

UNDERGROUND DEFORMATION MEASUREMENT USING NEW QUARTZ INSTRUMENTS

Bassam Saleh

Dept. of Surveying and Geomatics Engineering, Faculty of Engineering, Al-Balqa' Applied University,
Al-Salt 19117, Jordan.

E-mail: bassaleh@yahoo.com or E-mail: bsaleh@firstnet.com.jo

ABSTRACT

This work demonstrates the usage of two new quartz instruments, which are a tiltmeter and an extensometer that we developed lately to measure with high accuracy deformations of structures, volcanoes, tunnels, and ground surface. The stability of an underground quarry, near Paris in France was the subject of the study. The deformation of the quarry under different cases of loading during the process of constructing a highway that passes over it was analyzed. Tiltmeters were installed on the floor of the quarry and extensometers on the pillars to measure the deformations induced by the load of the fill materials applied over the quarry. The tilt and the compression were measured for different loading periods and for different durations depending on working conditions. Continuous records of measurements were executed during this experiment to show continuously all variations in the quarry deformation. The results of the tilt measurements showed instantaneous deformation associated with loading change. Meanwhile the compression measurement showed late effects after loading. A mathematical model was used to calculate the deformation under the same loading conditions. This was done in order to find positions of maximum tilt and compression in the quarry where the instruments can be installed. The model as well, enabled us to fix the range and sensitivity of the instruments. Finally, we compared between the measured and the theoretical values and we discussed the results.

Key words: Tiltmeter, extensometer, deformation, tilt, compression.

1. Introduction

The analysis of special phenomena such as earth tides, volcanic eruptions, earthquakes, failure of structures, etc. requires deformation measurement with specific instruments of high accuracy (King and Bilham 1973; Beauducel 1998; Dal Moro and Zadro 1998; Teskey 1988). This study demonstrates two types of measuring instruments, which are tiltmeter, and extensometer. Several types of sensitive tiltmeters and extensometers have been developed during the past three decades to observe and measure ground deformations (Shuhua et al. 1999; D'Orye 1998; Blair et al. 1997; Saleh et al. 1991; Wyatt and Berger 1980; Gaulty 1976). A tiltmeter gives the rotation of a line segment fixed in the earth about a chosen horizontal axis perpendicular to the local gravity vector. An extensometer measures the change in distance between two points on the earth which are a finite distance apart. Tiltmeters were first used for earth tides observation and evaluation (Melchior 1983; Blum 1977) and now are used in many fields such as volcanology, seismology, civil engineering, etc. (Beauducel 1998; Lesage et al. 1983; Saleh et al. 1990). Extensometers are used for strain, settlement, extension and compression measurements in many fields such as mining, geophysics, civil engineering, etc. (Lili 1997; Crochet et al. 1983). Due to the importance of measuring tilts and extensions using accurate devices of low drift and low cost, two instruments were developed by Blum and Saleh in 1986 (Saleh 1986), a tiltmeter and an extensometer of high resolution, in the range of 10^{-8} rad and 10^{-8} m respectively. The instruments were tested on many sites over the world for monitoring the stability of dams, buildings, tunnels, retaining walls, volcanoes, etc. (Saleh et al. 1990; Beauducel 1998). They enabled the detection of small deformations that cannot be detected and measured by ordinary surveying instruments. These instruments were used to study the behavior of an underground quarry under the impact of a fill material load during the construction of a highway. The underground quarry is situated in Villiers-Adam, at 50 km to the north of Paris. Two tiltmeters and two extensometers were used in the experiment for measuring the quarry deformation.

2. Instruments and measurements

2.1 Quartz tiltmeter

The Tiltmeter which has been developed is a horizontal pendulum of Zollner suspension, made of melted quartz that operates in a vacuum (Saleh et al. 1991) (see Fig. 1). A photoelectric detector is used to transform the rotation of the pendulum mass into voltage variation. The range, as well as the resolution, both depend on the pre-chosen natural period of the pendulum. For this case study, the natural period is 4 sec, which gives a resolution of 5×10^{-8} rad (0.01 sec) and a range of $\pm 100 \times 10^{-6}$ rad (± 20 sec).

2.2 Quartz extensometer

The extensometer which has been developed is a displacement transducer using a differential transformer. A deformable frame made of melted quartz is used in the device to transmit any compression or extension to the transducer (see Fig.2). The transducer is composed of a mobile ferrite moving inside a reel, and the two parts are fixed to the frame using quartz bars.



Fig. 1. Photography of quartz tiltmeter

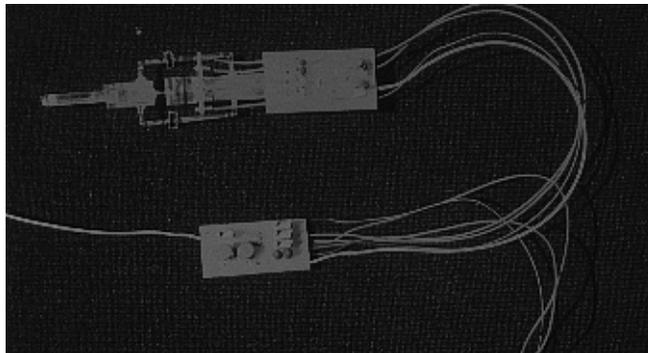


Fig. 2. Photography of quartz extensometer

2.3 Measurements

The tilt is measured in two directions by two tiltmeters oriented north-south and east-west. The tiltmeters were installed on the floor of the quarry between two pillars, at few meters of the load application. The compression is measured by two extensometers of one meter length each, installed vertically on different pillars under the load. A laptop is used for the acquisition of data, in the order of one measurement every 20 minutes. The thermal effect on the instruments and the rock inside the quarry is negligible, due to the low temperature variation inside it, which is less than one degree Celsius per year. The tilt signals recorded by the tiltmeters and extensometers for different cases of loading are shown in Fig. 3 and Fig. 4.

3. Analysis

3.1 Measured tilts and compressions

The tilt curves observed for one day and a loading of about 2800 m³ of fill are shown in Fig. 3. The results show that the tilts can be separated into different periods, depending on the change of tilt, which is correlated to the change of loading during the day as follows:

- (i) Before 7:30 am, no tilt variation before load application.
- (ii) Between 7:30 am and 12:00 noon, an important tilt variation is recorded in the east-west direction and in the north-south direction due to loading.
- (iii) Between 12:00 noon and 1:30 pm, the tilt variation is negligible due to a short stop (lunch time).
- (iv) Between 1:30 pm and 6:00 pm, the tilt variation is important due to continued load application.
- (v) After 6:00 pm, the tilt variation is negligible due to stop of loading.

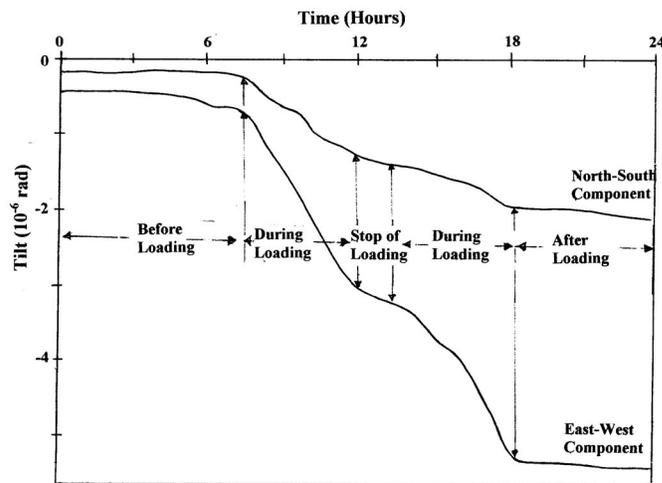


Fig. 3. Observed Tilts for one day of loading

The total tilt for one day of loading is about 5×10^{-6} rad for the east-west direction and 1.8×10^{-6} rad for the north-south direction, so the resultant tilt is 5.3×10^{-6} rad. The load was applied at 15 m from the tiltmeters and very close to the east-west direction, which explains a more important tilt in this direction.

The results in Fig. 4 show the compression signals recorded by two extensometers, which are installed over the pillars and for one day of loading. The compression measurements can be separated into different periods as follows:

- (i) Before 7:30 am, the compression variation is negligible before load application.
- (ii) Between 7:30 am and 12:00 noon, an important compression variation is recorded by the two extensometers due to loading.

- (iii) Between 12:00 noon and 1:30 pm, the compression variation is negligible due to a short stop (lunch time).
- (iv) Between 1:30 pm and 6:00 pm, the compression variation is important due to continued load application.
- (v) After 6:00 pm, end of loading, the compression variation is negligible for the first extensometer and important for the second extensometer, which is explained by a plastic deformation of the second pillar.

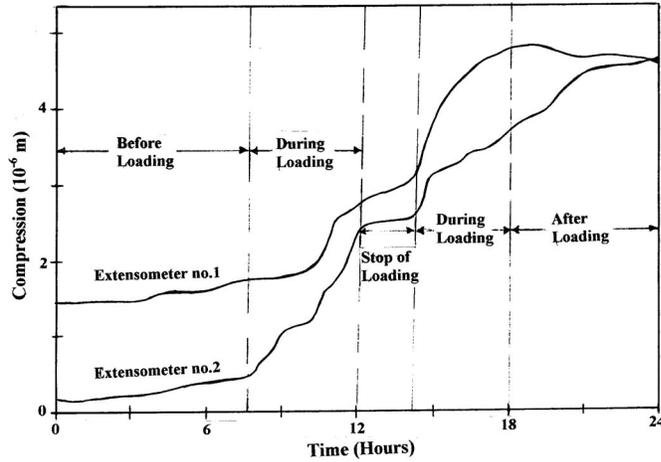


Fig. 4. Observed Compressions for one day of loading

The total compression recorded by the first and second extensometers between 7:30 am and 18h:00 pm is about 3×10^{-6} m for a volume of fill of 1600m^3 .

3.2 Theoretical tilts and compressions

The tilt and compression are calculated using Boussinesq model (Berest 1991). The model calculates the vertical displacement at any point inside a homogeneous, isotropic, linearly elastic half-space due to a concentrated point load acting perpendicular to the surface using the following equation:

$$W = \frac{F(1+\nu)}{E\pi} \left(\frac{1-\nu}{\rho} + \frac{z^2}{2\rho^3} \right)$$

Where:

- Z = Vertical distance
- $\rho = (r^2+Z^2)$
- r = horizontal distance
- ν = Poisson's ratio
- E = Young modulus
- F = Point load

The tilt is given by the first derivative of the above formula with respect to r. The compression is calculated by taking the difference between two vertical displacements for different values of Z and the same value of r. The Curves of calculated tilt and compression in function of the horizontal distance r are shown in Fig. 5. The following values were used in the tilt and compression calculation: $Z = 25$ m, $\nu = 0.2$, $E = 50\,000\text{kgf/cm}^2$, and $F = 10^3$ kgf.

Fig. 5 shows that the maximum tilt is located at 15 m from the point of application of the load and the maximum compression is exactly under it. At r equal 100 m, the tilt is (1/ 12) of its maximum value, and at r equal 60 m, the

compression is close to zero. The theoretically calculated tilt is 5×10^{-6} rad for a load of 5600×10^3 kgf (2800 m^3) at r equal 15 m. Meanwhile the measured value is 5.3×10^{-6} rad for the same conditions of loading which shows compatible results. The theoretically calculated compression value is 4×10^{-6} m for a load of 3200×10^3 kgf (1600 m^3) applied over the point of measurement. This theoretical value is compatible as well with the measured value 3×10^{-6} m for the same conditions of loading. It should be noted that the difference between the theoretical and the measured values is due to many approximations in the model as well as in the values of the parameters ν , E , Z and r .

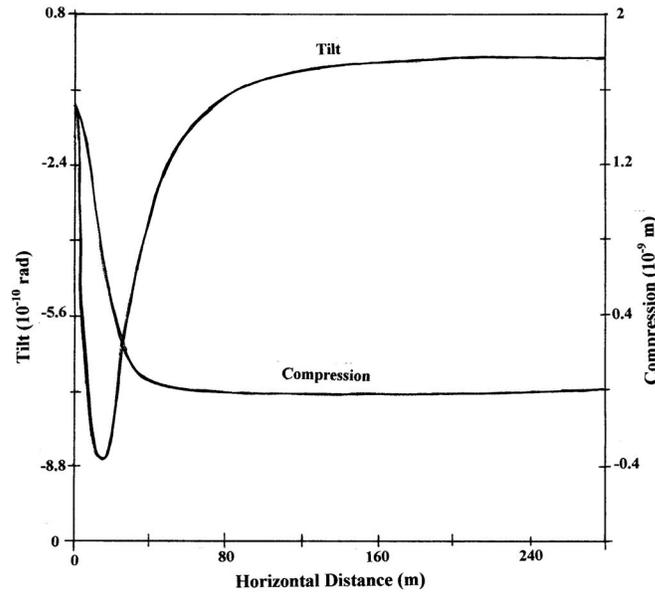


Fig. 5. Calculated tilt and compression

4. Conclusion

The following points can be concluded:

- The quartz tiltmeter and extensometer are accurate instruments and measure very small movements which cannot be measured with ordinary surveying instruments.
- The quartz tiltmeter and extensometer are low drift, low cost, easy to use and easy to install on a horizontal or vertical surface.
- Tilt and compression measurements enable to observe the behavior of a medium under loading, and whether its deformation is elastic or plastic. Our experiment showed negligible deformations under loading.
- Finally, the experiment could be considered as a nondestructive approach to evaluate the elastic modulus of the tested medium.

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