INTRODUCTION

The kinematics characterization of landslides is a prior to understand landslide mechanism for hazards and risk assessments. Because such natural processes are very sensitive to climatic conditions, their behavior is permanently changing in time and in space, thus making the characterization of landslide kinematics difficult with conventional and punctual geodetic measurements like tacheometry, extensometry and GPS surveys. The application of optical correlation methods is thus particularly efficient for monitoring the spatial heterogeneity of landslide displacements (Kääb, 2002; Casson et al., 2003; Delacourt et al., 2007; LePrince et al., 2008). The performance of the correlation technique on aerial (eg. IGN) and high-resolution satellite images (eg. SPOT, QuickBird, OrbView, EROS) is widely demonstrated for landslide monitoring (Casson et al., 2003; Delacourt et al., 2004; LePrince et al., 2008). However, the acquisition frequency and the spatial resolution of aerial and satellite images are some typical parameters that cannot be controlled by the user. These drawbacks can be very problematic in function of the size and the dynamics of the landslide. Correlation of optical terrestrial images is a good complementary method to aerial and satellite imaging and classical landslide monitoring techniques. Optical terrestrial images can be acquired from a fixed location, generally in front of the landslide with a high resolution and a frequency adapted to the landslide velocity. The images are systematically acquired in exactly the same geometry.
2 Experimental Site: The Super-Sauze Mudslide

The Super Sauze mudslide is located in the Callovo-Oxfordian black marls of the Southern French Alps (Alpes-de-Haute-Provence, France). Its extents over a distance of 920 m between an elevation of 2105 m at the crown and 1736 m at the toe with an average width of 150 m and a average slope of 25° (Figure 1). Last estimations of the total volume is evaluated at 560,000 m$^3$ (Travelletti & Malet, submitted). The mudslide is gradually covering a torrential stream located downstream with typical range of velocity between 1 to 3 cm.d$^{-1}$ and acceleration peak until 40 cm.d$^{-1}$ in the spring season (Malet et al., 2002). The kinematics of the landslides is currently monitored by DGPS survey, terrestrial laser scanning and the permanent camera monitoring system.

3 Methodology

3.1 Instrumentation

The monitoring system consists of a low-cost D70 Nikon non metric reflex digital camera (about 1500 €) installed on a concrete pillar located on a stable crest in front of the mudslide at a distance of 300 m from the lower part and 900 m from the upper part of the mudslide (Figure 1). The acquisition system is controlled by a datalogger (CR10) and the power is provided by a 40 W solar panel. The characteristics of the acquisitions are presented in Table 1. The focused of the camera lens is set to manual. The frequency of acquisition is four days. An acquisition consists in four photographs registered at 11:00 a.m., 12:00 p.m., 13:00 p.m. and 14:00 p.m in order to get at least one image taken during good meteorological conditions. Each photograph (6 Mb) is stored in a native file format without any loss of information.

3.2 Processing

3.2.1 Digital Image Correlation (DIC)

Different terminologies exist in the literature to designate methods searching for the greatest correspondence between two signals like Particle Image Velocimetry (PIV), Correlation Image velocimetry (CIV) and Digital Image Correlation (DIC). DIC is the most used terminology for applications in geosciences.

The correlation principle is to recognize identical intensity distribution patterns on a reference image and a second image after displacements. Most of DIC techniques are based on a maximization of a normalized cross-correlation function due to the reliability and the simplicity of the method (Lewis, 1995; Debella-Gilo and Kääb, in press). The function is solved either in the spatial domain or in the frequency domain by using FFT algorithm (Hild et al. 1999). The normalized cross-correlation function for two discretely sampled images is defined as:

$$
\Phi(u, v) = \frac{\sum_{x,y} [f(x,y) \overline{f_x}](x-u, y-v) - \overline{t} ]}{\sum_{x,y} [f(x,y) - \overline{f_x}] \sum_{x,y} (t(x-u, y-v) - \overline{t})^2} (1)
$$
...possible if a DEM is available to relate two-point for the next correlation with a higher resolution applied on the images to identify object texture. The parabolic formula between the pixel centers. The DEMs are usually produced with stereoscopic pair of images taken at the same time (Mikhail et al., 2001). This method is still a good estimation.

The external parameters of the camera are first determined. Then a projective transformation in the image plane is applied on the DEM to allocate a 3D position at each 2D pixel coordinates.

3.2.2.1 External parameters of the camera

The relationship between the image coordinates \((u,v)\) and the local coordinates system \((X,Y,Z)\) is given by the classical form of the collinearity equations (Mikhail et al., 2001):

\[
\begin{align*}
\frac{u - u_0}{m_{11}} &+ \frac{v - v_0}{m_{21}} + \frac{Z - Z_C}{m_{31}} = 0 \\
\frac{u - u_0}{m_{12}} &+ \frac{v - v_0}{m_{22}} + \frac{Z - Z_C}{m_{32}} = 0
\end{align*}
\]

The origin of the image plane system is located at the upper left corner of the image (Figure 1). \((u_0,v_0)\) are the coordinates of the principal point. \((X_C,Y_C,Z_C)\) are the coordinates referring to the camera station in the local coordinate system. \(f\) is the focal length of the camera. The X-axis is defined along the W-E direction and the Y-axis along the S-N direction in the local coordinate system. The Z-axis is the elevation perpendicular to the plane \((X,Y)\). \(m_{ij}\) are the components of the rotation matrix \(M\) that defines the external parameters of the camera. \(M\) is constructing by using three sequential rotation angles: \(\omega\) around the X-axis, \(\varphi\) around the once-rotated Y-axis and \(\kappa\) around the twice-rotated Z-axis:

\[
M = \begin{pmatrix}
\cos \varphi \cos \kappa & \sin \varphi \cos \kappa & \sin \kappa \\
\cos \kappa \sin \omega + \sin \kappa \cos \omega \sin \varphi & -\cos \omega \sin \varphi \sin \kappa - \sin \omega \cos \kappa \sin \varphi & \cos \kappa \cos \omega \sin \varphi - \sin \omega \cos \kappa \cos \varphi \\
\cos \kappa \cos \omega - \sin \kappa \sin \varphi & \sin \kappa \cos \omega \sin \varphi - \cos \kappa \cos \omega \cos \varphi & \cos \omega \cos \varphi + \cos \kappa \sin \omega \sin \varphi
\end{pmatrix}
\]

The estimation of the three independent angles involved in the rotation matrix is the most sensitive part in camera calibration (Mikhail et al., 2001). In order to compute the external parameters of the camera, Ground Control Points (GCPs) identified both in the image plane and in the local coordinate system are used as input data for a self calibration. 95 pairs of GCPs distributed on the image plane and in the local reference system were measured using a Differential Global Positioning System (DGPS) (Fig 2). The GCPs are measured in the local coordinate system with an average 3D accuracy of 0.02 m and a...
standard deviation of 0.01 m. The GCPs coordinates \((u_i, v_i)\) in the image plane are determined by manual picking with an estimated accuracy of about 2 pixels. Among the 95 GCPs, 45 are used to compute the rotation matrix \(M\) and 40 are kept for the accuracy analysis. Equ. 2 is then used to obtain the calculated image coordinates of the GCPs using the ground positions of the GCPs. A least mean squares minimization between observed and calculated GCPs in the image plane using Singular Value Decomposition allows to determine the rotational matrix \(M\) that satisfies the system of Equ. 2 (Heikkilä and Silven, 1997). The camera location measured by DGPS, the focal length (constant for each acquisition) and the central points coordinates \((u_0, v_0)\) provided by the manufacturer are included in the least mean squares minimization to better constrain the rotation matrix computation.

4 ACCURACY ANALYSIS

4.1 Accuracy of the multi-resolution correlator

The accuracy of the multi-resolution correlator was assessed by applying homogeneous synthetic displacement fields on a real image as suggested by Chambon et al. (2003). Three different levels of gaussian noise are added on the synthetic displaced image. The mean Gaussian noise is fixed to null and the variance \(\sigma_n^2\) is fixed to \(10^{-4}\), \(10^{-3}\) and \(10^{-2}\) respectively. The DIC is then applied on the real image and the synthetic displaced image. The difference between the calculated displacements and the imposed displacements allow to determine the accuracy of the correlator algorithm (Figure 3). As observed by Hild et al. (1999), the accuracy of the algorithm mainly depends on the pixel fraction of the displacement. For fifteen tests realized with a magnitude of imposed displacements between 1 to 23 pixels, the accuracy of the correlator varies between ±0.5 pixels for the highest degree of noise and ±0.1 pixels for the lowest degree of noise.
4.2 Influence of the image resolution

The effective pixel size is a limiting parameter for the correlation accuracy (Figure 4). The pixel size depends on (i) the distance between the terrain surface and the camera and (ii) the angle of incidence which is defined as the complementary angle between the line of sight of the camera and the normal terrain surface. The pixel size determines the minimum theoretical displacement that can be detected by the DIC technique for pixel-level correlation.

![Figure 4. Effective pixel size](image)

The pixel size varies from $1.10^{-2} \text{ m}^2$ in the lower part to $3.10^{-2} \text{ m}^2$ in the upper part of the landslide. Minimum displacements for pixel-level correlation in $u$ and $v$-direction of 0.15 m and 0.08 m in the lower part of the landslide and 0.30 and 0.10 m in the upper part are found (Figure 5A, B). Below these displacement thresholds, the accuracy mainly depends on the sub-pixel correlation accuracy.

![Figure 5. Minimum displacements for pixel-level correlation A) along v and B) along u-axis in function of the pixel size](image)

4.3 Accuracy of the external parameters

The 40 GCPs not introduced in the minimization processes are used to evaluate the absolute accuracy of the rotational matrix $M$ (Equ. 3). The shift between the projected and the observed GCPs positions in the image plane is determined (Figure 6). A mean shift error of 0.20 pixel and 0.08 pixel with a standard deviation of 1.59 pixel and 1.51 pixels in $u$ and $v$ direction respectively is found (Table 2). Because the standard deviation is close to the accuracy of the GCPs picking, the solution is judged acceptable.

![Figure 6. Residual $du$ and $dv$ misfits between projected and observed GCPs after the minimization](image)

To control the overall quality of the transformation, a synthetic image of the landslide is reproduced by interpolating the shaded relief value computed in the DEM. Regarding the accuracy of the transformation matrix and the realism of the synthetic image, the results are satisfying (Figure 2; Figure 6). Slight external parameters changes (movements of the camera) can lead to the occurrence of a homogeneous component in the calculated displacements field in the image plane. These artefacts can be corrected with an automatic routine by removal of the misfit determined in the stable part of the mudslide on the whole computed displacements. Then the accuracy of the displacement in the image plane is assessed by a null test over stable areas by looking at the residual (Casson et al., 2005).

4.4 Accuracy of the georeferencing

The accuracy of the georeferencing in the local coordinate system is calculated by comparing the back-projected GCPs with their DGPS position located in the stable part of the landslide where no geomorphic change occurred. The absolute accuracy in $X$, $Y$ and $Z$ coordinate are presented in Table 2.
Table 2. Mean $\mu$ and standard deviation $\sigma$ of the absolute accuracy for the projection in the image plane and the back-projection in the local coordinate system

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ (pixels)</th>
<th>$\sigma$ (pixels)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image plane (n=40)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$u$</td>
<td>0.20</td>
<td>1.59</td>
</tr>
<tr>
<td>$v$</td>
<td>-0.08</td>
<td>1.51</td>
</tr>
<tr>
<td>Local coordinate system (n=11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$X$</td>
<td>0.07</td>
<td>0.41</td>
</tr>
<tr>
<td>$Y$</td>
<td>-0.13</td>
<td>0.53</td>
</tr>
<tr>
<td>$Z$</td>
<td>0.01</td>
<td>0.29</td>
</tr>
</tbody>
</table>

5 RESULTS

5.1 Displacement field in the image plane

41 pairs of images are correlated for the year 2008. The residual misfit after correction of slight movements of the camera is evaluated at about 1 pixel on average and corresponds to an estimation of the displacement accuracy in the image plane. Loss of coherence is observed in areas where changes of surface texture are too important. Consequently, some points present unreliable displacements characterized with an amplitude and a direction very different from the neighboring points (eg. displacements going upslope). Such points can be thus easily detected and removed (Casson et al. 2005). Aberrant results are also removed according to their correlation coefficient. A correlation threshold coefficient has been fixed to 0.75. Below it, displacements are not considered reliable.

In spring 2008, persistent rainfalls and a fast melting of the snow cover were the main causes of an important acceleration. This acceleration could be measured by the DIC technique from the 20th of May when the snow cover on the landslide completely melt. Figure 7 shows the displacement field in the image plane the 20th of May and the cumulated displacements for 9 profiles crossing the landslide between the 20th of May and the 25th June. The profiles at positions $v$ of 200 and 400 clearly point out the stable crest in the center of the upper part ($u = 2000$ and $v = 400$) where cumulated displacements are null. On both sides of the crest, the largest pixels velocities are observed. They reach 6 pixels.day$^{-1}$ at the peak of the acceleration at the beginning of June 2008. In one month, cumulated displacements reach 110 pixels in the upper part. Figure 8B shows the cumulated displacement of fours points (Points 1, 2, 3 and 4) respectively located in the upper, medium, lower and stable part of the mudslide. The major mudslide displacements occur in the spring season when the ground water level reached its maximum level. Then, the normal landslide activity is recovered with an average daily velocity of 0 to 1 pixel.day$^{-1}$.

Figure 7. Displacement field computed at the 20th May and cumulated displacements over the acceleration period of the mudslide. The location of the points 1, 2, 3 and 4 are referring to Figure 8.
5.2 **Displacement field in the local coordinate system**

The horizontal displacements of the 20th of May corroborate the previous analysis in terms of metric displacements. The displacements field varies temporally and spatially. The total amplitude of displacements decreases from the upper part (10.5 m in 4 days) to the lower part of the mudslide (1.1 m in 4 days) as shown by the points 1, 2, 3, and 4 in Figure 10 in the local coordinate system.

The normal landslide activity is recovered with an average daily velocity of about 0.01 m day$^{-1}$ between the end of July and October 2008. Horizontal cumulated displacements reach 38 m in the upper part (Points 1, Figure 8) and 7 m in the lower part (Points 3). No significant velocity change is observed during that period.

The accuracy of the converted displacement is assessed by a null test over stable areas. 95% of the points located in motionless area present a residual displacement less than 0.30 m which is in agreement with the analyses of section §4.2. The global accuracy of the technique is better defined by comparing the displacements obtained with the DIC technique and displacement measured with the DGPS monitoring (Figure 9). The accuracy varies between 10 to 20%. The constant DEM used for the georeferencing and slight movements of the camera are the main causes of the error. When displacements are large, morphologic changes are significant. Consequently, the accuracy of the method decreases.
6 DISCUSSION AND CONCLUSION

The examples presented in this paper demonstrated the efficiency of the low cost monitoring system based on DIC technique.

If the landslide is mainly translational without excessive changes in elevation, the same DEM can be used to estimate the displacements in the local coordinate system. The accuracy of the converted displacements will obviously depend on the accuracy and the resolution of the DEM. Refining the internal parameters of the camera (e.g., radial distortion) might not significantly increase the accuracy because the constant DEM and the slight external parameters changes are the major sources of uncertainties in this method. Acquisitions of several accurate DEMs during the year and a systematic adjustment of the external parameters on fixed control points for each image acquisition would improve the displacement accuracy in the local coordinate system.

Despite its simplicity, the technique is limited by important changes in meteorological conditions (snow, clouds, rain storm), in surface conditions (important ground deformations due to rapid landslides) and in illumination conditions (changes in shadow length and orientation, only operational during the daytime) which drastically affect the correlation accuracy. These aspects have to be taken into account for integrating this technique in an early warning system. Development is also needed for direct data transfer.

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