On the Use of GPS Survey Method for Studying Land Displacements on the Landslide Prone Areas

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Key words: Landslide, GPS survey, Land Displacement, Ciloto, West Java, Indonesia

SUMMARY

Landslide is one of prominent geohazards that continuously affecting Indonesia, especially in the rainy season. It destroys not only environment and property, but usually also cause deaths. Landslide monitoring and mitigation is therefore very crucial and should be done continuously. One of the methods that can have a contribution in studying landslide phenomena is repeated GPS survey method.

Repeated GPS survey method can be used to precisely detect land displacements on the landslide prone area. This paper will present and discuss the operational performances and results of GPS surveys conducted in a well know landslide prone area in West Java (Indonesia), namely Ciloto, the hilly region along Bandung-Jakarta highway. Several techniques, geodetic and geotechnical have been utilized to study the characteristics of land movements in this area.

Three GPS surveys involving 17 GPS points have been conducted, namely on 21-22 January 2002, 4-5 April 2002 and 10 May 2003, respectively. The results of GPS surveys show that the magnitudes of land movements in the study area vary from cm to dm level, depending on the location and the observation period in relation with rainy and dry seasons. The paper will also discuss the constraints faced by GPS survey method in the landslide prone area environment, which is usually hilly and sloping sharply.

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1. INTRODUCTION

Landslide is one of prominent geohazards that continuously affecting Indonesia, especially in the rainy season. In mountainous terrains and areas of steep slope of Indonesia, landslides are frequent, especially where land cover has been removed. Landslides destroy not only environment and property, but usually also cause deaths. Landslide monitoring and mitigation is therefore very crucial and should be done properly. At the present times, monitoring of landslide in Indonesia is usually done by using terrestrial techniques, using the systems such as extensometer, EDM (Electronic Distance Measurement) and leveling. Recently the Department of Geodetic Engineering, Institute of Technology Bandung (ITB), in cooperation with the Directorate of Volcanology and Geological Hazard Mitigation (DVGHM) has used GPS survey method to study the land displacements at two landslides prone areas in West Java, namely Ciloto and Megamendung (see Figure 1). Ciloto and Megamendung are located along Bandung-Jakarta highway. Ciloto is closed to Cianjur town, while Megamendung is closed to Bogor town. Both sites are located in mountainous region. In this paper, only GPS surveys in Ciloto that will be described and discussed.

Figure 1: Location of Ciloto and Megamendung.

2. MONITORING LAND DISPLACEMENTS

Land displacement monitoring in a certain landslide prone area in principle is the monitoring of changes in distances, height differences, angles and/or relative coordinates of the stations (monuments) covering the area being studied. In this case, there are many methods and techniques that have been used for measuring landslide displacements. The examples are given in Table, which is adopted and updated, from *Gili et al.* (2000).

Table 1: Methods and techniques for measuring landslide displacements, adopted and updated from [*Gili et al.*, 2000].

Method/technique	Results	Typical range	Typical precision
Precision tape	distance change	< 30 m	0.5 mm/30 m
Fixed wire extensometer	distance change	< 10-80 m	0.3 mm/30 m
Rod for crack opening	distance change	< 5 m	0.5 mm
Offsets from baseline	coordinates differences (2D)	< 100 m	0.5 - 3 mm
Triangulation	coordinates differences (2D)	< 300 – 1000 m	5 - 10 mm
Traverse/polygon	coordinates differences (2D)	variable, usually < 100 m	5 - 10 mm
Leveling	height change	variable, usually < 100 m	2 - 5 mm/km
Precise leveling	height change	variable, usually < 50 m	0.2 – 1 mm/km
EDM (Electronic Distance Measurement)	distance change	variable, usually 1 – 14 km	1-5 mm + 1-5 ppm
Terrestrial photogrammetry	coordinates differences (3D)	ideally < 100 m	20 mm from 100 m
Aerial photogrammetry	coordinates differences (3D)	H flight < 500 m	10 cm
Clinometer	angle change	$\pm 10^0$	$\pm 0.01\text{-}0.1^0$
Precision theodolite	angle change	variable	$\pm 10''$
GPS survey	coordinates differences (3D)	variable	2-5 mm + 1-2 ppm

In studying landslide displacements in Ciloto, besides GPS survey method, the other survey methods that have been implemented are the measurements of horizontal distance changes using EDM and angle changes using theodolite (*Purnomo*, 1993; *Wahjono et al.*, 1995; *Panggabean & Darsoatmodjo*, 1998; *Sobarna et al.*, 2001).

3. PRINCIPLE OF LANDSLIDE STUDY USING GPS SURVEY METHOD

GPS (Global Positioning System) is a passive, all-weather satellite-based navigation and positioning system, which is designed to provide precise three dimensional position and velocity, as well as time information on a continuous worldwide basis (*Hofmann-Wellenhof*, et al., 1994). GPS could provide a relatively wide spectrum of positioning accuracy, from a very accurate level (mm level) to an ordinary level (a few m level). For studying landslide phenomena, in order to monitor the land displacement of even very small magnitude, the ideal positioning accuracy to be achieved is in mm level. In order to achieve that level of accuracy then the GPS static survey method based on phase data should be implemented with stringent measurement and data processing strategies (*Leick*, 1995).

The principle of landslide study using repeated GPS surveys method is depicted in Figure 2. With this method, several monuments, which are placed on the ground covering the landslide prone area, are accurately positioned using GPS survey relative to a certain reference (stable) point. The precise coordinates of the monuments are periodically determined using repeated GPS surveys with certain time interval. By studying the characteristics and rate of changes of these coordinates from survey to survey, the characteristics of land displacements can be derived. These land displacement characteristics in turn can be used to study the geometrical characteristics of landslide phenomena in the area.

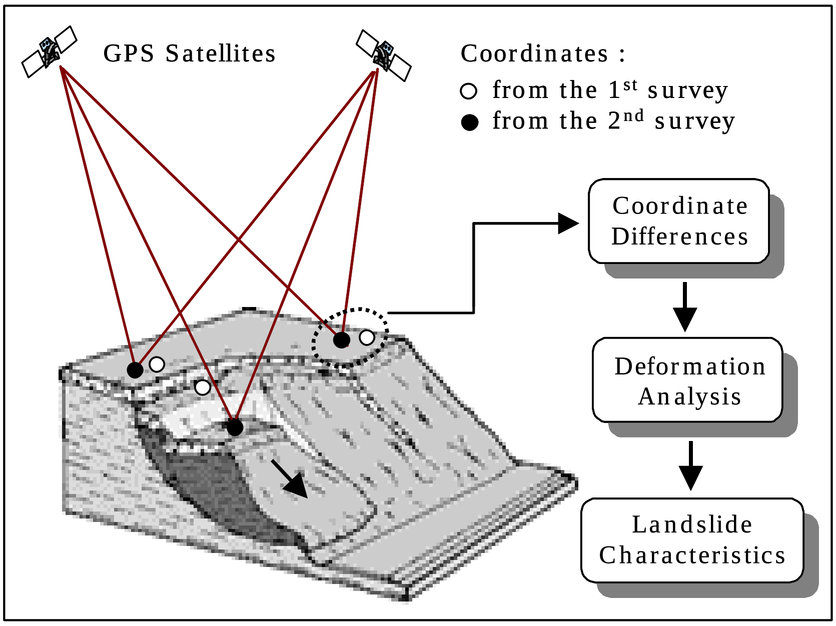

Figure 2: Principle of GPF Survey Method for Landslide Monitoring.

In order to obtain the coordinate differences with precision at several mm level, GPS survey should be conducted using dual-frequency geodetic type GPS receivers. Observation length at each monitoring point is adjusted according to its baseline length, and for baseline length less than 5 km, the observation period of about 3 hours are usually enough to achieve the precision level of several mm.

GPS survey method has been widely used for studying landslide phenomena (*Gili et al*., 2000; *Moss*, 2000; *Malet et al.*, 2002; *Rizzo*, 2002; *Mora et al.*, 2003). In order to obtain a comprehensive information about the landslide characteristics, the GPS derived information should be integrated and correlated with the hydro-geological characteristics of the area.

4. GPS SURVEYS IN CILOTO

In Ciloto, a relatively well-known landslide prone areas, several techniques, geodetic and geotechnical, have been utilized to study the characteristics of land displacements in this area, which one of them is GPS survey method. Three GPS surveys have been conducted since 2002 (see Table 2), and the configuration of observed GPS network is shown in Figure 3.

Table 2: GPS surveys in Ciloto

Survey	Observation Period	Observed GPS stations
1	21-22 Jan. 2002	POS, REF1, GPS1, GPS2, GPS3, GPS4, GPS5, GPS6, GPS7, GPS8, GPS9, M010, GPS10, GPS11, GPS12, GPS13, GPS14
2	4-5 April 2002	
3	10 May 2003	POS, REF1, GPS1, GPS2, GPS3, GPS4, GPS5, GPS6, GPS7, GPS8, GPS9, M010, GPS10, GPS11

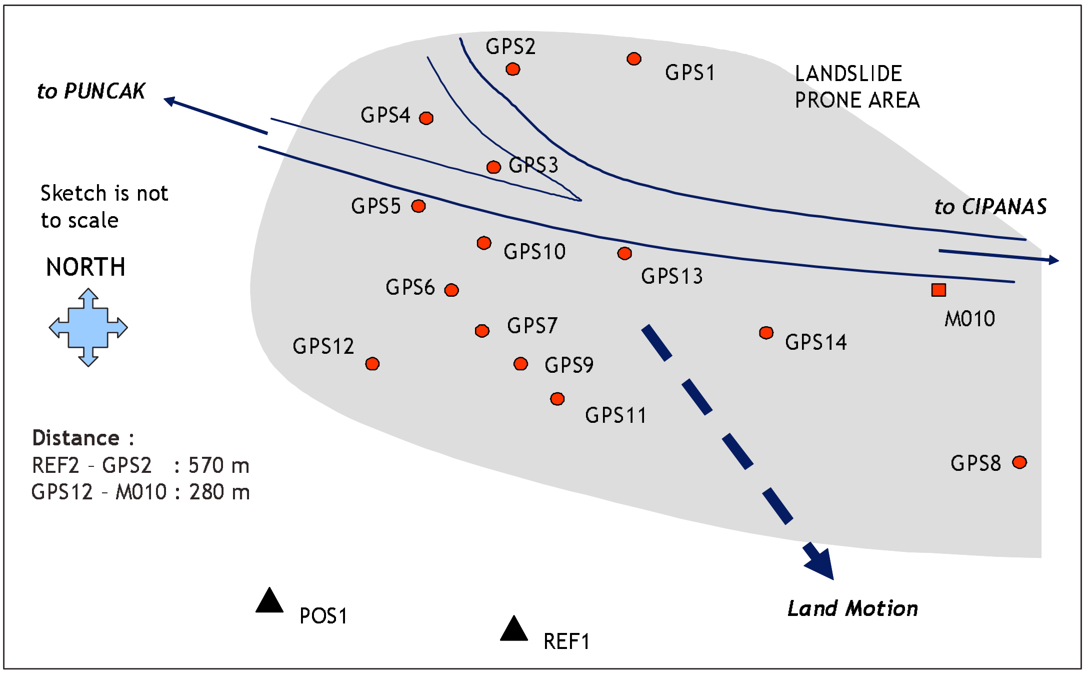

Figure 3: Landslide GPS monitoring network in Ciloto (West Java, Indonesia).

The first survey was conducted during the rainy season, while the second and third surveys were conducted during dry season. The time period between the first and second survey is about 2.5 months, and between the second and third surveys is about 13 months. Table 2 also shows that GPS12, GPS13 and GPS14 stations were not observed on the third survey. GPS12 and GPS13 stations were not observed due to severe signal obstruction caused by the already grown trees around the stations. GPS 14 station was already buried by local landslide and therefore could not be observed anymore.

Location and configuration of GPS network for studying landslide displacements in Ciloto area is shown in Figure 3. These GPS stations were selected to enable a reliable detection of landslide displacement signal in the area. At the same time these stations should satisfy the criteria for good GPS station, e.g. it is a relatively stable location, has a good sky view and relatively less affected by multipath (*Abidin*, 2000). POS and REF1 are the reference stations used for GPS survey and located outside the landslide-prone area. Considering its very good sky view, REF1 is the reference station used for computing the coordinates of the monitored stations. The distances between REF1 with other monitored GPS stations are between 200 m and 600 m, as shown in Figure 4. The GPS surveys at all stations were all carried out using dual-frequency geodetic-type GPS receivers. REF1 was used as the reference (stable) point with known coordinates. Since the baselines are relatively short, namely less than one km (see Figure 4), GPS observations were conducted with the session lengths of about 3 to 6.5 hours, respectively as shown in Table 3. The Table shows that the session lengths of the third survey are usually shorter than those of the previous two surveys. The data were collected with a 30 seconds interval, and elevation mask was set at 15^0 for all stations.

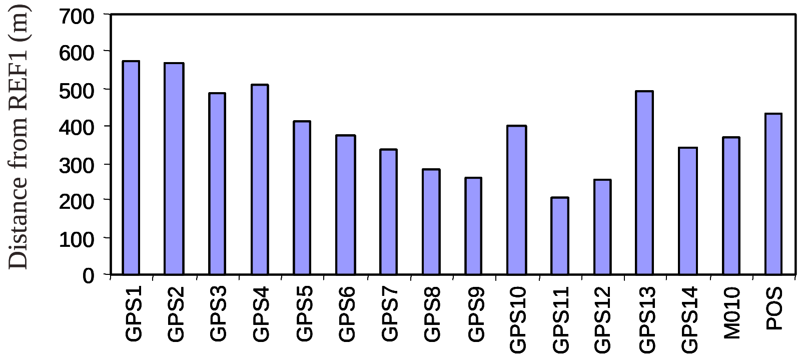

Figure 4: Distances between REF1 station and other GPS stations.

Table 3: Observation lengths at GPS points.

GPS points	**Observation length (hours)**		
	Survey - 1	**Survey - 2**	**Survey - 3**
POS	During the survey	During the survey	During the survey
REF1			
GPS01	5.0	5.0	3.8
GPS02	5.0	5.0	3.8
GPS03	4.8	4.5	4.5
GPS04	4.2	5.0	3.5
GPS05	4.2	5.0	4.5
GPS06	3.8	5.0	4.0
GPS07	4.0	4.5	3.0
GPS08	6.5	5.5	4.0
GPS09	4.0	4.0	3.0
GPS10	4.4	4.5	4.0
GPS11	3.2	4.5	3.0
GPS12	5.8	4.8	-
GPS13	3.0	4 .8	-
GPS14	6.2	5.5	-
M010	3.5	5.5	4.0

5. DATA PROCESSING, RESULTS AND ANALYSIS

The coordinates of REF1 were computed by using BERNESSE 4.2 scientific software (*Beutler et al.*, 2001) from an Indonesia IGS station in Bakosurtanal, Cibinong, Bogor, located about 100 km away. The coordinates of the monitored stations were then computed radially from REF1 by using the same scientific software. The SKIPro commercial software were used to compute the coordinates of GPS3 and GPS13 at the first two surveys, since it gave the better results compared to those obtained by using BERNESE 4.2. Considering the relatively short baselines, only broadcast ephemerides were used for data processing, and the residual ionospheric and tropospheric biases are considered negligible after data differencing.

The obtained standard deviations of the computed coordinates were typically in the order of several mm for Easting (E), Northing (N) and Ellipsoidal Height (h) components, respectively, as shown in Figure 5. This Figure shows that in general standard deviations of the horizontal components are better than 5 mm, and those of vertical component are better than 10 mm, except for one point from the first survey and two points from the third survey, which are not plotted in this Figure. These three points are GPS13, GPS02 and GPS07 respectively ; with standard deviations of (Northing, Easting, Ellipsoidal Height) are (43 mm, 4 mm, 20 mm), (18 mm, 5 mm, 29 mm) and (10 mm, 4 mm, 17 mm). These results indicate that GPS data processing has been properly performed.

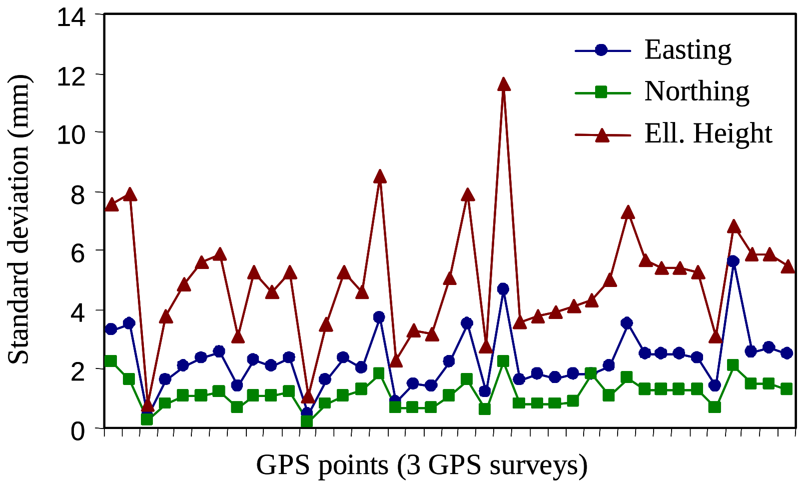

Figure 5: Typical standard deviations of the estimated GPS coordinates obtained from three GPS surveys. GPS

In this study, landslide displacements are obtained by differencing the coordinates of GPS stations obtained from two consecutive surveys. In this case, the obtained coordinate differences along with their standard deviations are shown in Table 4. It can seen from this Table that on the period of January to April 2002 (rainy to dry seasons), GPS7, GPS8, GPS11 and GPS14 stations experienced the relatively large displacements in the order of 1 to 6 dm compared to other stations. While on the period of April 2002 to May 2003 (dry to dry seasons), the stations with a relatively larger displacements are GPS5, GPS7, GPS8, GPS9 and M010, namely in the order of 0.5 to 1.2 dm.

Table 4: Coordinate differences of GPS stations and their standard deviations (in cm)

Station	Coordinate differences and their standard deviations (in cm) ; obtained from the 1st and 2nd GPS surveys (2.5 month period).					
	dE	σdE	dN	σdN	dh	σdh
GPS1	0.2	0.4	-0.8	0.3	-2.4	0.9
GPS2	-0.5	0.5	-0.7	0.2	-1.9	1.2
GPS3	-0.2	0.1	-0.5	0.1	-0.6	0.2
GPS4	0.2	0.2	-0.7	0.1	3.1	0.5
GPS5	0.5	0.3	-0.3	0.1	-0.6	0.6
GPS6	-0.3	0.3	1.3	0.2	0.5	0.8
GPS7	5.3	0.4	-63.5	0.2	-14.3	1.0
GPS8	1.9	0.2	-0.5	0.1	15.1	0.4
GPS9	-0.3	0.5	-0.2	0.2	-1.6	1.3
M010	0.0	0.3	0.4	0.1	2.3	0.6
GPS10	-0.6	0.3	0.0	0.1	0.0	0.7
GPS11	6.5	0.2	-25.0	0.1	-8.5	0.4
GPS12	-1.0	0.2	0.3	0.1	5.4	0.5
GPS13	-4.9	4.3	-0.6	0.4	-1.4	2.0
GPS14	13.2	0.3	-22.2	0.2	4.1	0.7
Station	**Coordinate differences and their standard deviations (in cm) ; obtained from the 2nd and 3rd GPS surveys (13 month period).**					
	dE	**σdE**	**dN**	**σdN**	**dh**	**σdh**
GPS1	-2.3	0.4	0.9	0.2	-1.2	0.9
GPS2	0.5	1.8	0.3	0.5	-1.3	3.1
GPS3	0.5	0.1	0.2	0.1	1.1	0.3
GPS4	-1.1	0.3	0.0	0.1	-3.1	0.6
GPS5	0.3	0.3	-1.5	0.1	6.5	0.6
GPS6	0.3	0.3	-1.7	0.2	1.1	0.7
GPS7	-6.3	1.1	-3.6	0.4	4.5	1.8
GPS8	1.2	0.2	0.1	0.1	-11.4	0.4
GPS9	5.5	0.7	0.2	0.3	1.8	1.3
M010	-1.1	0.3	-2.2	0.2	5.7	0.7
GPS10	0.7	0.3	-0.6	0.2	3.3	0.7
GPS11	0.4	0.3	-2.7	0.2	-2.6	0.7

In order to statistically check the significance of the displacements derived by GPS surveys, the congruency test (*Caspary*, 1987) was performed on the following variable

$$\delta d_{ij} = (dE_{ij}^2 + dN_{ij}^2 + dh_{ij}^2)^{1/2} . \qquad (1)$$

where δd_{ij} is the displacement of a station from epoch i to j. The null hypothesis of the test is that there is no displacement between the epochs. Therefore:

null hypothesis $H_o : \delta d_{ij} = 0$, (2)
alternative hypothesis $H_a : \delta d_{ij} \neq 0$. (3)

The test statistics for this test is:

$$T = \delta d_{ij} / (\sigma \text{ of } \delta d_{ij}) , \quad (4)$$

which has a Student's t-distribution if H_o is true. The region where the null hypothesis is rejected is (*Wolf and Gilani*, 1997):

$$|T| > t_{df,\alpha/2} , \quad (5)$$

where df is the degrees of freedom and α is the significance level used for the test. In our case, for GPS baselines derived using 3 to 6.5 hours of GPS data with 15 seconds data interval, then df $\rightarrow \infty$. Please note that a t-distribution with infinite degree of freedom is identical to a normal distribution. If a confidence level of 99% (i.e. α=1%) is used, then the critical value $t_{\infty,0.005}\ \infty$ is equal to 2.576 (*Wolf and Gilani*, 1997). If the values are adopted for the congruency test, then the testing results are summarized in Table 5.

Table 5: Summary on congruency test of GPS derived displacements

Station	δd_{12} (cm)	$\sigma\delta d_{12}$ (cm)	T	Significant displacement ?
GPS1	2.5	0.8	3.0	YES
GPS2	2.0	1.1	1.9	NO
GPS3	0.9	0.2	4.6	YES
GPS4	3.2	0.5	6.6	YES
GPS5	0.8	0.4	1.8	NO
GPS6	1.4	0.3	4.4	NO
GPS7	65.3	0.3	223.1	YES
GPS8	15.2	0.4	36.6	YES
GPS9	1.6	1.2	1.3	NO
M010	2.3	0.6	4.0	YES
GPS10	0.6	0.3	2.1	NO
GPS11	27.2	0.2	177.6	YES
GPS12	5.6	0.5	10.5	YES
GPS13	5.2	4.1	1.2	NO
GPS14	26.2	0.2	110.5	YES
Station	δd_{23} (cm)	$\sigma\delta d_{23}$ (cm)	T	Significant displacement ?
GPS1	2.7	0.5	5.5	YES
GPS2	1.5	2.9	0.5	NO
GPS3	1.2	0.3	4.6	YES
GPS4	3.3	0.6	5.4	YES
GPS5	6.7	0.6	10.9	YES
GPS6	2.0	0.4	4.7	YES
GPS7	8.5	1.3	6.7	YES
GPS8	11.5	0.4	27.7	YES
GPS9	5.8	0.8	7.1	YES
M010	6.2	0.6	9.7	YES
GPS10	3.4	0.7	5.0	YES
GPS11	3.8	0.5	7.8	YES

The results of statistical testing shown in Table 5 indicate that in general many stations have significant displacements. In the period of January to April 2002, only GPS2, GPS5, GPS6, GPS9, GPS10 and GPS13 that statistically show no significant displacements; while for April 2002 to May 2003 period only GPS2 station shows no significant displacement.

In order to further confirm the reliability of GPS derived displacements, after the above statistical testing, other two testing were imposed on the GPS derived displacement of each GPS station. These other two testing are:

- *testing on the agreement between the horizontal distance changes with the predicted direction of landslide displacement, and*
- *testing on the consistency of displacement directions on two consecutive periods.*

Based on the configuration of GPS network shown in Figure 3 and the predicted direction of landslide, then if the displacements do occur, the horizontal distances from REF1 station to other GPS monitored stations will be shortened, except for GPS14, M010 and GPS8 stations. For these three stations, the distances from REF1 could either be shortened or getting longer depending on the exact direction of the landslide displacement. Based on this hypothesis then testing on the agreement between the horizontal distance changes with the predicted direction of landslide displacement is applied, and the testing results are shown in Table 6. The testing only applied to those GPS stations that considered having significant displacement by the previous statistical testing.

Table 6: Testing results on the agreement between the horizontal distance changes with the predicted direction of landslide displacement

Baseline	hdc(12)	Concurring ?	hdc(23)	Concurring ?
REF1-GPS1	-0.8	YES	1.2	NO
REF1-GPS3	-0.5	YES	0.1	NO
REF1-GPS4	-0.8	YES	0.2	NO
REF1-GPS5	-	-	-1.5	YES
REF1-GPS6	-	-	-1.7	YES
REF1-GPS7	-63.5	YES	-3.6	YES
REF1-GPS8	1.6	YES	1.2	YES
REF1-GPS9	-	-	0.0	NO
REF1-M010	0.3	YES	-2.4	YES
REF1-GPS10	-	-	-0.7	YES
REF1-GPS11	-22.3	YES	-2.4	YES
REF1-GPS12	0.5	NO	-	-
REF1-GPS14	-16.5	YES	-	-
Note : hdc(ij) = horizontal distance change from survey-i to survey-j				

The results on Table 6 shows that after the statistical and horizontal distance changes agreement testing, the stations which considered to have significant displacements are GPS1, GPS3, GPS4, GPS7, GPS8, GPS11, GPS14 and M010 in the period of January to April 2002; and GPS5, GPS6, GPS7, GPS8, GPS10, GPS11 and M010 in the period of April 2002 to May 2003.

Finally in order to decide the stations that have significant and real displacements, the testing on the consistency of displacement directions on the consecutive survey periods is applied. This testing is based on the idea that for a station experiencing landslide displacement on a certain slope, then direction of its real displacement will be generally consistent from one survey period to the next period. In the context of previous testing, this consistency testing is actually similar to the previous agreement testing which is imposed to be consistent for consecutive survey periods. If this testing is applied to the stations that have passed the two previous testing, then the stations that show consistent direction of displacements on two consecutive periods are only GPS7, GPS8, GPS11 and M010 stations. Therefore in this study area, only those four stations that are considered to experience real and significant landslide displacements during the survey period between January 2002 to May 2003. The amounts of displacements have been given in previous Table 4.

If we see the configuration of GPS network shown in Figure 3, those four stations are located in southern part of the highway on a descending slope of the hill. The largest observed displacements are associated with GPS7 and GPS11 stations which are located about 100 to 200 m south of the highway section which was previously most affected by the landslides.

6. CLOSING REMARKS

Based on the results obtained from three GPS surveys that have been conducted in the landslide prone area of Ciloto, it can be concluded that GPS survey method is a reliable method for studying and monitoring landslide displacements. Precision level of mm to cm can typically be achieved, although achieving this level of precision is not an easy task to do. In this case the use of dual frequency geodetic type receivers is compulsory along with good survey planning, stringent observation strategy, and stringent data processing strategy. Considering its relatively high accuracy, all-times weather-independent operational capability, wide spatial coverage, and its user friendliness, the use of repeated GPS surveys for landslide displacement monitoring can be expected to gain more popularity.

From this study it can be suggested that in order to conclude the existence of real and significant displacements of GPS stations, the GPS derived computed displacements should be subjected to three testing namely: the congruency test on spatial displacements, testing on the agreement between the horizontal distance changes with the predicted direction of landslide displacement, and testing on the consistency of displacement directions on two consecutive periods.

Moreover, in order to provide physical meaning to GPS derived displacements, the results should be correlated with the hydro-geological and geotechnical characteristics of the studied area and its surrounding. The GPS derived results should also be integrated with the results obtained by other geodetic monitoring techniques such as leveling and EDM measurements. Finally it should be emphasized that further research is still needed to clarify the real mechanism and pattern of landslide displacements in Ciloto area.

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BIOGRAPHICAL NOTES

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