DO DEEP-SEATED LANDSLIDES SHARE COMMON KINEMATIC CHARACTERISTICS?

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Abstract: The detailed, long-term kinematics of major landslides in the primary stage of creep are very poorly known, for geotechnical sensors are destroyed after small amounts of movement and detailed geodetic monitoring records usually range up to a few years only. A unique, >20 years-long geodetic record describing the kinematics of two major deep-seated landslides at the rims of the reservoir of large dam in Greece was analyzed to shed some light to this problem. It was found for both landslides (1) that the slip of all monitoring stations can be described either by a single exponential curve, or by an exponential curve on which a linear trend is superimposed (2) that a log-linear relationship between the coefficient of the exponential term, reflecting the tendency for stabilization of the landslide, and the cumulative displacement of the corresponding station exists, and (3) that displacements of all stations are characterised by effects with the same period, 4 to 7.5 years, as the spectral analysis of their displacements reveals.

1. Introduction

A major problem with landslides is to understand their kinematics and predict a future anomaly that could lead to failure. For deep-seated landslides, i.e. for those with a basal failure surface at a depth >10m, understanding and prediction of their kinematics is very difficult, for their movement is controlled by a number of parameters, and precipitation is only one of them.

A main reason why the details of kinematics of deep seated landslides are very poorly understood is the nearly total absence of detailed records describing the movement of landslides over periods at least several tens of years long because of: (1) detailed systematic and long-term monitoring data of major landslides are very rare since surface monuments and in situ instruments are easily destroyed, (2) conventional geodetic work is difficult and expensive, while the available GPS landslide records are still too short (usually 3-5 years long [1]) to arrive at significant conclusions.

The long (> 20 years) geodetic record of the Mandria landslide, a large deep-seated landslide at the rims of the Polyphyton Reservoir, in Northern Greece provides an opportunity to study this problem. This landslide, as well as the Alexis landslide are next to Polyphyton dam, have been systematically surveyed by the Hellenic Public Power Corporation, owner of the dam, in order to detect possible acceleration of their movements.

A number of control points were established on the moving slopes for both landslides and their distance and elevation difference from some stable (reference) points were measured systematically for >20 years using similar geodetic instrumentation and techniques; hence two unique and precious surveillance records are available [2].

In this article, we present the results of the analysis of the geodetic monitoring record of the Mandria landslide, trying to investigate (1) if there are any similarities in the pattern of movement of the various control stations and (2) if the movement of all control stations is influenced by periodic effects.

Results of the analysis of the Mandria landslide were subsequently compared with those from the nearby major Alexis landslide in order to investigate whether they are of broader significance.

2. Geological setting

The 105m high and 297m long Polyphyton earthfill Dam was constructed in 1974 in a gorge of the Aliakmon River in Northern Greece, in a geologic background consisting of highly tectonised gneiss, and a reservoir with a capacity of 2 km^3 was formed.

The wider area is characterised by numerous landslides in the steep slopes of the highly deformed and fissured gneiss. Among them, the Alexis and the Mandria slide, shown in Fig. 1 are of major importance for the whole project.

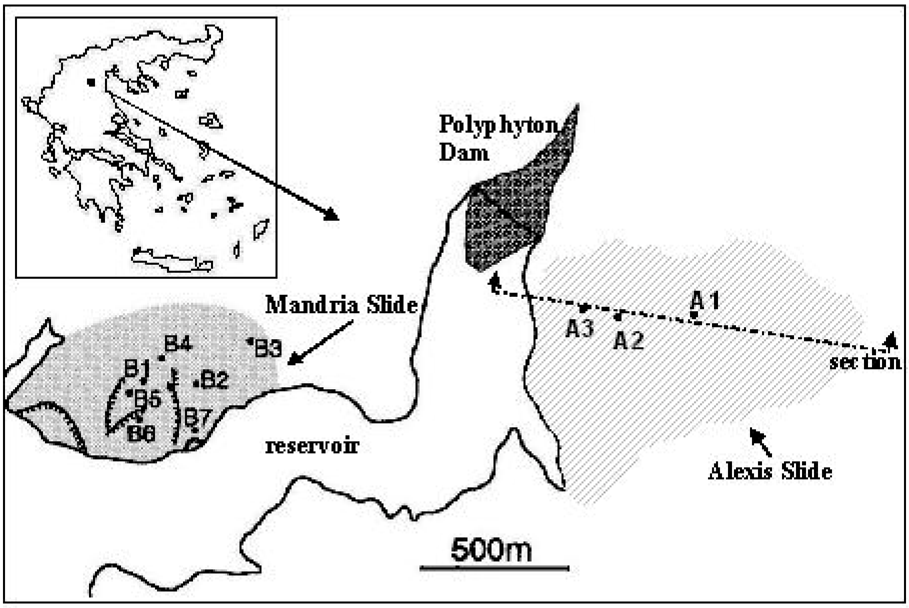

Figure 1: Location map of the Mandria and the Alexis landslides in the reservoir formed by the construction of the Polyphyton Dam. Control stations B1 – B7 and ground cracks (thin lines with ticks) of the Mandria landslide are also shown.

The Alexis slide, next to the east abutment of the dam, has a volume of $20*10^6$ m^3. It is semi-elliptical in form, up to about 1100 m long and 600 m wide, and its crown is approximately 400 m above the reservoir level. Major basal planes are to the depth of 40 to >100 m (Fig. 2). The first signs of movement were observed in 1972, and the monitoring system established in 1974 revealed a maximum surface velocity of up to 10 mm/day, but also a tendency for stabilization [3] (velocity up to the order of 1cm/yr since the 1980's, see Fig. 3b), partly imposed by stabilization works [3].

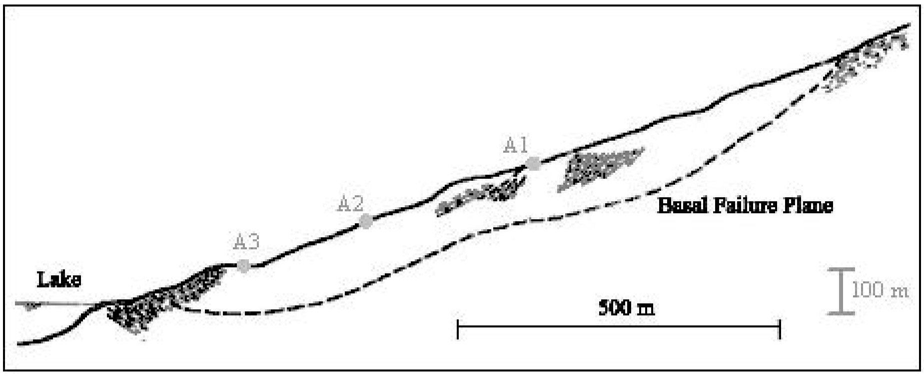

Figure 2: Cross section of the Alexis slide. The basal failure plane and the position of control points A1 – A3 are shown. For location see Fig. 1.

The Mandria slide covers an area about 750 m long and 450 m wide with a mass of 10^7 m^3 in a rather steep (average value 44 %) slope. The top of the landslide is at the height of 380 m, about 90 m above the maximum reservoir level, and its toe at the height of 230 m, about 40 m below the minimum function reservoir level; 60 % of the landslide mass is above the water level. This sliding mass has a roughly semicircular shape and is cut by numerous cracks. The basal shear failure plane is curvilinear, at a maximum depth of 35 m. Average slip rate is about 15 cm/yr, and there is also a clear tendency for stabilization [4] (Fig. 3a).

Interesting to note that both landslides proved insensitive to the 1995 Kozani –Grevena earthquake of magnitude 6.5, during which an acceleration of 0.052g was recorded at the dam [3].

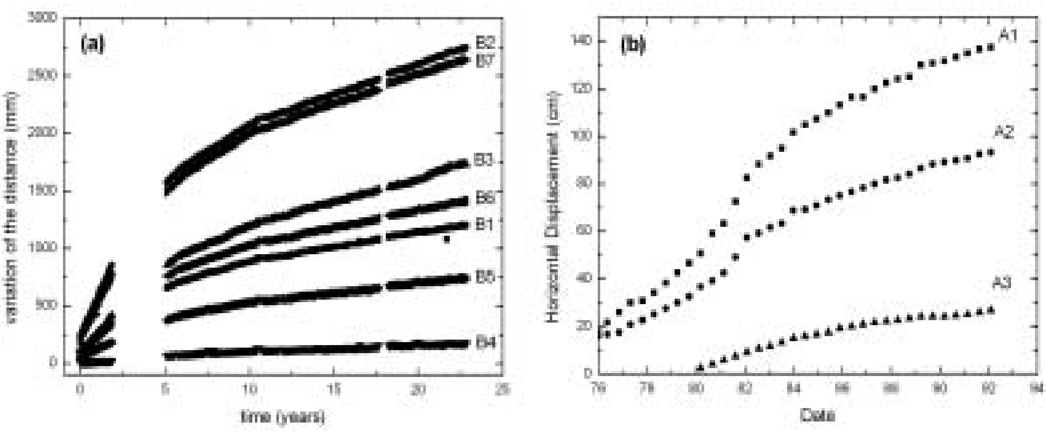

Figure 3: Distance changes versus time of seven (B1 to B7) control stations of the Mandria landslide (a) and of 3 control stations (A1, A2, A3) of the Alexis landslide (b), respectively, from stations in stable ground.

3. Available Data

The geodetic monitoring record of the Mandria landslide covers a period of 23 years (1978-2001) and consists of more than 500 unevenly-spaced epochs of nearly-horizontal distance changes of seven control points from a reference station in a stable area (Fig. 3a). Observed distance changes were compared with spirit leveling data and were found accurate to within a few mm, and fully representative of the landslide kinematics [4]. For the Alexis landslide a similar geodetic record of three monitoring stations covering a period of 17 years was also analysed (Fig. 3b).

4. Methodology

Our analysis of the geodetic monitoring record of the Mandria landslide was made in two phases. At the first step we modelled distance changes, describing landslide horizontal movement of all seven control stations by mathematical equations describing the displacement trend of each station. At a second step, we computed the differences between observed values and those predicted by our model, and formed a new set of observations of residuals (detrended values) for each control station. On the basis of spectral analysis we investigated whether the displacement records are characterised by periodicities.

5. Data Analysis and Results

5.1. Step 1: Computation of the displacement trends of control stations

Using the trial-and-error technique and the Least-Squares method we found that an exponential equation of the form

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

or

$$d_{ij} = A_j[1-\exp(-t_i / B_j)] + K_j * t_i + C_j + \upsilon_{ij} = dp_{ij} + \upsilon_{ij} \quad (2)$$

are a simple function that can excellently fit to the displacement records of all seven control stations of the lansdlide, and hence they can describe their displacement trend.

In eq. (1)

j is the index of the control station examined,

d_{ij} the observed horizontal distance changes of station j in epoch i,

A_j, B_j, C_j, K_j are unknown coefficients estimated from a system of N equations, one for each of the N observed distance changes

υ_{ij} is a the residual of the curve fitting, a normally small quantity reflecting the difference between observation and model prediction. This residual, known as detrended value describes errors in measurements and calculations, as well as the effect of parameters other than those defining the displacement trend.

dp_{ij} is the predicted horizontal distance changes of station j in epoch i

The results of the fitting (determination of the unkown parameters of eq. 1 and 2) are shown in Table 1, indicating that modelling was excellent (correlation coefficient >0.99!).

The same process was applied in the available displacement records of three control stations of the Alexis landslide as well. Results of fitting summarised in Table 2 clearly indicate that fitting was also excellent (correlation coefficient again >0.99!).

Model	Control point	Estimated Coefficients				Correlation Coefficient R
		A	B	C	K	
Model 1: $d=A(1-e^{-t/B})+C$	*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
Model 2: $d=A(1-e^{-t/B})+K*t+C$	*B1*	643.7 ± 13.5	1394 ± 67	70.41 ± 5.84	0.05915 ± 0.00216	0.99862
	B2	1534 ± 25	1314 ± 52	174.6 ± 12.3	0.1247 ± 0.0041	0.99885
	B3	825.2 ± 10.6	1261 ± 42	20.36 ± 5.77	0.1065 ± 0.0018	0.99944
	B4	67.88 ± 4.98	1505 ± 227	0.3637 ± 1.79	0.01309 ± 0.00077	0.99451
	B5	369.2 ± 6	1382 ± 51	31.34 ± 2.63	0.04131 ± 0.00096	0.99929
	B6	742.9 ± 8	1340 ± 34	70.11 ± 3.78	0.07264 ± 0.00131	0.99960
	B7	1505 ± 15	1392 ± 30	150.5 ± 6.3	0.1191 ± 0.0023	0.99967

Table 1: Estimated coefficients of the exponential model of (eq.1 & 2) describing the trend of the Mandria landslide kinematics. 95% confidence intervals and the corresponding linear correlation coefficients are also shown.

Control point	Estimated Coefficients			Correlation Coefficient R
	A	B	C	
A1	188.1 ± 28.2	157.6 ± 45.5	9.372 ± 5.542	0.99221
A2	130.6 ± 22.5	177 ± 54.6	9.103 ± 3.437	0.99282
A3	54.52 ± 1.84	79.83 ± 7.14	-23.4 ± 2.77	0.99947

Table 2: Same as Table 1, but for the Alexis slide

A question arising was whether there exists any relationship between the decay coefficient B_j and the cumulative (or maximum) displacement $d_{j,max}$ of each station *j*. This question is reasonable, for the two variables are slightly only correlated, since B_j is computed from the whole set of d_j values and not only from $d_{j,max}$.

Based on the trial-and-error approach we examined various functions, and found that a log-linear relationship, i.e. a function of the form

$$B_j=\lambda * log(d_{jmax}) + p \quad (\lambda, p \text{ unknown coefficients}) \tag{3}$$

is likely to characterize these variables. The plot of coefficients B_j versus the logarithm of the maximum displacement for each control station *j* for the model described by eq. (1) and eq. (2) respectively, are shown in Fig. 4. A linear trend is clearly seen in both diagrams indicating that coefficient B_j which expresses the attenuation of the rate of displacement depend on the amplitude of the maximum horizontal displacement.

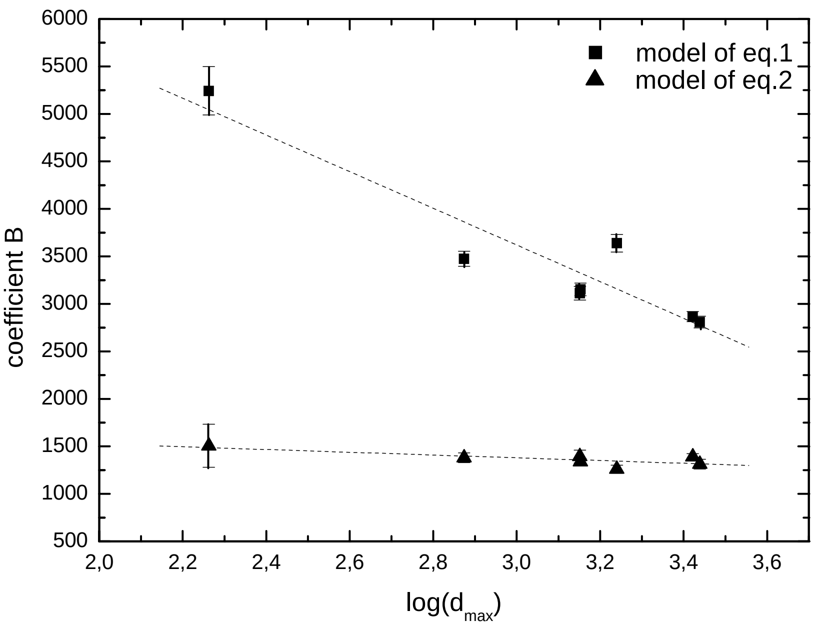

Figure 4: Plot of coefficients B_j of eq. (1) and eq. (2) versus $log(d_{max})$ for each control station j of the Mandria landslide. The dashed lines indicate the best fitting lines for the coefficients B_j of the models based on equations (1) and (2), respectively. The 95% confidence level bounds for coefficients B_j are also shown

5.2. Step 2: Spectral Analysis of residuals (detrended data)

The trend line analysis described above permitted for each observation d_{ij} at time i a predicted value dp_{ij} and their difference from observed values (residuals) to be computed. The question is whether these residuals are characterised by random errors only, or by periodic signals as well.

The simplest and most efficient way to identify periodic signals in a data set is spectral analysis of the corresponding detrended values. Fourier Transforms is the most commonly used method in Spectral Analysis. This technique, however, requires continuous and equidistant data. Datasets characterised by gaps or non-equidistant values, should either be divided in subsets, and hence either longer period signal are lost, or missing values should be added using interpolation, and hence additional noise is introduced.

Since our data are not equidistant and are characterised by gaps, in order to avoid the shortcomings of the conventional Fourier Transform analysis, we analysed our data using the ”Normperiod code” [4, 5], an original Fortran code compiled on the basis of an algorithm known as the Lomb periodogram [6, 7]. This last algorithm is equivalent to the fitting of a sine curve to the data using the Least-Squares method and does not require equidistant data.

The results of our spectral analysis of all seven points of landslide Mandria are summarised in Table 3 and Fig. 5. As can be seen in Fig. 5 there are a few statistically significant peaks above the 95% confidence level corresponding to periods of circa 4.0 to 7.5 years, common in the spectra of all control stations. A peak detected very close to zero frequency ($<10^{-4}$ (1/days)) was omitted as not statistically significant.

Control point	B1	B2	B3	B4	B5	B6	B7
T_1 (years)	3.9	3.9	3.9	3.8	3.9	3.9	3.9
T_2 (years)	3.3	7.5	5.0	0.9	7.5	7.5	7.5
T_3 (years)	7.5	5.0	8.2	2.5	5.00	5.0	5.0
T_4 (years)	5.0	3.3	3.2	-	3.2	3.2	3.2
T_5 (years)	-	-	2.3	-	-	2.3	2.0
T_6 (years)	-	-	-	-	-	-	2.3

Table 3: Dominant periods identified in the residuals of displacements of control stations of the Mandria landslide. Periods of circa 4 and 7.5 years are common in all records.

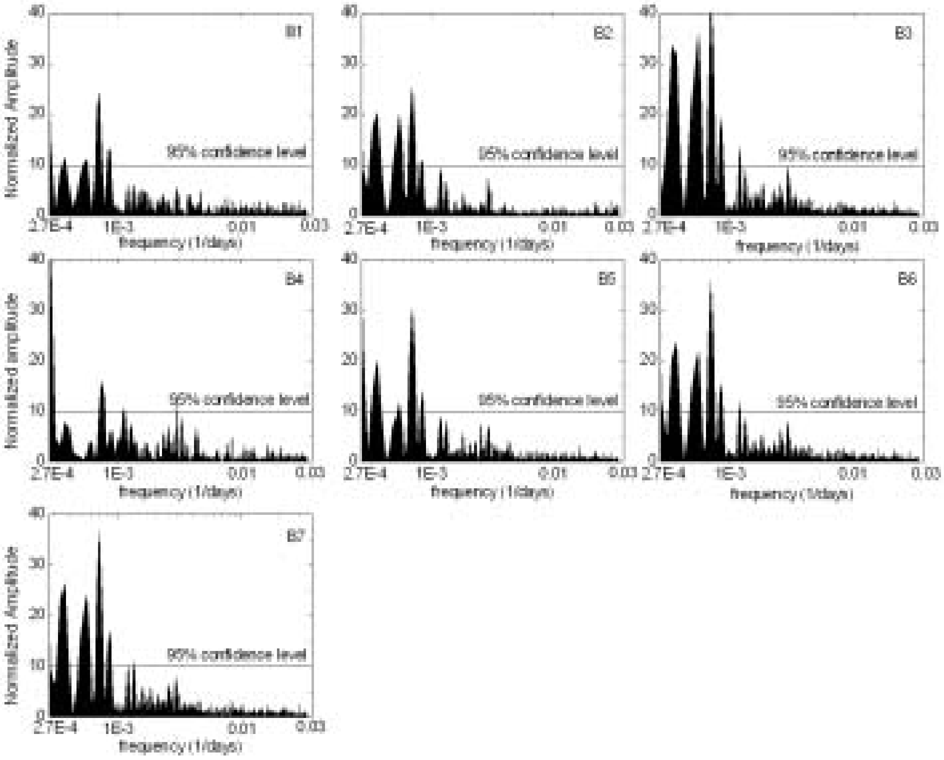

Figure 5: Spectra of the residuals of the displacements for all control stations of the Mandria landslide computed using the "Normperiod Code", based on the Lomb periodogram. Statistically significant peaks (above the 95% confidence level, represented by a straight solid line), common in the spectra of the displacements of all control stations, are also shown and listed in Table 3.

6. Discussion and Conclusions

A first main conclusion of our analysis is that the displacements of all seven control points of the Mandria landslide can be described by the same simple exponential functions (eq. (1) - they differ as far as the parameters of this function are concerned (see Table 1). This result seems not coincidental, for the same conclusion can be inferred for the Alexis landslide as well (Table 2), which, however, affects similar geological formations.

A second main conclusion is that a long-linear relationship between the coefficient of displacement rate attenuation and the cumulative displacement in any time window is also likely. Both these results have been confirmed by observations from the Alexis slide, a nearby landslide affecting similar geologic formations (tectonised gneiss).

A third main conclusion is that all control stations seem to be affected by the same periodic effects, with periods between 4 and 7.5 years. This reveals that except for some major deep landslides for which there is evidence of seasonal variation of their movement (e.g. the Slumgullion landslide [1] in southwest Colorado, USA), there are landslides with a much larger periodicity (some years). The type of landslide, involving the geologic materials, bedrock or soil, and the geometry, and degree of slope steepness, as well as hydrological effects [3] may control this periodicity which tends to accelerate or decelerate the landslide movement. Obviously, such hidden characteristics of landslide kinematics can only be identified using spectral analysis techniques.

Finally, another outcome of our analysis, probably the first based on a >20 years long detailed geodetic monitoring record, is that the cost of landslide monitoring may be reduced by focusing on a limited number of stations which seem to be representative of the overall kinematics of the sliding masses.

Acknowledgments:

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