OFFPRINT
from

LAND SUBSIDENCE CASE STUDIES AND CURRENT RESEARCH

Proceedings of the Dr. Joseph F. Poland Symposium

Edited by James W. Borchers

Star
PUBLISHING COMPANY

This offprint is from:
LAND SUBSIDENCE CASE STUDIES AND CURRENT RESEARCH
Proceedings of the Dr. Joseph F. Poland Symposium, edited by James W. Borchers.
Hardcover, 576 pages.
Special Publication No. 8
Association of Engineering Geologists
Sacramento Section and AEG Subsidence Committee

LAND SUBSIDENCE CASE STUDIES AND CURRENT RESEARCH Proceedings of the Dr. Joseph F. Poland Symposium, ISBN: 0-89863-197-1, may be purchased through your local bookstore, from AEG (the Association of Engineering Geologists) and directly from the publisher, at the addresses listed below.

Association of Engineering Geologists
323 Boston Post Road, Suite 2D
Sudbury, MA 01776
(508) 443-4639
fax (508) 443-2948

Star Publishing Company
PO Box 68
Belmont CA 94002
(650) 591-3505
toll-free FAX (800) 382-7591

Identifying Source Mechanisms Responsible for Subsidence Through Inversion of Measured Surface Displacements

Michael S. Bruno
Terralog Technologies USA, Inc., Arcadia, California 91006
e-mail: msbruno@terralog.com

ABSTRACT

Surface deformation can be induced by a variety of distributed and discrete subsurface deformation sources, including removal or injection of fluids, changes in temperature, natural or induced faulting, and tunneling or mining. There is often a critical need to identify the physical parameters of a known source, to assess the relative influence of multiple sources on surface subsidence, or to locate an unknown subsurface source of surface deformation. Measurement and analysis of induced surface displacements provides a powerful technique to perform such characterization. This paper presents numerical analysis techniques used to evaluate subsurface sources that cause surface displacements and describes several case studies demonstrating the practical application of this technology, including determining the orientation of hydraulic fractures, locating movement on suspected faults, and monitoring migration of injected fluids.

INTRODUCTION

Surface displacements commonly are induced by several types of man-made and natural subsurface processes. For example, ground-water withdrawal for irrigation has induced surface fissures and tens of feet of subsidence in many areas throughout the world. Sinkholes and surface subsidence are common occurrences in many shallow mining regions owing to collapse of abandoned underground openings. Long-term aseismic or short-term seismic fault slip has induced surface displacements from several inches to several feet. Other activities can produce minor surface displacement, on the order of millimeters or less, which are of no particular interest other than providing information regarding the subsurface source.

It is often necessary to characterize source mechanisms that produce surface displacement. For example, multiple sources may have contributed to harmful surface subsidence or fissures and it is sometimes necessary to determine the relative influence of each to take corrective actions or to determine responsibility. In other instances, it may be useful to evaluate the characteristics of a known subsurface source, such as the orientation of hydraulic fractures or the subsurface flow pattern of injected fluids. Occasionally, there is a need to locate a subsurface deformation zone, such as a collapsing underground cavern or a slipping fault, which should be avoided during drilling operations.

Measurement and analysis of surface displacements is a powerful technique to characterize deformation sources. Several numerical analysis tools, including finite element, finite difference, and discrete element methods, have been successfully applied to predict surface displacements induced by subsurface compaction, dilation, and faulting. Most recently, inversion techniques have been developed to evaluate subsurface deformation from measured surface displacements (Dusseault and others, 1993; Bruno and Bilak, 1994; Rothenburg and others, 1994). This paper includes an overview of surface deformation analysis, a description of numerical inversion techniques available to characterize subsurface sources from measured surface displacement data, and examples of specific applications of this inversion method.

OVERVIEW OF SURFACE DEFORMATION ANALYSIS

Analysis and inversion of measured surface displacements to characterize subsurface sources requires three basic tools:

(1) Accurate and reliable sensors to monitor surface deformations
(2) An effective numerical technique to evaluate surface deformations that may be induced by several subsurface source mechanisms
(3) An efficient algorithm to invert mea sured surface deformations to character ize the source mechanisms.

SURFACE DISPLACEMENT MONITORING

The choice of a displacement monitoring technology depends on the magnitude of displacements and the frequency of surveying required. For example, in the oil and gas, mining, and waste disposal industries, minute surface deformations (on the order of millimeters) induced by hydraulic fracturing, faulting, and pressure and temperature changes have been monitored with precision survey methods, with differential global position satellite (GPS) surveys, and with seismometers and tiltmeters.

First-order surveys can be conducted to monitor vertical surface displacements with high precision (to submillimeter scale) at periodic intervals. To eliminate near-surface effects owing to changes in temperature or water saturation changes, and to isolate only those displacements induced by a deep source, specially designed benchmarks must be installed. These benchmarks must be anchored about 10–15 ft below the surface and have sliding sleeves that decouple movement in the near surface material from the benchmark rod.

Surface deformations may be monitored on a continuous basis with borehole tiltmeters that produce DC signals proportional to changes in near surface tilt. Tiltmeters should be installed 10–15 ft below the surface and be decoupled from near-surface vibrations. Tiltmeters can easily measure surface slope changes on the order of a tenth of a microradian and less, equivalent to a change in elevation of a millimeter occurring over a distance of a kilometer. These devices have the ability to monitor minute changes continuously and remotely. A cellular modem can be connected to each tiltmeter to allow remote data acquisition and analysis.

Currently, differential GPS receivers and software can be applied to measure deformations to an accuracy of approximately a centimeter. These systems are commonly very cost effective for periodic monitoring of relatively large-magnitude surface displacements that occur over very large areal distances, such as surface subsidence above oil and gas reservoirs. (The large areal distances make precision level surveying cost prohibitive.)

Prediction of Surface Displacement

There are several types of distributed and discrete subsurface deformation sources. Distributed or continuum deformation sources include changes in pore fluid pressure and changes in temperature. Changes in volumetric strain are related to the product of either material compressibility and change in pore pressure, or material coefficient of thermal expansion and change in temperature. Discrete deformation sources include subsurface fracturing, faulting, or closure of underground openings.

Volume expansion and shear deformation in the subsurface are seen as surface displacements with magnitudes determined by the material properties of the overburden material. Surface displacements z at any location (x,y) above N subsurface deformation sources may be expressed in the generalized form

$$\Delta z(x,y) = F(x_n, y_n, z_n, \delta_n, \beta_n, L_n, W_n, \Delta V, \Delta S) \quad (1)$$

where x_n, y_n, z_n refer to the Cartesian coordinates of the origin of each deformation zone, δ_n and β_n are rotation vectors describing the orientation of the deformation zone with respect to the surface (such as dip and strike for a planar source), L_n and W_n are characteristic lengths and widths, respectively, of the deformation zone, and ΔV and ΔS represent the amount of volume change and shear distortion of the subsurface deformation zone, respectively. The influence function, F, can be of varying complexity, depending on the location and type of subsurface source and the overburden material behavior.

For example, when distributed deformation sources are deeply buried, strains within most of the overburden material remain elastic and the function F can take the relatively simple form of a linear combination of polynomial expressions for nuclei of strain in an elastic half-space (Geertsma, 1973a, b). When discrete deformation sources are deeply buried, such as faults, fractures, or caverns, the function F also can be defined analytically using functional relations for surface displacements induced by finite displacement discontinuities in an elastic half space (Davis, 1983; Okada, 1985). The nucleus of strain and displacement discontinuity functions can be modified to account for the effects of heterogeneous and anisotropic media. A step-wise linearization procedure can be developed to evaluate nonlinear and time-dependent behavior of overburden properties.

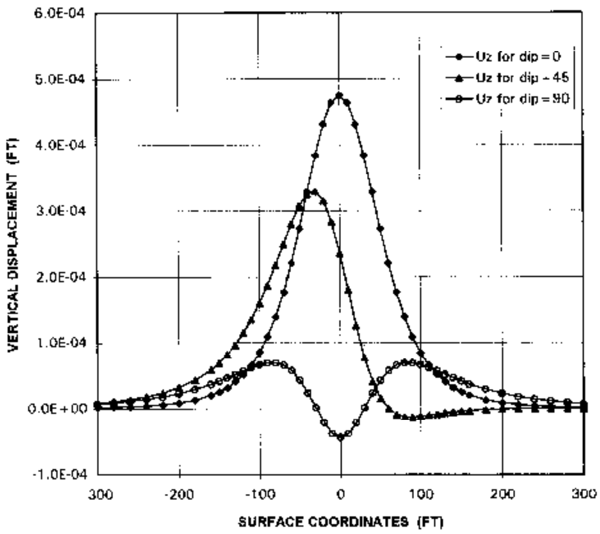

Figure 1. Surface displacement patterns above dilation zones of varying dip. Depth = 100 ft; length = 10 ft; width = 10 ft; tensile displacement = 0.1 ft.

Generally, surface displacement above a subsurface zone of dilation will be positive and symmetric above the center of dilation, as shown in figure 1. Surface displacement above a subsurface shear zone will be asymmetric above the shear center, with both subsidence and heave possible at the surface as shown in figure 2.

When subsurface deformation is large compared to the depth below land surface, or if the overburden is significantly anisotropic or heterogeneous or both, then more complex influence functions are required. These can be determined with numerical models, such as large strain and nonlinear finite element or finite difference codes. Parametric simulations can be performed to determine a set of influence functions for a wide range of source parameters and overburden properties.

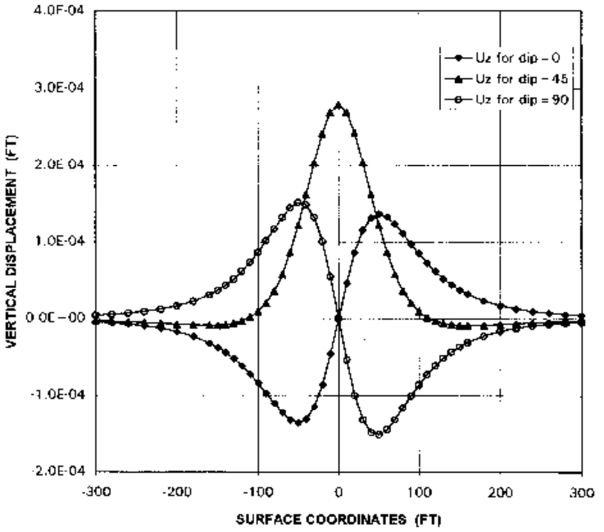

Figure 2. Surface displacement patterns above shear zones of varying dip. Depth = 100 ft; length = 10 ft; width = 10 ft; shear displacement = 0.1 ft.

Numerical Inversion Methods

Regardless of whether simple analytic expressions or more complex techniques are used to define the relation, equation 1 provides a forward model for the surface displacements expressed in terms of the location, geometry, and magnitude of subsurface zones of deformation. The inverse problem is to determine the subsurface deformation parameters from measured surface displacements. To accomplish this, the following procedure may be applied.

(1) Estimate (guess) the location and magnitude of one or more deformation zones in the subsurface.

(2) Use equation 1 to calculate theoretical surface displacements Δz produced by these assumed deformation zones.

(3) Evaluate the error between calculated displacements and field measured displacements.

(4) Minimize the error by adjusting the location and magnitude of the deformation zones until the calculated and measured surface displacements agree to within the accuracy of the surface sensors.

(5) Evaluate solution quality through uniqueness and convergence checks.

A variety of inversion techniques may be applied depending on the functional form for the forward problem and the availability of solution constraints. For example, conjugate gradient techniques can be applied for linear or nonlinear functions with relatively smooth gradients and few local minima. Simulated annealing and neural network techniques have been used with good success to evaluate nonlinear and discrete functions with multiple minima.

Evaluation of subsurface deformations from surface displacement data is an inherently nonunique problem. However, a good qualitative sense of subsurface deformation may still be obtained through intelligent solution constraints, even when many of the in-situ material properties are unknown. When the overburden depth is much larger than the thickness of the subsurface zone of collapse or disturbance, displacement patterns are relatively insensitive to overburden material heterogeneity. Linear elastic overburden models have been used to accurately predict surface deformations above compacting formations and mines, even when the subsurface compaction is massive and inherently nonlinear

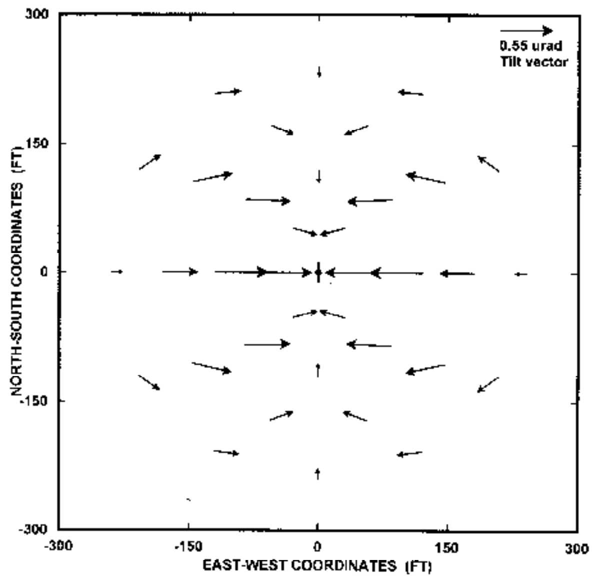

Figure 3. Theoretical surface tilts above a vertical fracture point inward toward fracture azimuth. Depth = 300 ft, length = 30 ft; width = 30 ft; tensile displacement = 2 in.

(Bruno and Bovberg, 1992). Often, the surface displacement pattern alone can provide useful insight on the location and relative extent of subsurface compaction.

FIELD APPLICATION EXAMPLES

Hydraulic Fracture Orientation

Surface deformation analysis is commonly applied to monitor hydraulic fractures in oil and gas fields. Hydraulic fractures are created to stimulate a well by increasing fluid communication between the well bore and the formation in low-permeability reservoirs. A water and sand slurry is pumped at high pressure into an interval and allowed to fracture the rock matrix. To optimize the placement and alignment of multiple wells in a production field, it is critical to know the orientation (azimuth and dip) of the induced fracture. Surface deformation analysis is a powerful tool to determine the orientation of hydraulic fractures shallower than about 5000 ft below land surface,

As shown in figure 1, the surface deformation pattern above a horizontal fracture is very distinct from the surface deformation pattern above a vertical fracture. Eight to twelve tiltmeters, appropriately place at the surface, are sufficient to accurately determine the dip and azimuth of induced fractures. Theoretically, the tilt induced at land surface by inflation of a vertical fracture is described by tilt vectors which point inward toward the centerline of the fracture azimuth in an asymmetric pattern (fig. 3). Figure 4 presents the theoretical surface tilts above a horizontal fracture; tilt vectors point away from the center of the fracture in a

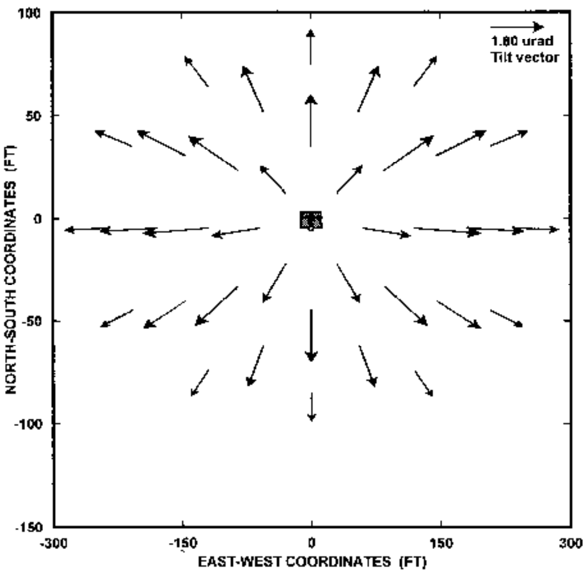

Figure 4. Theoretical surface tilts above a horizontal fracture point outward from fracture centerpoint. Depth = 300 ft, length = 30 ft; width = 30 ft; tensile displacement = 2 in.

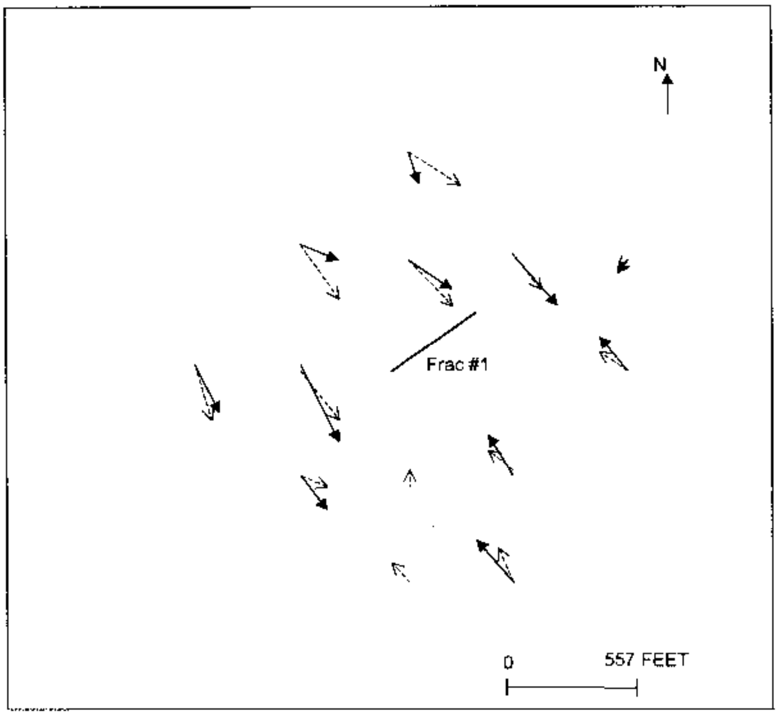

Figure 5. Measured and theoretical surface tilts above an oil field hydraulic fracture. Depth = 2060 ft; length = 500 ft; width = 175 ft; tensile displacement = 0.4 in. Measured tilt directions and relative magnitudes shown with solid line arrows and theoretical tilt directions and magnitudes shown with dotted arrows.

generally symmetric pattern.

A field example is shown in figure 5 in which a hydraulic fracture was induced at a depth of about 2060 ft. Surface deformations were used to evaluate the azimuth and dip of the fracture. Maximum deformations during the fracture job were on the order of 0.1 microradians. Analytical functions for a dipping hydraulic fracture (Davis, 1983) were used in the inversion process to determine that the fracture propagated at an azimuth of about 225° from north and dipped at an angle of about 10° from vertical. As shown in figure 5, there was a relatively good match between the tilts measured in the field and the theoretical surface tilts for the inversion solution.

Analysis of Suspected Fault Movement

Surface deformation analysis can also be used to locate and characterize slip on subsurface faults. Movement on subsurface faults creates very distinct surface displacement patterns (see fig. 2), which can be used to locate and characterize the fault. In a project in the former Soviet Union, an array of benchmarks had been installed to monitor subsidence above a large oil and gas field. Some of the benchmarks seemed to indicate that significant vertical movement had occurred and there was speculation that a particular fault in the subsurface was slipping. If this were so, then future drilling and production operations in the area might have to be modified. However, it was possible that the observed benchmark displacements were in error or that the source of the deformation was much shallower than the identified fault.

Figure 6 is a schematic of measured surface displacements and the approximate location of the suspected fault. The observed surface deformation pattern did not appear consistent with slip on the identified fault. Inversion techniques determined that for a fault with the given orientation to produce maximum vertical movement at the observed surface position, the actual fault location would have to be about 1 km away from the identified fault. Furthermore, as shown in figure 7, the surface deformation

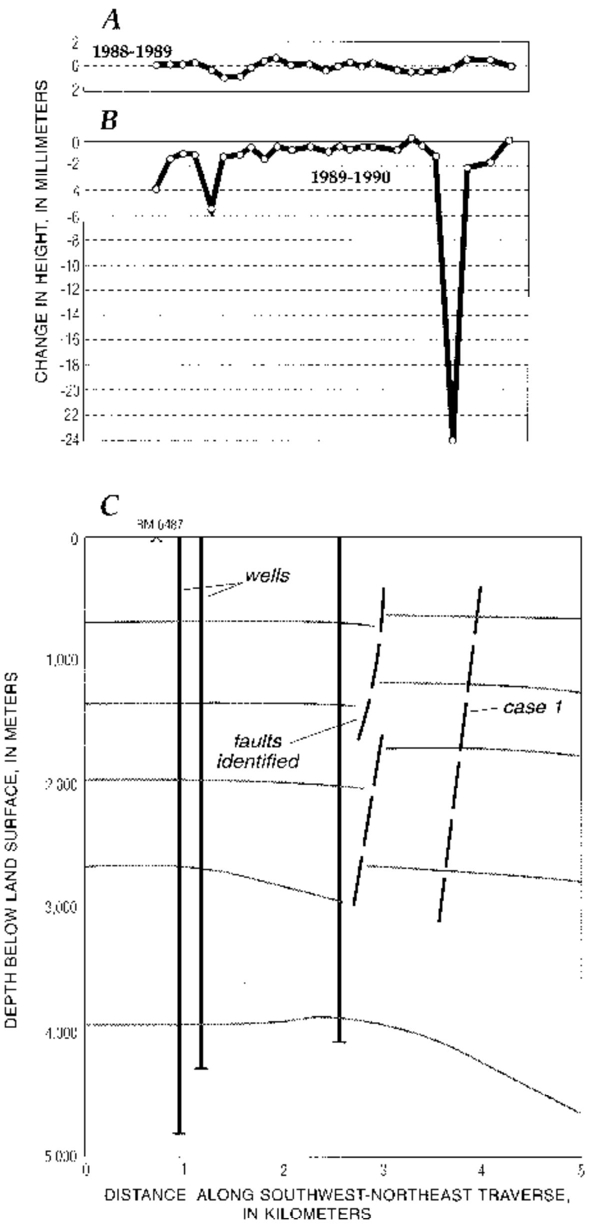

Figure 6. Measured surface displacements at an oil field (*A*) during 1988–1989 and (*B*) during 1989–1990 above identified faults in (*C*) a generalized cross section. Case 1 shows the fault location required to induce maximum displacement at observed location in (*B*), assuming fault orientation is consistent with identified fault.

pattern induced by slip on such a fault would be much more widely spread than the observed pattern. In general, subsidence above an underground source is distributed over lateral dimensions on the same order as the depth of the subsurface source. Therefore, the observed surface

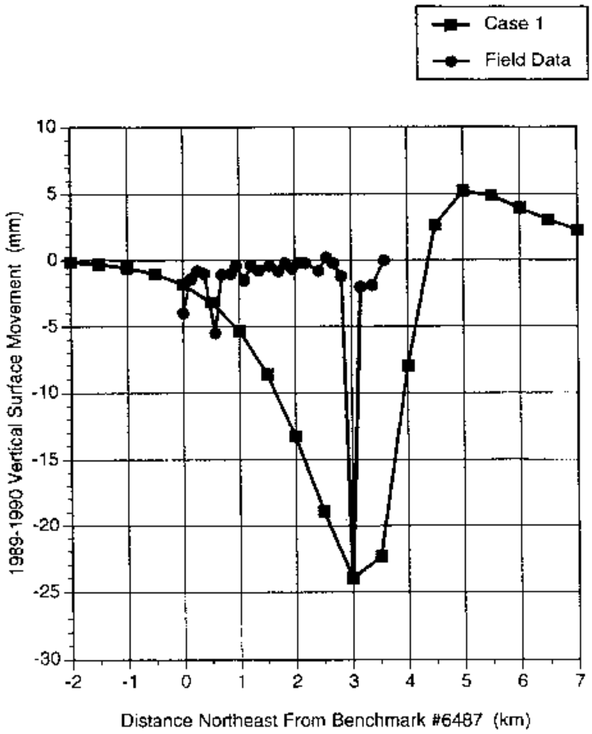

Figure 7. Comparison of theoretical surface displacements for the given fault (case 1) and measured surface displacements (field data) shows large discrepancy in lateral spreading of subsidence. Either the survey data are in error or the actual source location is much shallower than the suspected fault (probably less than 0.5 km deep).

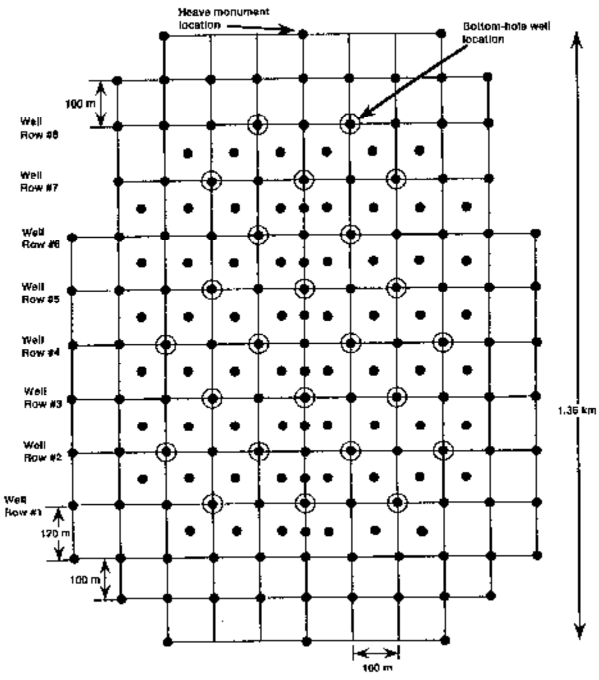

Figure 8. Benchmark and well locations at cyclic steam project.

displacement pattern could only have been caused by a very shallow source (less than about 0.5 km below land surface) and not by the suspected fault (3–4 km below land surface).

Analysis of Injected Steam Migration

Inversion of surface displacements is also often used to evaluate the migration of subsurface fluid pressure and temperature, as described by Bruno and Bilak (1994). A field study at an enhanced oil recovery project in western Canada illustrates this application.

Twenty-five cyclic steam stimulation wells were completed within a heavy oil reservoir at a depth of 1480 ft (450 m). The wells were aligned in eight rows, as shown in figure 8. Typically, steam is injected for a period of time to heat the formation and oil around the well bores to decrease the fluid viscosity. Then, the wells are pumped to recover the thinned oil. The monitoring objective at this project was to track the areal distribution of injected steam as alternating rows of wells were injected and to evaluate the recompaction behavior of the formation during subsequent flowback and production at each row of wells.

Surface displacements at this site were monitored with 186 benchmarks spaced on a regular grid over an area of about 3200 × 4500 ft (1 × 1.4 km). The displacement patterns for two north-south sections are presented in figure 9, which covers a period from July through September 1991, during which rows 1, 2, and 3 were on production cycles and rows 6, 7, and 8 were on injection and heating cycles. As expected, the areas to the north (above the injecting wells) were uplifted while the areas to the south (above the producing wells) subsided. The maximum uplift was about 1.2 in (30 mm) and the maximum subsidence was about 0.8 in (20 mm).

The measured displacements were used to determine subsurface zones of dilation and shear (corresponding to areas of increasing

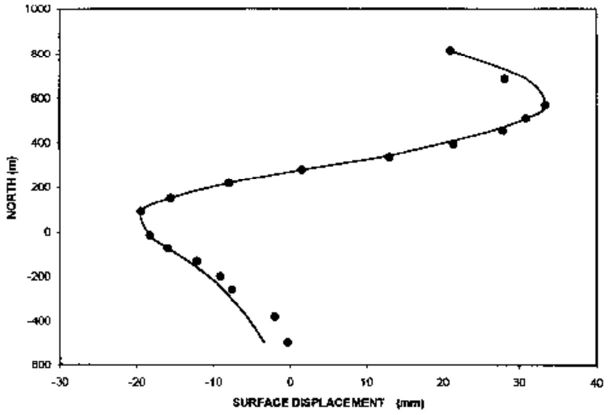

Figure 9. Comparison of measured and calculated displacements for north-south section through center of cyclic steam project for a period from July to September. Field measurements are indicated by dots and model results are indicated by the solid line.

pore pressure and temperature) and to determine subsurface zones of compaction (corresponding to areas of decreasing pore pressure and temperature). Dilation and compaction zones were modeled with multiple displacement discontinuity functions (Bruno and Bilak, 1994; Okada, 1985). Inversion of the surface data for the July to September period revealed that compaction is occurring along row 4 (darker shaded zones in fig. 10) while dilation is occurring along row 7 (lighter shaded zones in fig. 10). The calculated displacement compares favorably with measured displacement, as shown in figure 9.

DISCUSSION AND CONCLUSIONS

Evaluation of subsurface source mechanisms from inversion of surface displacement data is an inherently nonunique process. However, a good qualitative sense of subsurface deformation may still be obtained through intelligent solution constraints, even when many of the in-situ material properties are unknown. When the overburden depth is much larger than the thickness subsurface compaction or dilation zone, displacement patterns are relatively insensitive to overburden material heterogeneity. Linear elastic overburden models have been used to accurately predict surface deformation above compacting formations, even when the subsurface compaction is massive and inherently nonlinear (Bruno and Bovberg, 1992). Often surface displacement patterns alone, which are relatively insensitive to material heterogeneity, can provide useful insights on the location and extent of subsurface sources.

Surface deformation analysis and inversion to characterize source mechanisms has been applied with good success in the oil and gas and mining industries. The application of this technology is expanding into the civil construction and the environmental fields.

REFERENCES CITED

Bruno, M. S., and R. A. Bilak, 1994, Cost-effective monitoring of injected steam migration using surface deformation analysis: Proceedings of the SPE Western Regional Meeting, paper SPE 27888, p. 397–412.

Bruno, M. S., and C. A. Bovberg, 1992, Reservoir compaction and surface subsidence above the Lost Hills field, California: Proceeding of the 33rd United States Symposium on Rock Mechanics, p. 263–272.

Davis, P., 1983, Surface deformation associated with a dipping hydrofracture: Journal of Geophysical Research, v. 88, p. 5826–5834.

Dusseault, M. B., R. A. Bilak, and L. Rothenburg, 1993, Inversion of surface displacements to monitor in-situ processes: International Journal of Rock Mechanics and Mineral Science, v. 30, p. 1219–1222.

Geertsma, J., 1973a, Land subsidence above compacting oil and gas reservoirs: Journal of Petroleum Technology, June 1973, p. 734–744.

Geertsma, J., 1973b, A numerical technique for predicting subsidence above compacting reservoirs, based on the nucleus of strain concept: Verhandelingen Kon. Ned. Geol. Mijnbouwk., v. 28, p. 63–78.

Okada, Y., 1985, Surface deformation due to shear and tensile faults in a half-space: Bulletin of the Seismological Society of America, v. 75, no. 4, p. 1135–1154.

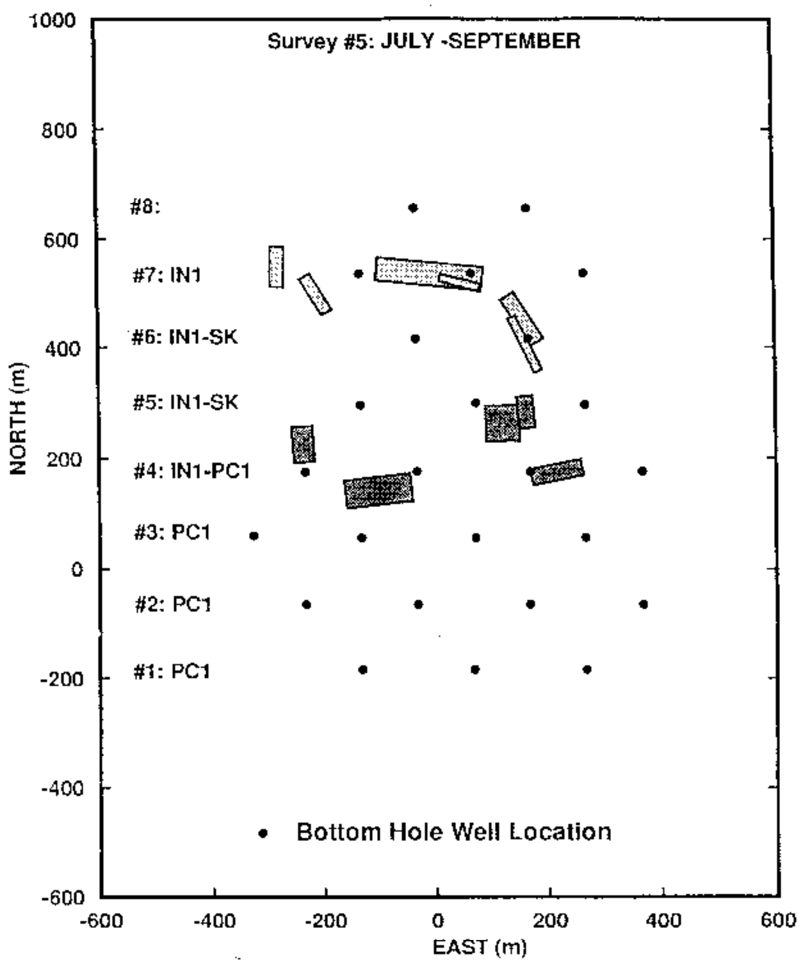

Figure 10. Location of dilation zones indicating pressure and temperature increase at steamfront (shaded rectangles near row 7) and location of compaction zones indicating pressure and temperature decrease in production area (shaded rectangles near row 4) for a period from July to September. Rows 1–3 were on production during this period. Row 4 was switched from injection to production. Rows 5–7 were on injection and soak cycles during this period.