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Research Article
Development of Landslide Deformation Monitoring and Analysis System: A Proof of Concept Study

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Abstract: This study introduces a novel landslide monitoring and analysis system, LANSDEMAS. LANSDEMAS is a kinematic deformation analysis model, developed using Kalman filtering procedures and implemented on MATLAB. This study describes the first deformation monitoring and analysis experiment conducted to validate the performance of LANSDEMAS. The experiment was conducted in the 3-D Measurement Laboratory, Department of Geomatic Engineering, Universiti Teknologi Malaysia using Leica TCA2003 Robotic Total Station. In the simulated deformation monitoring experiment, different magnitudes of millimeter-level artificial deformations were applied to four monitored points. The results of the computed movement parameters show that LANSDEMAS accurately detected the introduced deformations and has demonstrated the potential to meet the requirements for landslide deformation monitoring and analysis.

Keywords: Deformation monitoring experiment, Kalman filter, kinematic deformation model, landslide, LANSDEMAS, robotic total station

INTRODUCTION

Landslide is defined as ''the movement of a mass of rock, debris, or earth down a slope'' (Cruden, 1991). The main factors responsible for the occurrence of landslides include-prolonged precipitation, earthquakes, volcanic eruptions, rapid snow melting and various anthropogenic activities. Landslide is difficult to predict in time and in space. This is because landslide occurrence depends on complex interaction of many factors, namely slope, soil properties, elevation, land cover and lithology, among others (Dai and Lee, 2002). Also, the relationship and interaction between these factors are uncertain. Guzzetti (2005) identified a large spectrum of the landslide phenomena, which are diverse and complex in nature. This spectrum includes: landslide length, landslide area/volume, landslide velocity, total number of landslides, triggering time and landslide lifetime. These diverse and complex factors make it practically difficult to adopt a particular technique and instrumentation to map and monitor landslides.

Globally, there is an upsurge in landslide occurrence, which could be attributed to the increasing human activities on the environment (Glade, 2003; Sidle *et al*., 2004) and the impact of climate change (Geertsema *et al*., 2006). The consequences of landslides are enormous. Recent landslide disasters in many regions of the world have destroyed infrastructure, killed thousands of people and resulted in heavy economic losses. The continuous occurrence of disastrous landslide events has increased the demand for new and improved techniques for landslide monitoring and analysis.

The main goal of this study is to introduce a novel kinematic deformation system developed for landslide monitoring and analysis. The Landslide Deformation Monitoring and Analysis System (LANSDEMAS) is based on the 'single point' model. It is developed on MATLAB, using Kalman filtering procedures. LANSDEMAS has the capability to compute movement parameters, namely: displacements, velocities and accelerations. It can perform statistical tests, to determine moving points, using three consecutive epochs of episodic geodetic datasets. The developed system has been successfully utilized for a proof of concept study using simulated datasets from Total Station observations and the results of the test experiment are presented.

MATERIALS AND METHODS

Kalman filtering model for deformation analysis: The deformation analysis concept implemented in this study is based on the following work packages: data

acquisition using Leica TCA2003 Robotic Total Station: data adjustment using Baarda's data snooping (for detection of outliers in the data) and the least squares estimation (for determination of unknown parameters); and data processing for deformation analysis using the Kalman filtering technique.

Using the quadratic polynomial function (Welsch and Heunecke, 2001), a time-dependent 3D kinematic model consisting of position, velocity and acceleration of monitored points can be formed and applied to observation data as (Holdahl and Hardy, 1979; Yalçinkaya and Bayrak, 2005; Acar *et al.*, 2008):

$$X_{k+1} = X_k + (t_{k+1} - t_k)V_{Xk} + \frac{1}{2}(t_{k+1} - t_k)^2 a_{Xk}$$

$$Y_{k+1} = Y_k + (t_{k+1} - t_k)V_{Yk} + \frac{1}{2}(t_{k+1} - t_k)^2 a_{Yk} \quad (1)$$

$$Z_{k+1} = Z_k + (t_{k+1} - t_k)V_{Zk} + \frac{1}{2}(t_{k+1} - t_k)^2 a_{Zk}$$

where,
X_k, Y_k, Z_k = Adjusted point coordinates at period k
V_{Xk}, V_{Yk}, V_{Zk} = Velocity of point coordinates
a_{Xk}, a_{Yk}, a_{Zk} = Acceleration of point coordinates

The matrix form of the kinematic model in Eq. (1) can be represented as:

$$\bar{Y}_k = \begin{bmatrix} X \\ Y \\ Z \\ V_X \\ V_Y \\ V_Z \\ a_X \\ a_Y \\ a_Z \end{bmatrix}_{k+1} = \begin{bmatrix} I & I(t_{k+1}-t_k) & I\frac{(t_{k+1}-t_k)^2}{2} \\ 0 & I & I(t_{k+1}-t_k) \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ V_X \\ V_Y \\ V_Z \\ a_X \\ a_Y \\ a_Z \end{bmatrix}_k + \begin{bmatrix} I\frac{(t_{k+1}-t_k)^2}{2} \\ I(t_{k+1}-t_k) \\ I \end{bmatrix}_{k,k+1} w_k$$

$$(2)$$

$$\bar{Y}_k = T_{k,k+1}\hat{Y}_k \quad (3)$$

where,
$\bar{Y}_k$ = The predicted state vector (position, velocity and acceleration) at period k (current time)
$\hat{Y}_k$ = The predicted state vector at preceding time
$T_{k,k+1}$ = The transition matrix
I = The unit matrix

The Kalman filtering prediction step at period k and its covariance matrix can be written as Eq. (4) and (5):

$$\bar{Y}_k = T_{k,k+1}\hat{Y}_k + N_{k,k+1}w_k \quad (4)$$

$$Q_{\bar{Y}\bar{Y},k} = T_{k,k+1}Q_{\hat{Y}\hat{Y},k}T_{k,k+1}^T + N_{k,k+1}Q_{ww,k}N_{k,k+1}^T, \quad (5)$$

where,
$N_{k,k+1}$ = The system noise matrix
w_k = The random noise vector at period k
$Q_{\hat{Y}\hat{Y},k}$ = The covariance matrix at preceding time
$Q_{ww,k}$ = The covariance matrix of system noise

The adjustment of the kinematic model can be given in matrix form in Eq. (6) and (7). Equation (7) is the functional model for the Kalman filtering procedure. The stochastic model for the Kalman filtering procedure is given in Eq. (8):

$$V_k = L_k - A_k\hat{Y}_k \quad (6)$$

$$\begin{bmatrix} \bar{Y}_k \\ I_k \end{bmatrix} = \begin{bmatrix} I \\ A_k \end{bmatrix}\hat{Y}_k - \begin{bmatrix} V_{\bar{Y},k} \\ V_{L,k} \end{bmatrix} \quad (7)$$

$$Q_k = \begin{bmatrix} Q_{\bar{Y}\bar{Y},k} & 0 \\ 0 & Q_{LL,k} \end{bmatrix} \quad (8)$$

where,
V_k = The innovation vector
L_k = The actual observation
$A_k\hat{Y}_k$ = The predicted observation

The kinematic model using Eq. (7) and (8) were solved and their movement parameters (positions, velocities and accelerations) were computed with two periods of observations.

Deformation monitoring experiment: The experiment to validate the developed landslide deformation monitoring and analysis system, LANSDEMAS, was conducted in the 3-D Measurement Laboratory, Department of Geomatic Engineering, Universiti Teknologi Malaysia. The primary goal of the experiment was to test the capability of LANSDEMAS to detect millimeter movements. In the experiment, a Robotic Total Station (Leica TCA 2003) was used to monitor the movements of 4 points, 1, 2, 3 and 4 (Fig. 1). Leica TCA2003 Robotic Total Station was used in 'lock' mode from a single set up, recording every, 2 min interval. Using the Robotic Total Station, the reference coordinates (x, y, z), consisting of 10 series of observations for each of the 4 points were determined. Using these reference coordinates, artificial deformations were applied to the x, y, z- coordinates of the 4 points (Table 1), to generate 3 epochs of simulated data, as follows: Point 1 (no deformation was applied); Point 2 (1 and 2 mm deformations were

Fig. 1: Deformation monitoring experiment

applied to epoch 1 and 2, respectively); Point 3 (3 and 4 mm deformations were applied to epoch 1 and 2, respectively); and Point 4 (5 and 6 mm deformations were applied to epoch 1 and 2, respectively). The assumed standard deviation values were: 3 mm for easting, 3.1 mm for northing and 3.5 mm for height. The assumed time interval between epochs of the simulated data was 3 months. LANSDEMAS was used to detect these simulated deformations.

Software development for landslide deformation analysis: The software package called LANSDEMAS

was developed to validate the mathematical model and to detect stable/unstable 3-dimensional monitored points. The software is based on the 'single point' model and developed on MATLAB, using Kalman filtering technique. It has the capability to compute movement parameters, namely: position, velocity and acceleration and to perform statistical tests, to determine stable and moving points, using 3 consecutive epochs of geodetic data sets.

The software package consists of 2 main modules: the Adjustment and Deformation modules (block diagram in Fig. 2). The adjustment module involves the detection of outliers in the observations (E1, E2 and E3) using Baarda's data snooping technique and the determination of unknown parameters using the least squares estimation technique. The main components of the deformation module are: parameter extraction from the input data files, data processing using Kalman filtering technique, Model Validation Test (MVT), Deformation Detection Test (DDT) and presentation of results in the output file.

The software implementation of the deformation module is in two stages. The first stage uses data from epochs 1 and 2 observations (E1, E2) and their standard deviation values (S.D.1, S.D.2) and the second stage uses data from epochs 1, 2 and 3 observations (E3) and

Table 1: Deformation case studies

Epoch	Pt. 1 East	Pt. 1 North	Pt. 1 up	Pt. 2 East	Pt. 2 North	Pt. 2 up	Pt. 3 East	Pt. 3 North	Pt. 3 up	Pt. 4 East	Pt. 4 North	Pt. 4 up
1	*ND	*ND	*ND	1	1	1	3	3	3	5	5	5
2	*ND	*ND	*ND	2	2	2	4	4	4	6	6	6

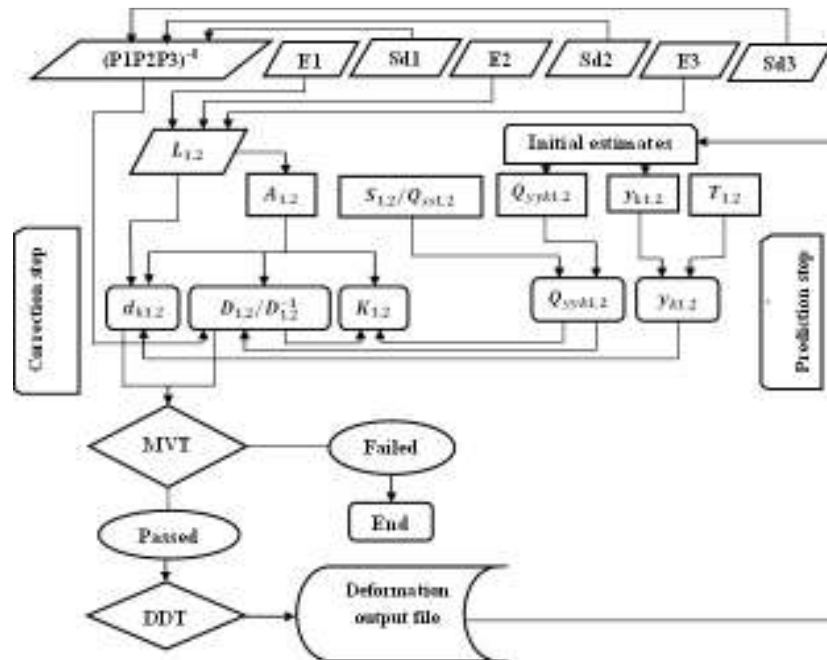Simulated deformations (mm); *ND: No deformation

Fig. 2: Block diagram of landslide deformation analysis software

their standard deviation values (S.D.3), to generate observation vectors ($L_{1,2}$) and weight matrices (P1, P2, P3). Other input data include: observation matrices ($A_{1,2}$), transition matrices ($T_{1,2}$), system noises ($S_{1,2}$) and their variance covariance matrices ($Q_{ss1,2}$), month and year of observations, a priori variance of unit weight, degrees of freedom and significance level for hypothesis testing.

The Kalman filter is initialized by setting the initial states (y_k) to zero and the variance covariance matrix (Q_{yyk}) of the initial states is computed. These initial values are then used for the one-step prediction of the state parameters (y_{k1}) and their variance covariance matrices (Q_{yyk1}). The correction step involves the computations of the innovation (d_{k1}), the variance covariance matrices (D_1) of the innovation and their inverse (D_1^{-1}) and the Kalman gain (K_1).

The Model Validation Test (MVT) is carried out based on the innovation sequence and the Fisher's distribution. The failure of the model validation test may be attributed to incorrect weighting of the observations and further analysis should be terminated at this stage (Olyazadeh and Setan, 2010). The Deformation Detection Test (DDT) is carried out for every monitored point using the 'single point' displacement analysis technique and Student's t-distribution. If a monitored point fails the test at the specified confidence level (typical confidence level is $\infty = 0.05$), the point is described as 'unstable', otherwise it is regarded as 'stable'.

The final stage of the deformation module involves the generation of the deformation output file. This file contains a summary report of the following: date and time of analysis, model validation test results, summary of movement parameters (position, velocity and acceleration) and the test statistics, showing stable and unstable points.

RESULT ANALYSIS

In the kinematic model, movement parameters are point displacements, velocities and accelerations. The movement parameters were solved based on Kalman filtering technique on MATLAB, using two periods of measurements, which were sufficient to solve movement parameters using the model. Three months was adopted as the time interval between periods of measurements.

The results of the data adjustment module are given in Fig. 3 and 4 (outliers detection) (least squares estimation results), respectively.

The results of the model validation test using the innovation vector are given in Fig. 5 and 6, respectively. In the 1st stage given in Fig. 5, the critical value (t) is 1.068 and the F-table value is 1.444. In the 2nd stage given in Fig. 6, the critical value (t) is 1.031 and the F-table value is 1.433. These results show that the null hypothesis is true and the computed results given in Table 2 to 6 are acceptable.

In the kinematic model, critical values (t) for the movement parameters were computed for positions, velocities and accelerations and compared to the t-distribution table values (qt) to ascertain whether the movement parameters were significant or not. If the movement parameters have significantly changed (unstable), a (+) sign is given; otherwise (stable), a (-) sign is given. The kinematic model deformation results are given in Table 2 to 6. The first stage of the kinematic model deformation results was computed using epoch 1 and 2 simulated data. The results of the computed movement parameters (positions and velocities) in Table 2 and 3 shows that the introduced deformations were accurately detected by LANSDEMAS.

Fig. 3: Outliers detection

Fig. 4: Least squares results

Fig. 5: Model validation test results -1st stage

Fig. 6: Model validation test results -2nd stage

Table 2: Kinematic model deformation results (1st stage) -position

Points	1	2	3	4
dx (cm)	0.01	0.10	0.30	0.50
Tdx	0.24 (-)	3.96 (+)	11.87 (+)	19.78 (+)
Decision	Stable	Unstable	Unstable	Unstable
dy (cm)	0.01	0.10	0.30	0.50
Tdy	0.23 (-)	3.83 (+)	11.49 (+)	19.14 (+)
Decision	Stable	Unstable	Unstable	Unstable
dz (cm)	-0.01	0.10	0.30	0.50
Tdz	0.20 (-)	3.39 (+)	10.17 (+)	16.94 (+)
Decision	Stable	Unstable	Unstable	Unstable

Position (dx, dy, dz); If t>qt then (+) ''unstable''; If t<qt then (-) ''stable''; qt: t-test value; t (Tdx, Tdy, Tdz): Critical value; qt = 1.98

Table 3: Kinematic model deformation results (1st stage) -velocity

Points	1	2	3	4
Vx (cm/month)	0.00	0.03	0.10	0.17
Tvx	0.17 (-)	2.79 (+)	8.38 (+)	13.97 (+)
Decision	Stable	Unstable	Unstable	Unstable
Vy (cm/month)	0.00	0.03	0.10	0.17
Tvy	0.16 (-)	2.70 (+)	8.11 (+)	13.52 (+)
Decision	Stable	Unstable	Unstable	Unstable
Vz (cm/month)	0.00	0.03	0.10	0.17
Tvz	0.14 (-)	2.39 (+)	7.18 (+)	11.96 (+)
Decision	Stable	Unstable	Unstable	Unstable

Velocity (Vx, Vy, Vz); If t>qt then (+) ''unstable''; If t<qt then (-) ''stable''; qt: t-test value; t (Tvx, Tvy, Tvz): Critical value; qt = 1.98

Table 4: Kinematic model deformation results (2nd stage) -position

Points	1	2	3	4
dx (cm)	0.02	0.20	0.40	0.60
Tdx	0.64 (-)	8.04 (+)	16.09 (+)	24.13 (+)
Decision	Stable	Unstable	Unstable	Unstable
dy (cm)	0.02	0.20	0.40	0.60
Tdy	0.62 (-)	7.79 (+)	15.57 (+)	23.36 (+)
Decision	Stable	Unstable	Unstable	Unstable
dz (cm)	-0.02	0.20	0.40	0.60
Tdz	0.55 (-)	6.89 (+)	13.79 (+)	20.68 (+)
Decision	Stable	Unstable	Unstable	Unstable

Position (dx, dy, dz); If t>qt then (+) ''unstable''; If t<qt then (-) ''stable''; qt: t-test value; t (Tdx, Tdy, Tdz): Critical value; qt = 1.98

Table 5: Kinematic model deformation results (2nd stage) -velocity

Points	1	2	3	4
Vx (cm/month)	0.01	0.07	0.13	0.20
Tvx	0.26 (-)	3.29 (+)	6.57 (+)	9.85 (+)
Decision	Stable	Unstable	Unstable	Unstable
Vy (cm/month)	0.01	0.07	0.13	0.20
Tvy	0.25 (-)	3.18 (+)	6.36 (+)	9.54 (+)
Decision	Stable	Unstable	Unstable	Unstable
Vz (cm/month)	-0.01	0.07	0.13	0.20
Tvz	0.23 (-)	2.82 (+)	5.63 (+)	8.44 (+)
Decision	Stable	Unstable	Unstable	Unstable

Velocity (Vx, Vy, Vz); If t>qt then (+) ''unstable''; If t<qt then (-) ''stable''; qt: t-test value; t (Tvx, Tvy, Tvz): Critical value; qt = 1.98

Table 6: Kinematic model deformation results (2nd stage) -acceleration

Points	1	2	3	4
ax (cm/month^2)	0.00	0.01	0.01	0.01
Tax	0.11 (-)	1.08 (-)	1.08 (-)	1.09 (-)
Decision	Stable	Stable	Stable	Stable
ay (cm/month^2)	0.00	0.01	0.01	0.01
Tay	0.10 (-)	1.04 (-)	1.05 (-)	1.05 (-)
Decision	Stable	Stable	Stable	Stable
az (cm/month^2)	0.00	0.01	0.01	0.01
Taz	0.09 (-)	0.93 (-)	0.93 (-)	0.94 (-)
Decision	Stable	Stable	Stable	Stable

Acceleration (ax, ay, az); If t>qt then (+) ''unstable''; If t<qt then (-) ''stable''; qt: t-test value; t (Tax, Tay, Taz): Critical value; qt = 1.98

The second stage of the kinematic model results was computed using epoch 1, 2 and 3 simulated data. The results of the computed movement parameters (positions, velocities and accelerations) in Table 4 to 6 show that the introduced deformations were also accurately detected by LANSDEMAS. The non-

deformed point (Point 1) was also accurately detected by LANSDEMAS in both stages.

CONCLUSION

Landslides have become one of the major causes of natural hazards worldwide. Landslide monitoring and analysis can aid in detecting critical displacements before the slope reaches its failure stage and can also provide vital information for prevention of human and economic losses and mitigation of damages to valuable public infrastructure and utilities. This study is focused on the development of a novel Landslide Deformation Monitoring and Analysis System (LANSDEMAS). The deformation solutions in this study were realized based on a combined epoch solution approach, using the Kalman filtering technique, implemented on MATLAB. In the simulated deformation monitoring experiment, different scenarios of artificially introduced deformations were used to test millimeter-level movements. In all cases LANSDEMAS successfully detected the movements and has demonstrated the potential to meet the requirements for landslide deformation monitoring and analysis.

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