing shifts in the basic bench marks. The ground movements presented herein are believed to be approximately correct, at least within sufficient accuracy for the purposes of this paper.

A plan of subsidence rate contours in the Baldwin Hills area (as of 1961) is shown in Fig. 1. The available data do not permit drawing contours of total subsidence. However, the data do define a tpyical bowl shaped subsidence pattern. Vectors of measured total horizontal movements for a known period of time are also shown. As typical in all subsidence cases, the direction of the horizontal movements is toward the center of the subsidence bowl. This leads to extension strains (with the possibility of ground cracks) at the outer edges of the bowl and compression near the center. Indeed, there are numerous ground cracks at the edges of the Baldwin Hills

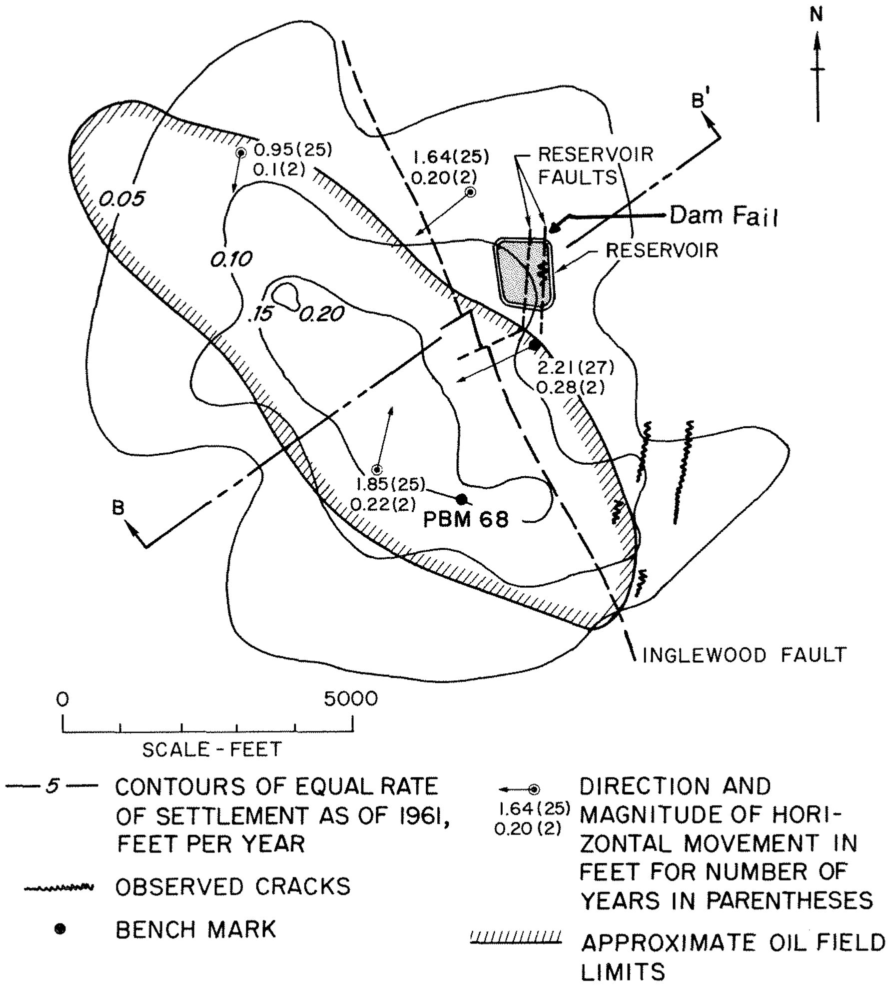

Fig. 1. Horizontal Movements and Subsidence Rates in Baldwin Hills Area

subsidence bowl. The crack pattern is complicated however, by the existence of several pre-existing old near vertical tectonic faults. Two of these faults pass through the Baldwin Hills Dam, and the seepage piping failure of the dam occurred at the location of one of these faults.

One hypothesis (Casagrande et al, 1972) for the cause of the dam failure is that the lining of the reservoir was inadequate and that the material within the fault zone was highly erodable. Thus, when seepage water penetrated through the asphalt lining of the reservoir it then washed out the material along the fault, accelerating with time to produce a complete piping failure of the dam. This action is viewed as being independent of any subsidence induced horizontal extension strains at the fault. An alternate hypothesis

(Leps, 1972) favors the opinion that subsidence led to extension strains at the fault which initiated the above described erosion process.

A photograph looking from south to north over the Baldwin Hills reservoir and dam after failure is shown in Fig. 2. With the water drawn down, a crack could be traced through the reservoir from the V-notch at the top of the photograph to the pavement at the construction joint in the parapet wall at the bottom of the photograph. This crack followed the pre-existing fault trace shown in Fig. 1. Certainly the weak soil in the pre-existing tectonic fault zone contributed to the failure, but the question still remains whether or not the fault opened to develop a crack in the foundation as a result of oil field subsidence induced horizontal ground motion.

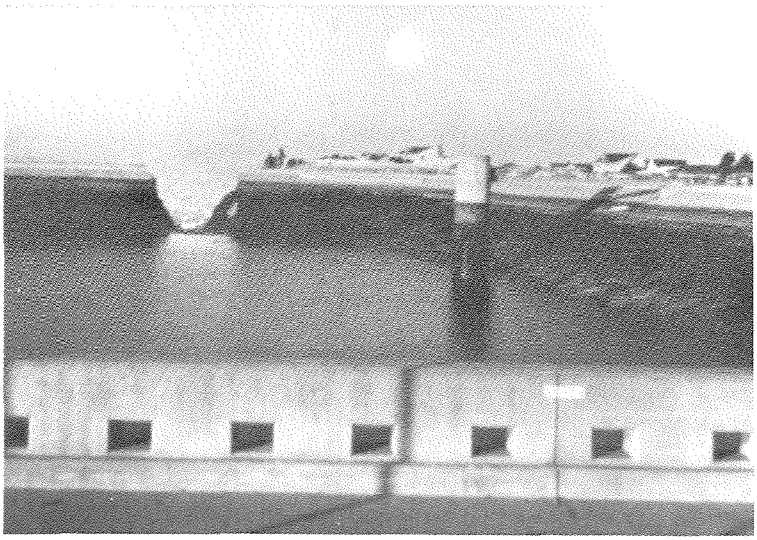

Fig. 2 Photograph of Failed Baldwin Hills Dam Looking North Along Reservoir Faults. Construction Joint has opened and Pavement in Front has Cracked Recently.

A chronological history of significant ground movements and related events at the Baldwin Hills area is shown in Fig. 3. Note the well defined relation between reservoir pressure drop, oil production and ground movements. The data in Fig. 3d are particularly interesting in that they show the widening of a crack in an inspection tunnel which crossed the fault through the reservoir. This extension strain movement continued progressively with the oil production and ground subsidence up to the time of failure. The reservoir pressures (Fig. 3a) were obtained at one of the producing wells. It is expected that the average pressure in the field away from the well would not have reduced as fast as at the well (Castle and Yerkes, 1969).

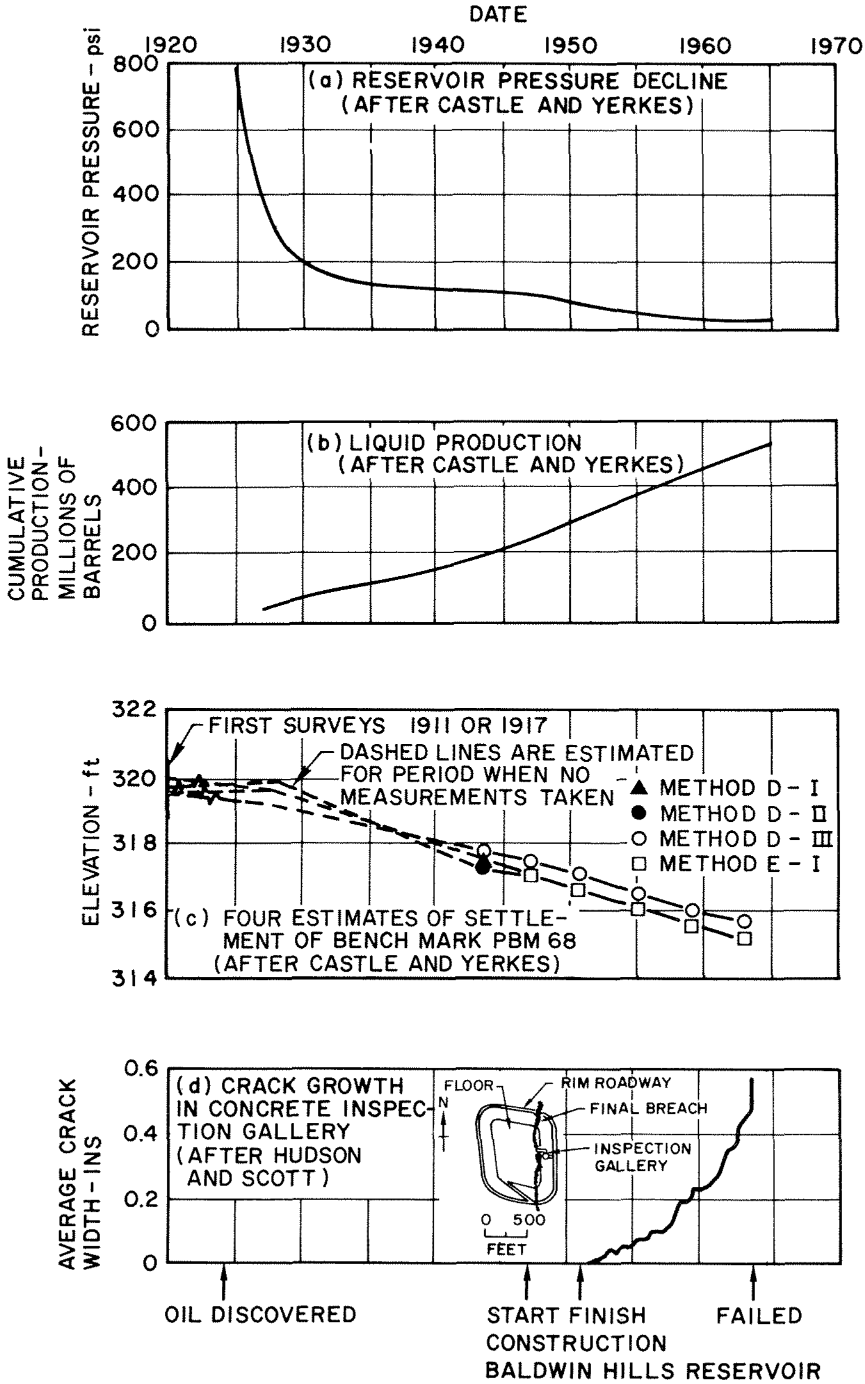

Fig. 3 . Oil Production and Subsidence at the Inglewood Oil Field

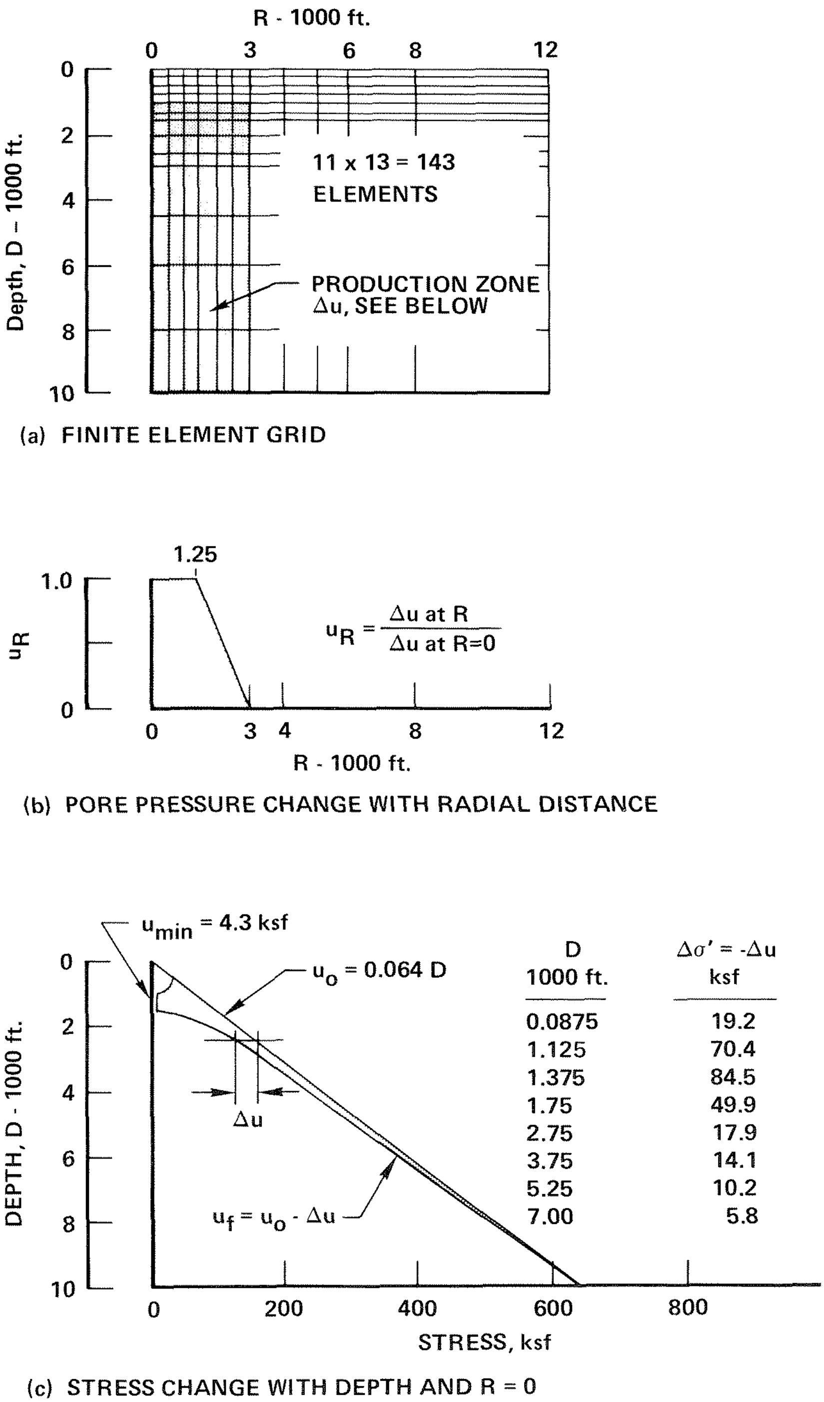

Fig. 4. Finite Element Grid and Stress Distribution

Finite Element Model: The element modeling technique used herein was essentially the same as used by Lee (1975) in a similar study of the movements at the Wilmington Oil Field in Long Beach. The model and the pressure changes are shown in Fig. 4.

The finite element program was a standard axis-symmetric, linear elastic program written by the writer. From the Lee (1975) data, Poisson's ratio was taken to be 0.1 and Young's modulus was assumed to vary with depth (D ft) according to the equation

$$E = 500\ D^{0.5}\ \text{psf} \qquad (1)$$

The loading used to simulate the oil removal was defined in terms of changes in pore pressure throughout the producing zone shown by the shaded areas in Fig. 4. The three dimensional extent and the magnitude of these pore pressure changes were estimated from the known limits of the oil field (Fig. 1) along the Section BB', and the other information described above. No data were available for pore pressure changes in the deep zones, but since the deep zones were not the source of major oil production, it was reasoned that it would likewise not by a zone of major pore pressure change.

Following the basic principle of effective stress and as described by Lee (1975), the only net loading that need be considered in the analysis is the isotropic change in effective stress which is equal and opposite to the change in pore water pressure, $\Delta\sigma' = -\Delta u$. No other loading changes occurred, and the calculations were intended to define the movements caused by only this change in loading. Therefore, the appropriate values of $\Delta\sigma'$ at the center of each element within the shaded producing zone (Fig. 4) were converted to nodal point forces as the sole source of loading.

It should be noted that the extent of the oil producing zone and the pore pressure reduction used in the analysis correspond to the 25 year period, 1937-1962, because the data available to the writer pertained to this period. Note also that the oval shaped producing zone (Fig. 1) has been approximated in the calculations by a circle of radius, R = 2000 ft with an assumed linear transition zone of pore pressure reduction beginning at R = 1250 ft and extending to R = 3000 ft where $\Delta u = 0$.

Calculated Ground Surface Movements: The computer output from a finite element calculation provides detailed information concerning deformations, strains, and stresses at every location within the grid system. For this study, only the movements at the ground surface were of interest, since this was the only location where actual observed field data were available. Note however, that in a previous similar study by Lee (1975), the calculated results at various vertical as well as horizontal locations were of interest since they could be compared with field measured data within the ground as well as at the ground surface.

The calculated ground surface movements at the Baldwin Hills area are shown in Fig. 5 along with field measured data points. In considering a comparison between measured and calculated movements, a few brief comments on the measured data are appropriate. The horizontal movement data over the periods shown in Fig. 1 are believed to be fairly reliable. The three points closest to Sec. BB' have been transferred to this section and are shown in Fig. 5. The vertical subsidence profile follows the shape of the subsidence rate contours in Fig. 1, with magnitude interpolated on the basis of the measured vertical subsidence at bench mark PBM 68 (Fig. 1 and 3) which Castle and Yerkes (1969) believe to be the most correct. The single strain data point was obtained from a measured extension of 0.4 ft in the 1100 ft long NE-SW diagonal of the Baldwin Hills water reservoir between the 13 year period 1950-1963. Assuming that the stretching would be proportional to the measured subsidence at PBM 68 back to 1937, a value of horizontal extension strain of 0.1 percent was obtained for the 25 year period at this location. As can be seen in Fig. 5, there was excellent agreement between the calculated and the observed field ground surface movements along the section BB'.

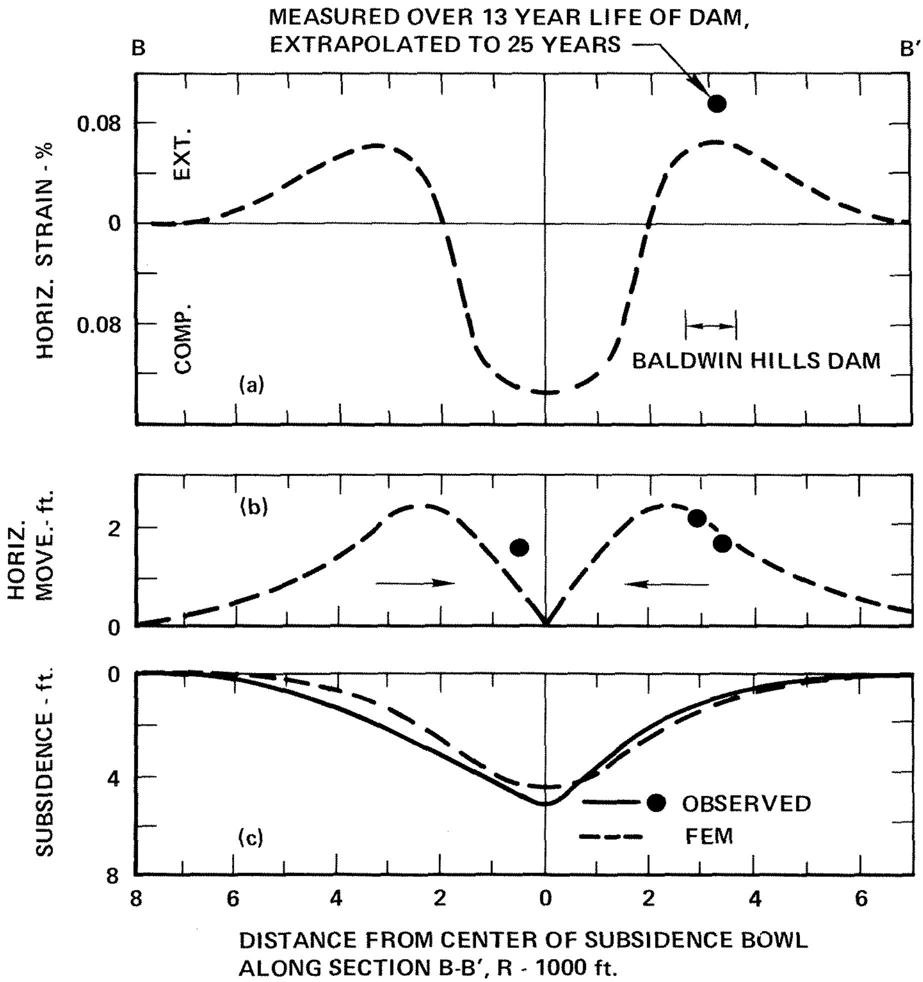

Fig. 5. Observed and Computed Ground Surface Movements at Baldwin Hills Area for 25 Year Period; 1937-1962.

Concluding Comments: A simple linear elastic finite element calculation has been used to calculate ground surface vertical and horizontal movements for comparison with measured field data. The purpose of this study was to check whether this method of calculation would be able to reproduce the observed movements, and therefore would it be reasonable to use the method for future studies of similar problems. The results suggest an affirmative answer to each of these questions. Furthermore, the reader is referred to the cited previous similar studies by the writer which have also produced similar confirming results. Taken together, it would appear that the technique described herein should provide a useful method for predicting in advance the nature of ground surface movements likely to be associated with subsurface fluid withdrawal.

Of course, the accuracy of the predictions depends greatly on the accuracy of the boundary and loading conditions used in the analytical formulation. Nevertheless, the results from this and the previous similar study at the Wilmington field, suggest that with estimates of boundary and loading conditions that should be possible to make in advance, useful results can be obtained. Alternatively, the technique can provide a means of studying the effect of boundary or loading conditions that might be possible to control, such as the extent of the underground fluid zones that are produced and the amount of fluid pressure reduction allowed without resorting to auxiliary fluid pressure injection.

Since the geographical study area for this paper involved the site of the Baldwin Hills Dam, perhaps a brief comment on the application of the results to the dam failure would also be appropriate. The ground strain data (Fig. 5) and the plan view (Fig. 1) illustrate that the dam was situated in the most inappropriate location and orientation from the point of view of ground surface movements caused by fluid removal from the underlying oil field. The dam was located toward the edge of the subsidence bowl where the largest extension strains developed. The embankment was oriented in an approximate radial direction, so that the extension strains in the ground would have the maximum adverse affect by stretching the axis, which would be favorable to crack development. Had the dam been turned by about 90 degrees, the axis would have been parallel to the subsidence contours, which would have led to compressive axial strains as described by Lee (1975) for the Commodore Heim Lift Bridge in the Wilmington field.

Finally, it was unfortunate that the ground contained a weak fault zone also located unfavorably across the dam foundation where the subsidence alone would produce fairly large extension strains. Assuming that the fault was weaker than the surrounding rock foundation, it follows that the extension strains would tend to concentrate at the fault where a crack would develop, as was actually observed.

It is beyond the scope of this paper to speculate on what might have happened without any subsidence or without a pre-existing fault or to suggest responsibility for the failure. The results of the study do indicate however, that the subsidence could be expected to produce substantial extension strains along the axis of the dam, which would be unfavorable to its stability. Thus, had an analysis such as this been performed prior to the dam construction, it would have shown this unfavorable situation and probably led to precautionary or alternative procedures with regard to a water storage facility in the area. Unfortunately, the finite element method had not been invented in 1948 when construction began on the dam.

References

Casagrande, A., Wilson, S. D. and Schwantes, E. D., 1972, The Baldwin Hills Reservoir Failure in Retrospect: Performance of Earth and Earth Supported Strctures, Proceedings of Specialty Conference, ASCE, p. 551-558.

Castle, R. O., and Yerkes, R. F., 1969, A Study of Surface Deformations Associated with Oil-Field Operations: Report of the U.S. Geological Survey, Menlo Park, California.

Castle, R. O. and Youd, T. L., 1972, The Baldwin Hills Reservoir Failure: Discussion: Proc. Specialty Conference on Performance of Earth and Earth Supported Structures, ASCE, v. iii, Purdue University, p. 91-102.

Hudson, Donald E., and Scott, Ronald F., 1965, Fault Motions at the Baldwin Hills Reservoir Site: Bulletin of the Seismological Society of America, v. 55, No. 1, p. 165-180.

Investigation of Failure, Baldwin Hills Reservoir, 1964, Department of Water Resources, Sacramento California.

Jansen, Robert B., Dukleth, Gordon W., Gordon, Bernard B., James, Laurence B. and Shields, Clyde E, 1967, Earth Movements at Baldwin Hills Reservoir: Journal of the Soil Mechanics and Foundations Division, ASCE, v. 93, No. SM4, p. 551-575.

Lee, Kenneth L., 1975, A Mechanism for Subsidence Earthquakes at the Wilmington, California Oil Field : Paper presented at the First International Symposium on Induced Seismicity, Banff, Alberta, Canada.

Lee, Kenneth L. and Shen, C. K., 1969, Horizontal Movements Related to Subsidence: Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 95, No. SM1, p. 139-166.

Lee, Kenneth L. and Strauss, Michael E., 1969, Prediction of Horizontal Movements Due to Subsidence over Mined Areas: Proc. International Symposium on Land Subsidence, held in Tokyo, Publication No. 88, Vol. II, IASH-UNESCO, p 512-522.

Leps, Thomas M., 1972, Analysis of Failure of Baldwin Hills Reservoir; Performance of Earth and Earth-Supported Structures, Proc. of Specialty Conference, ASCE, p. 507-550.