Analysis of the Kinematics of a Deep-Seated Landslide

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SUMMARY

A >20 years long geodetic monitoring record of a major, slow moving (about 15cm/yr) deep-seated landslide in Northern Greece was analyzed. The same exponential function was found to describe the long-term kinematics of all control points on the sliding mass, as well as of another neighboring, >1km long and 600m wide landslide. This evidence indicates that for major, deep-seated landslides the long-term kinematics of all their parts reflect an overall exponential trend, on which smaller events of accelerated movement are superimposed. Such events correspond to the residuals of observations after their non-linear detrending, have a mean return period of 4.0 to 7.5 years, as a least-square derived spectral analysis indicated, and are most likely triggered by meteorological events. These results are the first to be ever obtained, for long, detailed geodetic records of landslides are extremely rare.

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1. INTRODUCTION

Monitoring of unstable slopes is not an easy task. Surface monuments are in most cases easily destroyed, conventional geodetic work is expensive, while the available GPS landslide records are still short. For these reasons, detailed systematic and long-term monitoring data of major landslides are very rare, and questions such as whether the various parts of a landslide follow the same trend, or whether periodic signals characterize creeping slopes, are questions that cannot be answered satisfactorily.

An opportunity to answer these questions presents the analysis of the >20-yr long geodetic record of Mantria landslide, a large deep-seated landslide at the rims of the Polyfyton Reservoir, in Northern Greece. The displacements of several control stations at various parts of this landslide were processed using least-squares curve fitting and spectral analysis techniques to examine whether they can be simulated by specific mathematic formulas, and whether the spectral characteristics of the displacements of the various stations were similar. The results were compared with results from an analysis of selected control stations of the nearby Alexis landslide, in order to investigate the significance of these results.

2. LANDSLIDE GEOMETRY AND MONITORING DATA

The Mandria landslide is a major landslide at the rims of the Polyfyton Reservoir (Fig.1). Its behavior is vital for the just 1km away 105m high and 297m long earthfill Polyfyton Dam constructed in 1974, on Aliakmon River. The slipping mass consists of about $10^7 m^3$ of highly tectonized gneiss above a curvilinear, shear failure plane. Its maximum depth is 35m and covers a rather steep slope, about 750m long and 450m wide. The top of the landslide is 90m above the average reservoir level. The sliding mass has a roughly semi-elliptical shape and is cut by numerous cracks. Slip rate is low up to 15cm/yr.

The geodetic monitoring record analyzed consists of >500 epochs of distance changes of seven control points from a stable, reference station, covering a period of 23 years, between 1978 and 2001 (Fig. 2a). From a comparison with spirit leveling data, these distance changes were found accurate to within a few mm and representative of the landslide kinematics (Stiros et al., 2004).

The nearby Alexis landslide corresponds to a larger slipping mass, in similar geologic conditions (Riemer et al., 1996). For this landslide a record of three monitoring stations covering a period of 17 years was available (Fig. 2b).

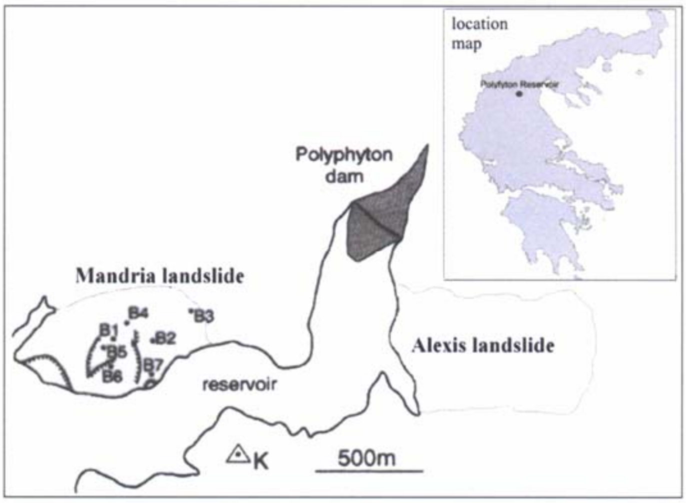

Fig.1 Location map of the Mandria (1km away from the Polyfyton dam) and the Alexis (next to the dam) landslide. The 7 control stations B1 – B7, the fixed station K on the stable ground, and the cracks (thin lines with ticks) of the Mandria landslide are also shown.

3. DATA ANALYSIS

Based on the trial and error, we found that an exponential model of the form

$$d_{ij} = A_j[1 - \exp(-t_i / B_j)] + C_j \qquad (1)$$

(where j is the index of the control station whose displacements are examined, d_{ij} is the observed horizontal displacement (mm) of station j in epoch i, and A_j, B_j, C_j, K_j are unknown coefficients to be determined from the displacements of station j) best fit to the available record of all seven monitoring stations (correlation coefficients R>0.99). Results are summarized in Table 1. The same function was found to provide an optimum fit to the monitoring record of the Alexis landslide (Fig. 2b)

Residuals remaining after curve fitting to all seven control stations of the Mantria landslide were analysed on the basis of the Lomb normalized periodogram in order to derive their spectral characteristics. Results are shown in Fig 3, for the range between the Nyquist frequency ($\frac{1}{2T}$) and the frequency $\frac{N}{2T}$, where T is the whole time interval analyzed, i.e. the interval in which results are statistically significant (Bath, 1974).

As can be seen in Fig. 3, there are a few statistically significant peaks (Table 3) corresponding to periods of 2.5 to 7.5 years, common in all control stations' spectra. A peak detected at a very low frequency was omitted since it was attributed to the "edge" effect (Press et al., 1988).

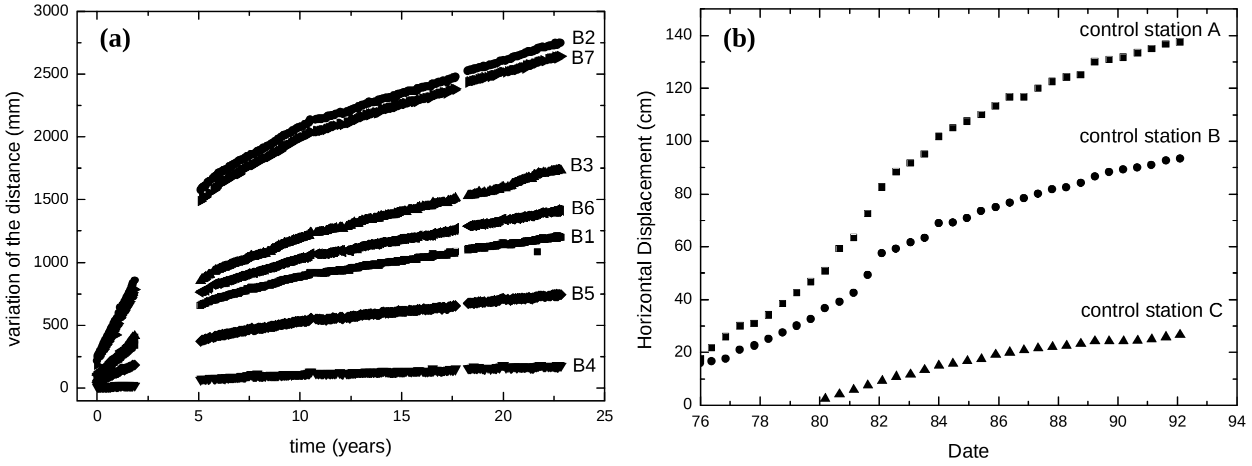

Fig. 2 (a) Distance changes of control stations B1 to B7 of the Mandria landslide from the stable station K and (b) Distance changes of 3 control stations of the Alexis landslide.

Table 1 Coefficients of the exponential model (eq.1) along with the corresponding 95% confidence bounds, and the corresponding linear correlation coefficients R for the Mandria slide

Model	**Control point**	**Estimated Coefficients**			**Correlation Coefficient R**
		A	**B**	**C**	
Model : $d=A(1-e^{-t/B})+C$	B1	1128 ± 10	3113 ± 72	112.9 ± 7	0.99642
	B2	2493 ± 20	2809 ± 62	279.1 ± 16	0.99633
	B3	1744 ± 17	3640 ± 92	97.09 ± 10	0.99641
	B4	208.2 ± 4.7	5243 ± 254	6.055 ± 1.47	0.99250
	B5	724.2 ± 6.2	3475 ± 80	58.81 ± 3.96	0.99686
	B6	1335 ± 10	3152 ± 67	124.3 ± 7.3	0.99705
	B7	2443 ± 16	2866 ± 52	241.6 ± 12.7	0.99751

Table 2 Coefficients of the exponential model (eq.1) along with the corresponding 95% confidence bounds, and the corresponding linear correlation coefficients R for the Alexis slide

Model	**Control point**	**Estimated Coefficients**			**Correlation Coefficient R**
		A	**B**	**C**	
Model : $d=A(1-e^{-t/B})+C$	*B1*	992 ± 5.8	2194 ± 34	83.87 ± 2.17	0.99972
	B2	2232 ± 11	2003 ± 28	209.3 ± 5.5	0.99974
	B3	1452 ± 12	2319 ± 48	46.52 ± 3.96	0.99954
	B4	178.9 ± 11	3806 ± 408	2.499 ± 1.307	0.99398
	B5	625.7 ± 5.4	2400 ± 51	40.66 ± 1.67	0.99954
	B6	1166 ± 7	2176 ± 35	87.79 ± 2.69	0.99969
	B7	2196 ± 14	2094 ± 34	180.2 ± 5.3	0.99968

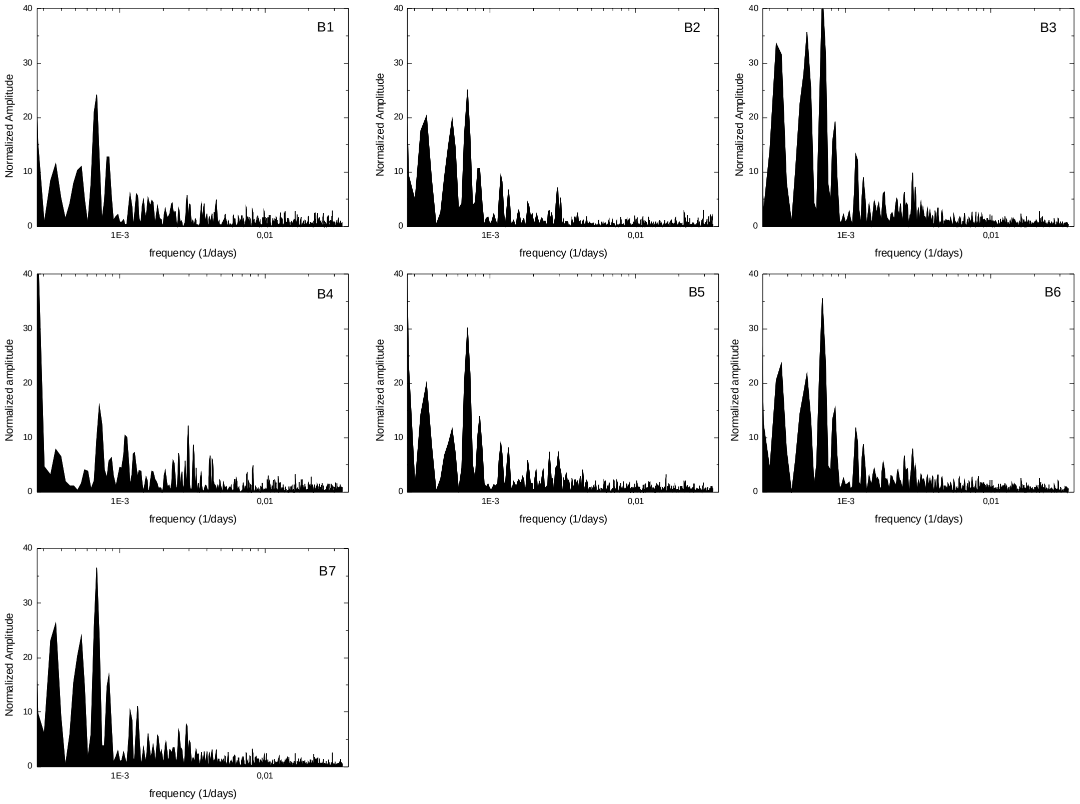

Fig. 3 Spectra of the residuals of the displacements for all control stations of the Mandria landslide computed using the Lomb periodogram. Some statistically significant peaks (Table 3), common in the spectra of the displacements of all control stations are also shown.

Table 3 Dominant periods of the residuals of distance changes for the Mandria landslide

Control point	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**
T_1 (years)	3.92	3.92	3.92	3.75	3.92	3.92	3.92
T_2 (years)	3.22	7.50	5.15	0.93	7.50	7.50	7.50
T_3 (years)	7.50	4.85	8.24	2.50	3.22	5.15	5.15
T_4 (years)	5.00	3.22	3.22	-	5.00	3.22	3.22

4. DISCUSSION - CONCLUSIONS

As can be deduced from Tables 1 and 2 the long-term (>20 years) kinematics of all control points of the Mantria and the Alexis landslides can be described by the same exponential function.

Since the results were identical with those obtained from the analysis of the displacements of another neighboring landslide as well, we can conclude that for major deep-seated landslides the long-term kinematics of all their parts reflect an overall exponential trend, differing only as far as on the amplitude of displacements.

This result is supported by spectral analysis. Events of accelerated movement with a mean return period of 4.0 to 7.5 years are superimposed on this general trend. Such movements are possibly triggered by meteorological events.

A few monitoring points in each landslide seem, therefore, representative of its overall kinematics.

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