LONG-TERM AND TIDAL VARIATION OBSERVED BY TILTMETERS AND EXTENSOMETERS AT THE ALA-ARCHA OBSERVATORY (TIAN SHAN)

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Introduction

The deformation of the crust is studied in many tectonically active parts of our planet. The measurements with tiltmeters and extensometers are useful in geodynamic investigation. Such measurements are performed in the northern part of the Tian Shan mountain system (Central Asia) at Ala-Archa seismological station (30 km to south from Bishkek, Kyrgyzstan) since 1985. The Underground Laboratory of Ala-Archa is located in an underground gallery specially escavated at almost 50 m under ground level. First seismological observation started at 1982. Tilt and strain instruments were installed at October of 1985. Long series of tilt and strain data have been observed at this station. These experimental data give an opportunity to estimate the tidal deformations and the level of long-term variation of tilt and strain for this region with high seismic activity. The goals of our study were the tidal analysis of these data and the analysis of long-term deformation in connection with regional seismic activity. When possible we have also evaluated and separated the local effects from the global tidal deformation model.

Ala-Archa Observatory and its tectonic surroundings

The North Tian Shan mountain region is an active deformation zone of Central Asia. Modern space geodetic data show that the southern part of this region is indenting into the northern part with a speed of 2cm/year [1].This intracontinental tectonic system is associated with strong seismic activity and surface deformations. The main tectonic feature for this region is compression. Thrust fault systems are connected with these compressive stresses. This stress mechanism is generated by the India-Eurasia convergence spreading northwards fan-shaped and affects a large part of the Asian plate [2]. Observations and measurements on special geophysical stations contributes to the knowledge of the intracontinental deformation processes, supply the field constraints necessary to test and validate theoretical deformation models and provide new data that will contribute to seismic hazard assessment in that region.

The measurements were made in the geodynamic observatory Ala-Archa (coordinates 42°38’13’’N, 74°29’43’’E, altitude 1700m) situated on the northern slope of the Kirgizskogo mountain range in northern Tian Shan, 33 km south from Bishkek – the capital of Kyrgyzstan. This underground observatory is located near the North end of the North-South Chonkurchatskii thrust fault. The fault plane is dipping to the South with a 30° dip angle[3]. Surrounding territory is covered by complex fault systems and the boundary of a sedimentary basin lays 10 km to the North. This region presents an high seismic activity. Strong earthquakes occurred during the observation period.

The underground laboratory Ala-Archa is shown on Figure 1. It has a U shaped form with two 80m long entrance galleries and a 33m perpendicular gallery. The entrances are protected by 3 successive doors to increase thermal stability. Along the galleries there are side rooms for the installation of geophysical instruments. The ceiling, walls and floor of the galleries were covered with a special cement layer so that we have an hard core surrounded by fracturated rock. The pillars placed in the side caves are not connected with the floor of the gallery. We can consider the whole underground laboratory as a long-base instrument located inside the mountain. The entrances of Laboratory are located 40 meters above the level of the small Ala-Archa river. The annual thermal stability in the underground gallery is close to 0.25°C (Figure 2). In this region the frozen layer is 17cm thick during the winter. An important feature of this gallery is the strong seasonal effect connected with spring snow melting and raining. In winter period the gallery is practically dry but in spring or summer time there can be even water in the gallery. This feature affects the observation results especially for tilt and strain measurements.

Long-term observation with tiltmeters and extensometers from 1985 to 1997.

As shown on Figure 1 the tiltmeters were installed on a special basement in a side vault($3.4x3.4m^2$) at 23m from the entrance. To measure tilt in north-south and east-west directions we use ASNS type tiltmeters developed at the Institute of Physics of the Earth (Moscow). This instrument is similar to the Ostrovsky metallic tiltmeters but is equipped with a capacititive transducer. An electromagnetic step function is used for calibration. The scale of record is of the order of 5mm/mas.

A dual quartz tube (diameter 45mm) extensometer developed at the Institute of Physics of the Earth (Moscow) was installed along the axis of the 33m and 80m long galleries with two extremities in North-South and East-West directions respectively. The instrument has base lengths of 30m. The ends of the extensometer and the support systems are installed on special basements placed on the floor of gallery. Capacitive sensors are used for registration. The sensitivity of the instrument is at least 0.05 µmeter/mm(1.6 nanostrain/mm) on the recording paper. Piezoelectric crystals are used for calibration. The calibration is performed usually once per week. The recorders room is located in the seismological station building at 300m from the gallery entrances. The connection to the sensors is insured by a special buried line crossing the Ala-Archa river.

To estimate the regional stresses we can use the information given by the local earthquakes. During the observation period strong earthquakes happened near the observatory. On Figures 3,4,5 and Table 1,2,3 one can find the solutions for the following earthquakes: 13h30m 17.06.1988, coordinates 43.00°N, 77.42°E, M= 5.0, R=200 km; Tash-Bashatskoe 13h48m 05.03.1989, coordinates 42.57°N, 74.73°E, M=4.6, R=20 km; Susamskoe 02h04m19.08.1992, coordinates 42.07°N, 73.63°E, M=7.2, R=110 km.

TABLE 1.
The solution for the 13h30m 17.06.88 earthquake
(43.00°N, 77.42°E, M=5.0, R=200 km)

T (extension)		P (compression)	
PL	AZM	PL	AZM
90	239	22	150

TABLE 2.
The solution for the 13h48m 05.03.89 earthquake
(42.57°N, 74.73°E, M=4.6, R=20 km)

T (extension)		P (compression)	
PL	AZM	PL	AZM
33	356	90	264

TABLE 3.
The solution for the 02h04m 19.08.92 earthquake
(42.07°N, 73.63°E, M=7.2, R= 110 km)

T (extension)		P (compression)	
PL	AZM	PL	AZM
31	352	59	165

According to the Figures 3, 4, & 5 one can see that for the M=7.2 strongest earthquake we had a compressive stress in a near North-South direction which is typical for this region. For the smaller ones we had different situations with compressive or extensive stress in a near East-West direction reflecting the complex fault situation in the region.

The observed long-term curves of tilts in North-South and East-West directions are shown on Figure 6. First of all one can see the strong seasonal effect during the 1987 spring. In this period surface water infiltrated the gallery and produced tilts up to 7”. In the following years this effect corresponds to a step in the curve with amplitude varying between 0.1” and 3”. The step is always to the North and to the East.

Long term tilt during the period 1985-1997 reached nearly 2” to South in the meridian and near 7” to West in the prime vertical. It is more correct to consider the results only after the middle of year 1987 as in this case we have a lower seasonal effect on the curves. For this ten-years period a systematic drift to South was observed reaching 5”. For the second component we see that the tilt returned in 1997 to the middle 1987 level. We observe two different periods : during the first two years we have 3” drift to West and in the second part a tilt to East returning to the middle 1987 level. The inversion of the tilt coincide with the M=4.6 earthquake with epicenter at 20km from the station. In 1992 the strongest earthquake with magnitude 7.2 affected the tilt in both directions but did not change the sign of tilt rate. A small earthquake (M=4.6, R=20 km) with epicenter near the observatory had a stronger effect than the M=7.2, R=110 km earthquake at a larger distance.

Figure 7 shows the observed curves of the extensometers. As already mentioned for the tiltmeters one can see the strong seasonal effect ($2x10^{-6}$) during the spring 1987, but we can see other variations at this level during the observation period. It is no more the most important effect. The different reactions to spring water influence may be connected with the different base-lengths of the instruments. For the tiltmeters we have either the base of instrument (20cm) or the size of the basement (2.5m) and for the extensometers we have a longer base (30m). Long-term variation of strain had a systematic character for the east-west direction reaching $10x10^{-6}$ during the 1985-1997 period with different annual rates. For the North-South component an extension up to $3.5x10^{-6}$ is observed during the first three years. A compression of $7x10^{-6}$ is observed during the second part, after the large M=7.2 earthquake in 1992. This effect may be connected with the typical stress situation of the region: a compression along the NS direction and an extension along the EW direction.

Steps in strain variation are observed at pre- and post-earthquake period. The effect reaches $1x10^{-6}$ as well for the small M=4.6 earthquake as for the strong M=7.2 earthquake. The step amplitude is nearly constant at the µstrain(10^{-6}) level and we can create an equation connecting the magnitude and the distance for equal strain release:

$M=A. \log R$ (1)

where M is magnitude and R is the distance in km from the epicenter to the observation point. We find the constant A when we use the information given by two earthquakes: M=7.2 and R=110 km ; M=4.6 and R=20km. The value of A is equal 3.51 and we have :

$M = 3.51. \log R.$ (2)

It means that if we observe a strain level $1x10^{-6}$ for M=7.2 at 110 km distance , we should obtain the same level of deformation for M=6 at distance $R=10^{(6/3.51)} = 10^{1.709} = 51$ km .

This equation for equal strain level reflects the properties of the region.

The tilt and strain components reflected the air pressure variation (Figures 8 & 9).The first figure shows short period variations in strain and tilt at the tidal deformation level. The second figure shows long-term changes in tilts for different seasons. The high level of correlation with air pressure reflects the fracturation of the rock surrounding the underground laboratory.

Earth Tide Analysis of Tilts and Strain.

The earth tide analysis of the tiltmeters and extensometer data set 1993-1996 has been carried out with program ETERNA 3.0 using the Tamura tidal potential catalogue and numerical band pass filtering. The adjusted tidal parameters are given in Table 4 for North-South component and in Table 6 for East-West component. The standard deviation for different components and for different periods is large of the order of 3 to 4 mas. As the results for the three years series and for partial analysis of one year series do agree within the RMS errors, we can conclude that the main problem is not to be found in temporal variations of the calibration factor but most probably in temporal variations of signal cable resistance. This last effect is also responsible of the large S1 amplitude. This situation is typical for a long signal cable with analog registration devices.

For comparison with the observed tidal parameters, the tilt tide parameters have been predicted from the Wahr-Dehant (1987)[4] model and the oceanic tidal load vector **L** computed using the Schwiderski model for the North-South and East-West components. If we call **B** the difference between the observed tidal vector and the predicted body tides according to [4], the discrepancy in amplitude and phase is given by the final residual vector **X=B-L** (Tables 5 & 7).

For North-South component the amplitudes of the diurnal waves are very small and we consider only the main semi-diurnal wave M2. The residual vector B for M2 is close to the oceanic load correction L in amplitude but has a large phase discrepancy. Consequently the discrepancy in amplitude of the anomalous vector X reaches 6.5 percents of the M2 amplitude. It corresponds roughly to a 10% attenuation of the strain amplitude. The observed amplitude factor $g = 0.645$ is low compared to $g_{md} = 0.705$.

For the East-West component we observe a stronger effects in amplitude and phase for the different tidal waves. The anomalous vector B reaches 1.5 mas for the main waves. It is ten times more than the oceanic correction. Strong phase anomalies reach 16^{o}-22° for diurnal waves (0.7°-1.0° is the RMS error level) and 7-14° for semi-diurnal waves (0.3°-0.7° is the RMS error level). Here also a negative amplitude discrepancy is observed for all waves. For diurnal components X amplitude reaches 25 percent of the observed tidal amplitudes. For the strongest wave M2 it is 13 percents with RMS error level 1 percent.

The anomaly for tidal tilt parameter may be due to cavity and topographic effects as well as to the regional geological conditions.

The earth tide analysis of the strain data set 1993-1996 has been carried out with programs VEN66 with CTE550 potential and ETERNA 3.0 with the Tamura tidal potential catalogue and numerical filtering. The adjusted tidal parameters are given in Table 8 & 9 for North-South component and in Table 10 & 11 for East-West component. The following results are not yet corrected for the air pressure or ocean loading. The standard deviations for different components and for different periods are at the 2-5 nstrain level. The error level reaches 2 percents for M2 in NS component and is higher for the other waves. The results of tidal analysis by two methods are similar as well in amplitude as in phase except for the semi-diurnal waves in EW. The residues with respect to a theoretical model with given Love (h=0.621) and Shida(l=0.090) are presented in the last columns of Tables 8 & 10. The negative discrepancy in amplitudes reaches 30-60 percents for the largest waves. For the main diurnal and semi-diurnal waves in NS as wel as for the diurnal waves in EW the observed amplitude factor is close to 0.6. The semi-diurnal waves have a negligible amplitude in EW. The discrepancy in phases is only 1-4 degrees and corresponds to the RMS error level.

These large anomalies are probably due to the installation conditions as we get strong cavity effect when the fixed point of the dual instrument is placed at the angle of two perpendicular galleries (Figure 1). A second reason may be the surrounding rock fracturation. A third reason may be the complex fault conditions and the compressive stress in the area. Practically we are close to the model, with a 6.5 percents discrepancy, only for tilt wave M2 in North-South direction.

TABLE 5.

Results for tilt in North-South

X(X,c) =**B**(B,b) –**L**(L,l)

Wave	**Theor. Ampl.**	B	b	L	l	X	c
N2	1.51	0.22	169.4	0.08	66.1	0.25	-173.4
M2	7.88	0.33	178.2	0.28	61.2	0.52	-152.7
S2	3.66	1.34	117.1	0.13	25.5	1.35	122.7

TABLE 7.

Results for tilt in East-West

X(X,c) =**B**(B,b) –**L**(L,l)

Wave	**Theor. Ampl.**	B	b	L	l	X	c
O1	4.41	1.25	105.3	0.09	64.9	1.18	108.3
K1	6.21	1.41	117.3	0.16	47.2	1.37	123.5
N2	2.23	0.42	156.3	0.04	167.1	0.38	155.1
M2	11.63	1.68	147.6	0.17	164.7	1.52	145.7
S2	5.41	1.16	72.9	0.06	160.4	1.15	69.7

Conclusions.

The observations in the underground observatory Ala-Archa show interesting long term effects. These variations reflected the pre- and post-earthquake regional deformation. We observed changes in the E-W tilt curve and in the N-S strain curve after a M=4.6 earthquake at 20km from the station. After it the extensometers reflected the typical stress situation of the region – a compression along the North-South direction and a extension along the East-West axis. For a given 1×10^{-6} deformation(1µstrain) observed with the extensometers we found a relation between the magnitude of earthquakes and the distance from the epicentre:

$$M = 3.51 \log R,$$

where R is in km.

For tidal amplitude we found negative anomalies for tilt and strain. It means that the amplitudes are systematically reduced compared to the models. Only the M2 wave in tilt NS is close to the model. For the other components we have anomalies in amplitude of more than 10 percents. For tilt the phase differences are generally large. For strain phase the discrepancy is at the RMS error level. Cavity and geological effects may explain these discrepancies [5].

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TABLE 4.

Tidal Analysis Results for tilt NS

TABLE 6.

Tidal Analysis Results for tilt EW

TABLE 8.

Tidal Analysis Results for strain NS VEN66 method

TABLE 9.

Tidal Analysis Results for strain NS ETERNA method

TABLE 10.

Tidal Analysis Results for strain EW VEN66 method

TABLE 11.

Tidal Analysis Results for strain EW ETERNA method

Figure 1: Sketch of Ala-Archa underground laboratory

Figure 2: Temperature variations at Ala-Archa in 1989 and 1990 showing the annual variation

1- ground temperature
2- temperature inside the laboratory

Please note the scale difference. The lag of the annual wave in the laboratory is close to three months. An offset has been applied on curve 2 on January first 1990 to avoid superposition.

Figure 3: Focal mechanism of the 17/06/88 M=5.0 earthquake

Figure 4: Focal mechanism of the 05/03/89 M=4.6 earthquake

Figure 5: Focal mechanism of the 19/08/92 M=7.2 earthquake

Figure 6: Non tidal tilt variations in NS and EW components

Figure 7: Non tidal strain variations in NS and EW components

Figure 8: Typical short term correlation between tilt(a,b), strain(c,d) and pressure changes(e)

Figure 9: Typical correlation between long term A Tilt variations(a,b) and air pressure(c)
B Strain variations(d,e) and air pressure(f)

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