ON STRAIN AND TILT MEASUREMENTS IN SEISMIC AREAS

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ABSTRACT

Results given by tilt- and strainmeters installed in cavities in a seismic area can be usefully combined with those of fault-plane solutions provided that cavity effects are taken into account. A first approach is presented by using Priuli available data.

Keywords: Seismic strains, tilmeters, strainmeters, earthquake prediction

1. INTRODUCTION

The advantage of carrying out strain and tilt measurements in seismically active areas is that, once the state of strain is known, the orientation of its principal axes can be compared with that of the principal stresses easily determined from the distribution of the polarity of first-arrivals of P-waves at nearby seismic stations. The analysis of such distribution, provided that enough data are available, gives the fault-plane solution from which the orientation of the principal axes can be found.

In the present paper we inquire on the possibility to combine the information offered by tilt- and strainmeters in order to improve the determination of the strain tensor and to compare the latter with the results of the fault-plane solutions.

It is well-known that under the hypothesis of an isotropically deforming surrounding medium, a station equipped with a set of six strainmeters forming a tetraedron, with vertices fixed at the rock is sufficient to give all the components of the irrotational strain tensor. Nevertheless several difficulties of both practical and technical nature discourage the employ of such kind of fully equipped stations. On the other hand stations with one, two or three strainmeters disposed in a horizontal plane are being widely used. It follows that the longitudinal strain can be determined along one, two or three directions in the horizontal plane; moreover in the last case the horizontal plane components of the irrotational strain tensor can be found provided that the three directions above are linearly independent. If in the latter case a couple of strainmeters are added then the determination of the strain tensor is bettered by two components provided that certain assumptions be made.

Let us assume an orthogonal cartesian system of axes $x, y, z$, with $x$ and $y$ in the horizontal plane and $z$ along the vertical, and the associated displacements $u, v, w$ along the corresponding directions; the tilt recorded along the two directions $x$ and $y$ correspond to the quantities $\omega_x/\omega_x$ and $\omega_y/\omega_y$ respectively. For particular but practically realizable cases the irrotational hypothesis can be realistically assumed for underground cavities strained by constant-rate regional tectonic fields. In this case

$$\omega_{xz} = \frac{1}{2}(\frac{\partial u}{\partial z} - \frac{\partial v}{\partial x})$$
$$\omega_{yz} = \frac{1}{2}(\frac{\partial v}{\partial z} - \frac{\partial v}{\partial y})$$
$$\omega_{xy} = \frac{1}{2}(\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x})$$

are evanescent and the information given by a triade of horizontal strainmeters as well as by a pair of horizontal pendulums allows the determination of all but one ($\omega_{z}/\omega_{z}$) six-strain tensor components.

On the other hand in the case of surface measurements given by the same instrumentation, the boundary conditions being

$$\varepsilon_{xz} = \frac{1}{2}(\frac{\partial u}{\partial z} + \frac{\partial v}{\partial x})$$
$$\varepsilon_{yz} = \frac{1}{2}(\frac{\partial v}{\partial z} + \frac{\partial v}{\partial y})$$
$$\varepsilon_{zz} = \frac{\partial v}{\partial z}$$

evanescent, again all the six-strain tensor components in addition to the rotational components $\omega_{xz}, \omega_{yz}$ can be found.

The case we are mostly interested in is the irrotational one, since for practical reasons natural underground cavities represent the best solution in order to avoid disturbances caused by human activities, air draft, thermal and other environmental effects.

However it is clear that under the above hypothesis the time dependent rotation, if any, can also be determined when subsequent states of irrotational deformations are known. The irrotational deformation is indeed represented by a symmetric matrix, but two subsequent irrotational deforma-
tions are represented by the product of the two corresponding matrices which is not, in general, a symmetric matrix. It follows that the rotation undergone from the initial state to the last one is represented by the skew-symmetric part of the off-diagonal elements of the product matrix.

Spherical cavities in the seismic area are taken to be deformed into ellipsoids the principal axes of which are co-axial with the directions of the principal stresses revealed by the fault-plane solutions.

It was also assumed that the tilt measured in any particular place on the cavity surface corresponds entirely to the shear strain in the direction connecting the particular place to the cavity centre.

Thus given $l$, $m$, $n$ the direction cosines of the direction above with respect to the principal strains $e_1$, $e_2$, $e_3$ the shear strain

$$(\gamma/2)^2 = (e_1 - e_2)^2 \bar{I}^2 \bar{m}^2 + (e_2 - e_3)^2 \bar{m}^2 \bar{n}^2 + (e_3 - e_1)^2 \bar{I}^2 \bar{n}^2.$$ 

Moreover holding the assumptions above the directions of tilting will be such that if $l_1$, $m_1$, $n_1$ are the direction cosines of the direction above after deformation:

$$l_1 = \left( \frac{1^2(1+e_1)^2/(1+e_3)}{D} \right)$$

$$m_1 = \left( \frac{m^2(1+e_2)^2/(1+e_3)^2}{D} \right)$$

$$n_1 = \left( \frac{n^2}{D} \right)^{1/2}$$

where:

$$D = (1^2(1+e_1)^2/(1+e_3)^2 - 1) + m^2((1+e_2)^2/(1+e_3)^2 - 1)^2.$$ 

Thus given the orientation and values of the principal strains the post-deformation directions making a pre-strain angle with the principal axes will be known as well as the shear strain along them.
2. THE FRIULI CASE

At the initial stage of the present investigation in the seismic area of Friuli the only instruments suitable for our purpose and readily available at the Istituto di Geodesia e Geofisica were the Marussi tiltmeters (Ref. 1).

Owing to difficulties arising from the fact that in order to provide reliable data such instruments need to rest upon stable horizontal not fractured rock surfaces it was decided to equip several stations with merely a single couple of them.

Thus starting from December 1976 five tiltmeter couples were progressively installed and run by the staff of the Istituto in the seismic area. The stations (Fig. 1) are the following ones:

(1) Villanova delle Grotte, in an underground natural cave, recording tilts from December 1976. In the same place a triade of horizontal Cambridge wire strainmeters are functioning from September 1978;

(2) Raibl, in an active mine operating from March 1977; it has been recently removed due to the mine activity that caused strong drifts;

(3) Cesclans, in an old military underground fortification from August 1977;

(4) Castelmonte, in the cavern of an old Abbey from March 1978;

(5) Barcis, in an underground natural cave from September 1978; reliable data can not yet be available due to the new installation perturbations.

Up till now the best results can be considered those of the oldest stations, that is stations (1) and (3), and for the last months station (4).

After a period of strong initial drifting the three stations mentioned above were synchronously recording tilt variations with common characteristics. Hence it was clear that the single stations were all recording tilts of regional interest (Ref. 2).

Moreover the tilts measured at the different stations were observed to be the result of the superposition of a short-term tilting of a few-days duration on a seasonal tilting of about six-months duration (Ref. 2).

A comparison of the recorded tilt with the seismic activity revealed by the teleseismic network of the Osservatorio Geofisico Sperimentale, Trieste, showed that strong tilt variations occur starting some days before an increase of the seismic activity in the zone (middle-term tilting), and that short period perturbations (short-term tilting) are generally recorded as pre-seismic, co-seismic and post-seismic effects. A statistical analysis has been carried out in order to detect middle- and short-term tilting. The intensity of the mean deflection of the tilting vector has been computed...
12 by 12 hours taking into account the five preceding days. The relation of the middle-term tilting with the seismic activity has been confirmed; an example concerning Cesclans and Villanova stations, for four months of records, as well as the compared seismic activity, is shown in Figure 2. Analogous graphs have been obtained taking into account the short-term tilting: the characteristic parameters of the ellipses of the tilt deviations from the mean value, regardless the time sequence, have been computed for the same five-day periods, and the length of the maximum axis has been plotted. A comparison of such lengths with the seismic activity gives roughly the same results as the middle-term tilting.

On the other hand a preliminary inspection of the directions of tilting during the periods above did not seem to follow any apparent rule.

Thus an effort was made to interpret the variations of the directions of middle-term tilting at the different stations. The assumption was made that in the whole seismic area the strain is homogeneous.

The Villanova tiltmeters are installed in a cave the shape of which can be approximated rather well by an ellipsoid and the direction defined by the ellipsoid centre and the position of the instruments on its surface plunges a few degrees along an azimuth slightly east of south. Unfortunately both the Cesclans tiltmeters and the Castelmonte ones are not installed in cavities representative by simple geometrical shapes and nothing can be said about the centre-tiltmeters directions.

Data regarding the period May 1977-September 1978 have been inspected in order to find periods of abnormally fast, constant-rate, pre-seismic tilting. The most evident cases which also yield clear fault-plane solutions are concerned with the tilts recorded on September 2, 1977 and during the period May 27-June 3, 1978.

Being these cases of pre-seismic deformations the direction of greatest shortening was assumed to be parallel to that of the greatest compression obtained from the fault-plane solutions of the shocks which occurred in those very periods or in periods immediately preceding them.

The fault-plane solution of the shocks recorded (Ref. 3) in the period May 27-June 3, 1978 (Fig. 3) was not particularly well-defined but the directions of the principal axes of stress had to be contained in rather narrow cones.

The tilt recorded in that period at the Villanova station was toward E47°S. In order to make such direction compatible with the possible orientation of the axis of greatest extension and thus of minimum compression this would have to bear as far east as possible obviously still in the cone derived from the fault-plane solution. In addition to that, the surfaces on which the direction with initial orientation centre-of-cave - tiltmeters at Villanova had to be deflected in order to yield the observed tilt direction and sense in cases of constant-volume deformations revealed conditions ranging from plane strain (Fig. 4) to uniaxial extension (Fig. 5) whereas the uniaxial shortening
Figure 5. Surfaces like those shown in Figure 4 in the case of uniaxial extension. Symbols and period like in Figure 4.

(Fig. 6) was unacceptable.

In the same diagram the cones in which the orientation of the Cescians and of the Castelmone centre-of-cave - tiltmeters directions could be spotted; in fact in such cones a plane tangent to the surface of deflecting lines had to strike E8°S and E54°S respectively.

In the case of the tilts recorded on September 2, 1977, the seismic activity preceding that period was very low and thus a cumulative fault-plane solution (Ref. 4) for the whole period from August 7 to September 2 was sought. In reality two alternative solutions were found (Fig. 7) similar to each other but with their axis of intermediate principal stress plunging shallowly either to the NW or to the SE. However interestingly both these solutions imply a direction of minimum compressional stress bearing west of south while the directions of tilt observed at Villanova and at Cescians have been W and E51°W respectively. Thus following the procedure above a similar range of values (Fig. 8) of the ratios between the principal strains was found.

Comparing the cones in which the Cescians centre-of-cave - tiltmeters direction must be contained in the two cases above one finds that there cannot be superposition in the case of uniaxial extension and that the superposition in the case of plane strain yields a much narrower cone.

The results above have been compared with those of typical case of co-seismic deformations observed in the period September 19-21, 1978. The fault-plane solution of the shocks recorded (Ref. 5) in the period from September 14 to September 21 (Fig. 9) are rather similar to those found for the May-June period but the directions of tilting at all stations have been quite different. In fact bearings of W53°W, W10°S and W63°S have been observed at Villanova, Cescians and Castelmone respectively. Obviously the reversal in the sense of tilting at Villanova might be explained assuming that the direction of maximum extension bears west of south still being in the cone of the directions of minimum compression; however such possibility would not explain the reversal in the sense of tilting at Cescians (Fig. 10).

Figure 6. Surfaces like those shown in Figure 4 and 5 in the case of uniaxial shortening. Symbols and period like in Figure 4.

Figure 7. Fault-plane solution of the shocks recorded in the period August 7-September 2, 1977. Full lines and broken lines represent two alternative solutions. Symbols like in Figure 3.
A possible interpretation of the reversals could be that co-seismic deformations are related to strain release. In fact, assuming that the orientation of the principal axes of strain is similar to that of the May-June period but with a reversal of the axes of maximum shortening and maximum elongation, one obtains the observed directions.

It was shown that the amount of the tilting according to the above-mentioned assumptions is a function of the differences between the principal strains. However, when the values observed at the various stations do not turn out correct, the constant-volume assumption has to be modified. In fact, volume changes are most likely to occur in seismic areas as proposed for example by the dilatancy theory.

3. CONCLUSIONS

Cavity effects have been extensively treated by several authors (Refs. 6, 7); both from theoretical and experimental results it follows that the tilt and strain measurements strongly depend upon the instrument position inside the cave as well as upon the strain field, especially when tectonic fields are involved. On the other hand, the cavity deformations can be computed by modelling the shape of the cavity and by assuming a realistic strain field hypothesis; for particular simple cavity shapes, infinitesimal theory or finite deformation theory can as well be adopted, according to the particular characteristics of the problem; in any case the finite-element method can be applied.

We wish to stress here that the results above, instead of discouraging the use of tilt- and strainmeters in seismic areas, indeed imply new views on experimental methodology.

Figure 8. Surfaces like those shown in Figure 4 when the principal axes of strain are parallel to the principal axes of stress of the solution represented by the full lines in Figure 7. Direction of tilts on September 2, 1977. Symbols like in Figure 4.

Figure 9. Fault-plane solution of the shocks recorded in the period September 14-21, 1978. Symbols like in Figure 3.

(1) These kinds of instruments are usually installed in seismic areas in order to detect pre-seismic, co-seismic and post-seismic effects, the equipment being in general a pair of tiltmeters and one or two strainmeters the most interesting si-

Figure 10. Surfaces like those shown in Figure 4. Principal axes of strain parallel to those of principal stress of Figure 9, the axis of minimum compression being as far west as possible. September 19-21, 1978. Symbols like in Figure 4.
signal being the variation of the drift. In that case a suitable choice of the installation site allows a big amplification of the effect itself. Moreover, if teleseismic network results are available, fault-plane solutions are helpful in the interpretation of the data.

(2) When more instruments are available (minimum a triade of strainmeters and a couple of tiltmeters) all but one of the six tensor components of the strain can be determined by knowing the geometry of the cave; again, data coming from the fault-plane solutions can be of advantage.

4. REFERENCES


