Proceedings, 11th FIG Symposium on Deformation Measurements, Santorini, Greece, 2003.

MEASUREMENT OF SURFACE DEFORMATION ASSOCIATED WITH HYDROFRACTURE

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Abstract

The growth of a shallow hydrofracture can be monitored by observation of the ensuing deformation of the earth's surface. The field data are processed and analyzed to yield a characterization of the deformation source. Several methods are used for measuring the surface deformation. Geodetic techniques are used for monitoring slow deformation over large areas, where tiltmeters may be used to complement geodetic networks by providing continuous records. In this paper, two different case studies are presented in which tiltmeters are used for measuring surface deformation. The first case deals with measurements of surface tilts obtained during an induced hydraulic fracture experiment. The fracture characteristics are obtained by comparing the measured deformation with those provided by a mathematical model. Nonlinear inversion of surface tilts gave estimates of the fracture geometry: depth, orientation, length, and thickness. The second case deals with tilts measured during a naturally induced hydraulic fracture in a volcanic area. The analysis of field data enabled good understanding of the volcano behavior.

1. Introduction

Recently a considerable research effort has been directed toward the formulation of practical guidelines for predicting the geometrical characteristics of hydraulic fractures. Substantial advances have been made through theoretical and laboratory studies of the various mechanisms thought to play a role in determining fracture geometry. Different techniques are used in fracture mapping. The seismic method is used to locate the path of fluid penetration into the medium from the hypocentral distribution of microseismic emissions stimulated as a result of increased pore pressure (Cornet and Jianmi, 1992). Geodetic techniques are used in volcanic areas to obtain the vertical and horizontal displacements due to an inflation or deflation induced by a magmatic source (Dvorak, 1997). GPS and total stations are used for measuring these displacements (Beauducel, 1998). Fracturing pressure records can be used to determine some aspects of fracture behavior (Lilli, 1997; Nolte and Smith, 1981). The latter approach to fracture mapping has become known as the surface tiltmeter technique, it is found that the most practical way of obtaining a satisfactory description of the elastic field is through the deployment of an array of continuously recording tiltmeters (Evans et al., 1982). The surface tiltmeter technique has the advantage over other techniques in that it is sensitive to the broad-scale geometry of fractures rather than being limited to near-wellbore fracture detection. It is particularly well-suited to the study of shallow fracture growth and shut-in consolidation characteristics. Mean width of the fracture also can be estimated from the amplitude of the surface deformation.
Different analytic models are used for the interpretation of tilt data. These models represent the fracture as a planar discontinuity in the displacement field within a homogeneous, isotropic linear-elastic half-space of known Poisson's ratio. The dislocation model of Davis (1983) represents the fracture by an opening mode slit of arbitrary dip that is rectangular in both cross-sectional and plane views. Fracture pressure and deformation modulus of the medium do not

enter into the model formulation. The model of Pollard and Holzhausen (1979) represents the fracture as a uniformly pressured fluid-filled crack of a dipping plain-strain. The model of Sun (1969) considers the case of a horizontal coin-shaped crack in which the fluid pressure is uniform. Sun's model is used in this paper to calculate the geometric characteristics of the fracture in the first experiment, because the induced hydraulic fracture is horizontal. Finally, Mogi model (1958) is widely used in the literature for volcanic areas and represents the magma chamber as a spherical source of dilatation (Beauducel, 1998; Corrado et al., 1977).
In this paper we present two case studies, in which surface tiltmeter technique is used for fracture mapping.

2. Application to induced hydrofracture

This experiment is carried out in the east of France in order to connect two wells by an induced hydraulic fracture at 200 m depth. This technique is applied to increase the permeability of a petroleum reservoir or to make use of rocks at large depths for geothermal energy and other purposes. The surface deformation which is induced by the fracture is measured by 16 tiltmeter stations, installed around the injection well. Each station is equipped by two tiltmeters, one to measure the radial tilt and one to measure the tangential tilt. The resultant of the two components gives the tilt at each station. A quartz tiltmeter of high resolution developed by Blum and Saleh was used in this experiment (Saleh and Blum, 1990).

2.1 Results and discussion

The tilt signals were recorded continuously by XY recorders to follow the growth of the fracture in real time. Then they were digitized by taking one point each two minutes. Fig. 1 shows a typical example of tilt signals recorded at station No. 9 during the experiment. Tilt variations were observed during the first two hours of the experiment due to injection interruptions. Then the rate of tilt becomes constant during 8 hours of injection. The observed tilt at all the stations is large in the radial direction and very small in the tangential direction. This indicates that the fracture is horizontal. Fig. 2 shows tilt resultants or vectors observed at the different stations.
The horizontal coin-shaped crack model (Sun, 1969) is used in the analysis of the experimental results. This model gives the vertical displacement of the surface at a distance d from the injection well in terms of the fracture depth, radius, volume and d. The tilt is calculated by taking the derivative of the vertical displacement with respect to d. A nonlinear inversion method based on the theory of probability was used to determine the geometric characteristics of the fracture. The fracture radius, thickness, and depth are found to be 77 m, 0.008 m, 225 m respectively for an injection volume of 100 m^3.

3. Application to naturally induced hydrofracture

This experiment is carried out at Piton de la Fornaise volcano on the Reunion Island in the Indian Ocean. This volcano is considered as one of the most active volcanoes in the world. Five tiltmeter stations were installed around the central crater to study the behavior of the volcano before, during and after eruption.

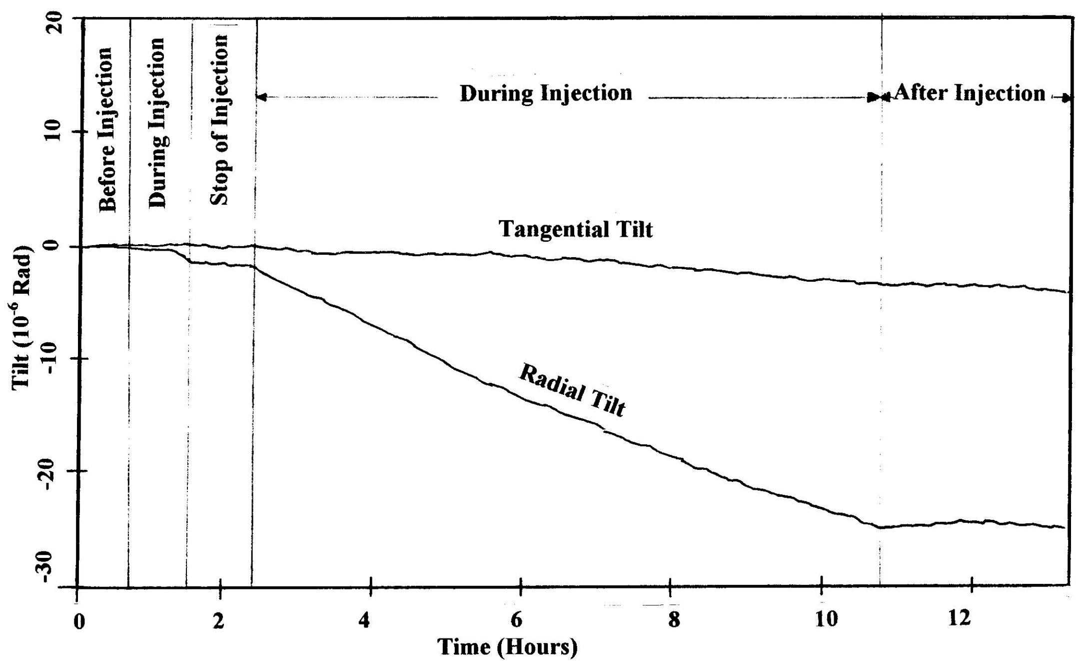

Fig. 1. Typical tilt signals recorded by station No. 9

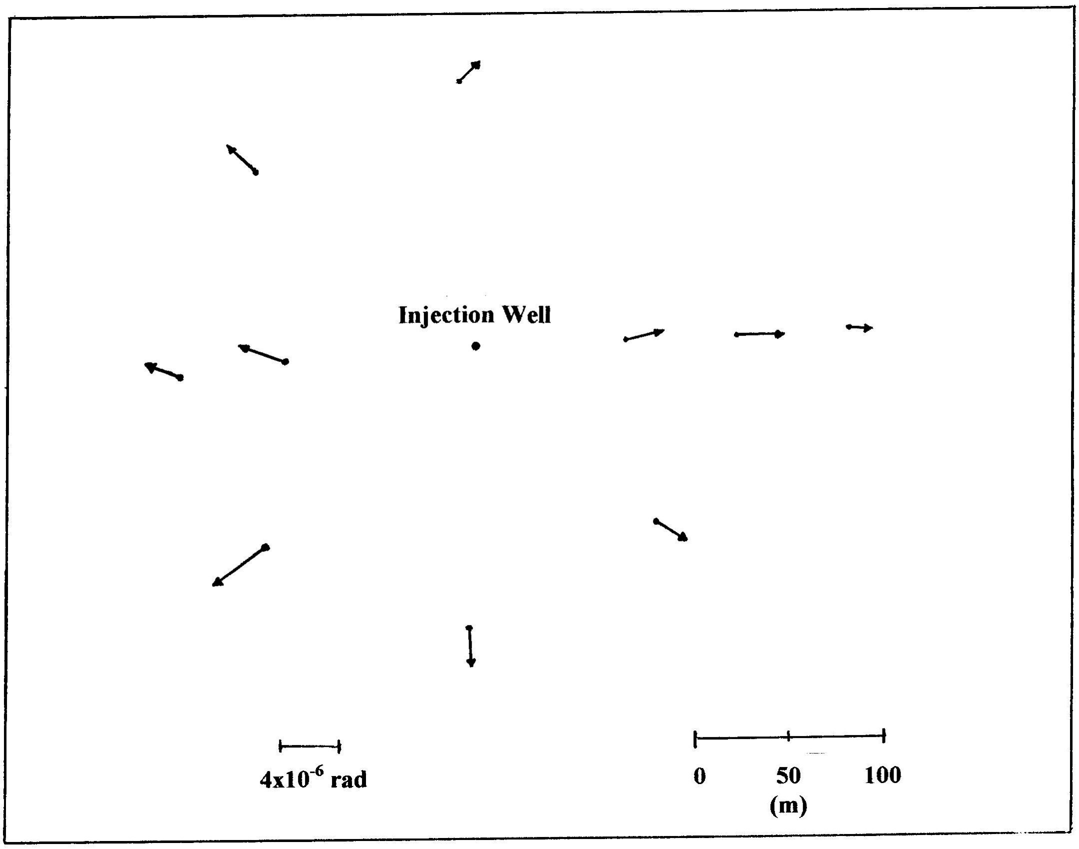

Fig. 2. Tilt vectors observed at different tiltmeter stations

3.1 Results and discussion

Fig. 3 shows the tilt curves recorded by one of the stations during an eruptive period. The surface deformation follows three phases:

(i) The inflation phase which is observed before eruption, the total measured deformation over 8 months is $70x10^{-6}$ Rad, which is due to the pressure increase inside the magmatic chamber.

(i) The eruption phase which is associated with a variable deformation (Fig. 3), the magma flow passes through one or more fissures.

(ii) The deflation phase which is observed during and after eruption (Fig. 3), it is due to the pressure decrease inside the magmatic chamber.

4. Conclusion

The surface tiltmeter method of studying the development of shallow hydraulic fractures has the following merits:

1. The measurement is entirely passive and neither interrupts nor is interrupted by the injection operation or volcanic eruption.
2. The technique is sensitive to broad-scale features of the fracture geometry rather than having a field of view restricted to the immediate vicinity of the wellbore. Fracture orientation and dip are easily resolvable.
3. The technique is sensitive to fracture width, and, hence, the closure behavior of the fracture following shut-in can be inferred.
4. The occurrence of changes in the plane of fracture growth during any phase can be detected.

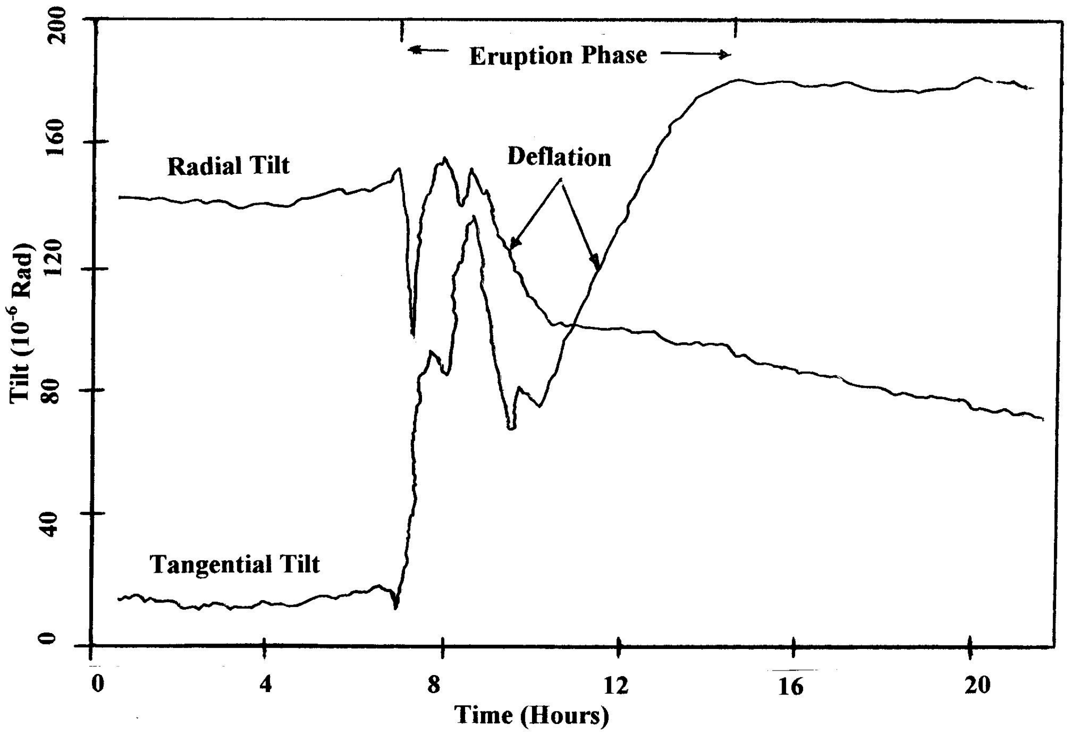

Fig. 3. Tilt curves observed during an eruption

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