FOUR DIMENSIONAL MONITRORING OF DEFORMATION AS DEDUCED FROM REPEATED GPS CAMPAIGNS

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Abstract: Recent development of GPS performance enables us to apply four dimensional monitoring of ground deformation or any other engineering structure with precision of ~3 mm in horizontal position and ~10 mm in vertical direction. We demonstrate two examples of change determination derived from repeated GPS campaigns. The one is the ground subsidence monitoring inside Kawasaki city in Japan, and the other is the subsidence measurement of viaduct along the high speed railway during construction work in Taiwan. In these cases, we performed continuous GPS observation more than 12 hours by dual frequency receiver. The observed data are analyzed with aid of Bernese Ver4.2 or Gamit Ver10.1 software. Finally three dimensional positions are deduced referring to the IGS stations located in and around the respective countries.

Repeated GPS campaigns had been performed during February ~ March every year since 2003 to 2007 inside Kawasaki city, Kanagawa Prefecture, in Japan, in order to realize practical GPS/Leveling employing the latest hybrid geoid model. Traditional precise leveling was also repeated. We can compare two kinds of results of orthometric height change; one is obtained from GPS survey and the other from leveling survey. We recognize that discrepancies between these two do not exceed over 15mm/year. Also we deduce horizontal displacement vector and find significant trend of northward movement at some bench marks that are distributed on the ground of past remarkable subsidence.

The Taiwan high speed railway of 350km length was constructed by the Taiwan High Speed Rail Corporation. Various kinds of surveys were carried out with special attention on the ground subsidence along the rail way, especially for segment C270 of 42.8km length. The repeated GPS surveys were carried out to investigate viaduct deformation caused by the ground subsidence in March and September, 2004, respectively. We find viaduct subsidence of 10cm/year at the most that is the same order obtained from repeated precise leveling performed on the viaduct, and also horizontal movement of 2~3cm directed westward on the viaduct during the respective period. This trend is confirmed, though we have some small discrepancies between two results obtained from applied software Bernese Ver4.2 or Gamit Ver10.1.

1. INTRODUCTION

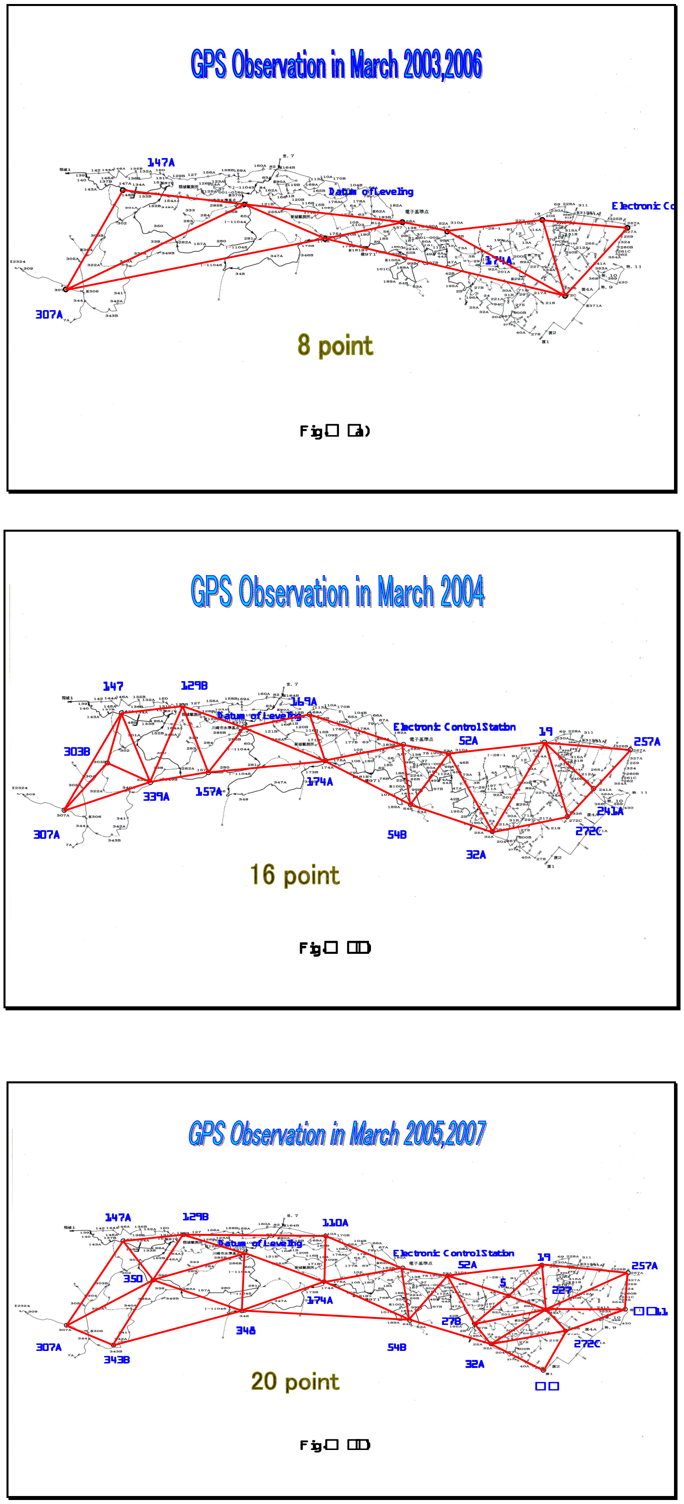
Repeated GPS survey had been applied for monitoring ground subsidence since early year of GPS [e.g. Chrzanowsky et al (1990), Sharif et al (1997), Heus (1998)]. Advancement of GPS geodesy, especially improvements of accuracy of height determination replace precise leveling by GPS height determination [e.g.,Zikoski (1999)], and also development of hybrid geoid model enables us to apply repeated GPS/Leveling. Furthermore recent development of GPS performance enables us to apply four dimensional monitoring of ground deformation or any other engineering structure with precision of ~3 mm in horizontal position and ~10 mm in vertical determination. We demonstrate two examples of deformation deduced from repeated GPS campaigns. The one is the ground subsidence monitoring inside Kawasaki city Kanagawa Prefecture, in Japan, and the other is the subsidence of viaduct along the high speed railway during construction work in Taiwan. In these cases, we performed out continuous GPS observation more than 12 hours by dual frequency receiver. The observed data are analyzed with aid of Bernese Ver4.2 or Gamit Ver10.1 software. Finally three dimensional positioning are deduced referring to the IGS stations located in and around the respective countries.

2. FOUR DIMENSIONAL MONITORING OF GROUND DEFORMATION IN KAWASAKI

For a long time, Kawasaki city, Japan had been suffering from ground subsidence with the order of several cm/year, some times exceeding 20cm/year at the specified bench marks. Extensive precise leveling works had been carried out in order to monitor the subsidence at least once in a year covering whole area of Kawasaki city. When GPS survey is proved to provide reliable information of ground subsidence instead of precise leveling□we may save many of the tedious works. Thus application of GPS/Geoid leveling is expected to replace precise leveling, and test observations started in 2003 and continued to 2007.

We performed continuous GPS observations with two 12 hours sessions at the selected bench marks more than ten inside Kawasaki, and determined their horizontal position and ellipsoidal height. The employed dual frequency receivers were Trimmble 4000SSE and sampling interval was 15second with 15 degree of elevation angle. We adopted IGS final ephemerides for analyzing the data with BerneseVer.4.2. Three dimensional position determination was carried out referring to the IGS stations such as WUHN(China), USUD(Japan), NTUS (Malaysia) , and GUAM(USA). Also we applied the GSIGEO2000 [Kuroishi et al (2002)], a hybrid geoid model covering whole area of the Japanese Island, and determined the orthometric height. We also performed ordinary precise leveling at the same stations of test GPS observation. Figure 1 indicates occupied stations for GPS and leveling work in 2003, 2004,2005,2006,2007 respectively. The occupied stations in 2003 were 8, and successively increased to be 16 stations in 2004 and finally 20 stations in 2005 as shown in the Figure 1.

Temporal change of geoidal height ranges +0.2mm/year over the world after Ardalan and Grafarend(2001).So we may neglect time change of geoidal height inside comparatively narrow area such as Kawasaki. Thus time change of height difference between two bench marks obtained from leveling should be coinciding with the one from GPS. We can estimate the same rate of change with respect two height systems of leveling and GPS height.



. Figure 1- Occupied stations for GPS/leveling work during
The period from 2003 to 2007 respectively

Figure 2 indicates the successive results of comparison with respect to height change of GPS orthometric height and of precise leveling orthometric height since 2003 to 2007. No remarkable changes more than 20mm/year are detected. This moderate change may be due to effect of recent regulation of pumping out of groundwater by replacement of special water supply for industrial use only. Our experiences indicates two height coincide within accuracy of ±15mm/year.

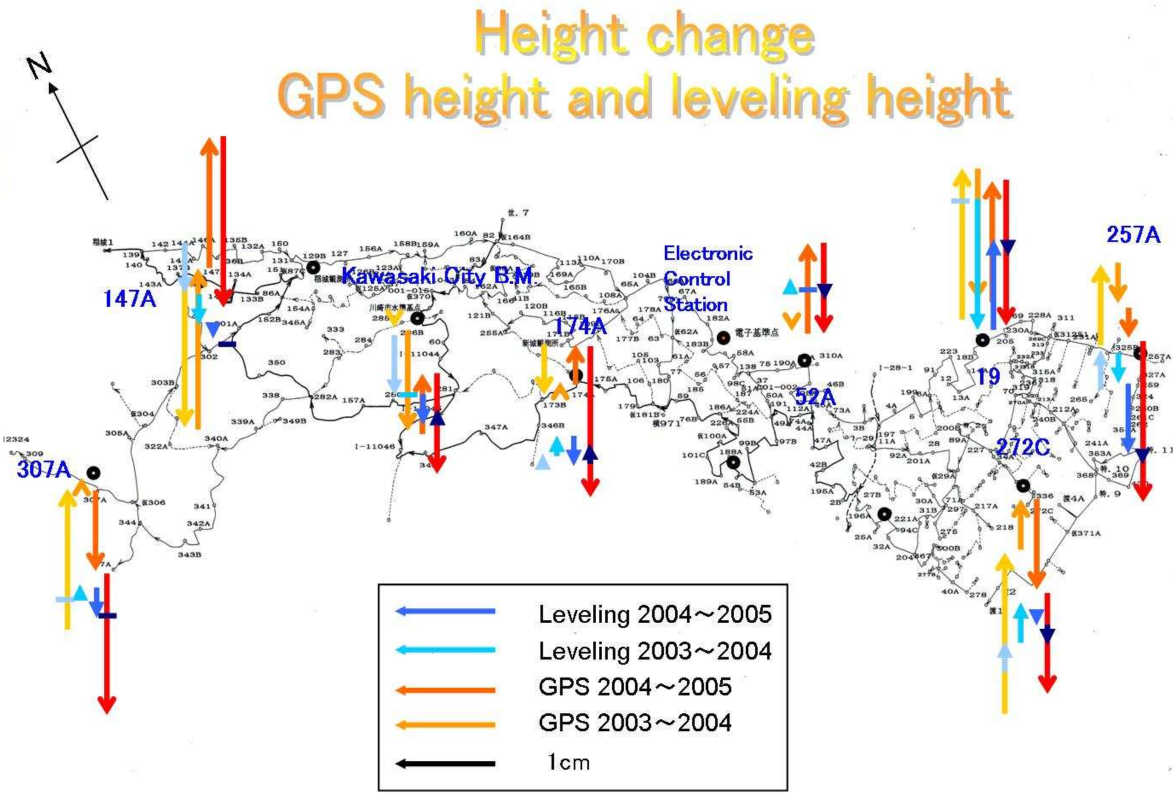


Figure 2: Successive results of comparison with respect to height change of GPS orthometric height and precise leveling orthometric height during the period 2003-2007. Electronic control station is fixed.

Furthermore we can deduce horizontal displacement vector at every stations that were occupied by GPS/leveling. Figure 3 indicates successive displacement vectors, from 2003 to 2004, from 2004 to 2005, from 2005 to 2006, from 2006 to 2007, respectively. The successive displacement vector at 307A benchmark indicates some irregular movement, and this may be due to unknown accident at the observation station. Neglecting this bench mark, we estimate standard deviation of yearly rate of horizontal movement is several mm/year, and conclude that successive displacement vectors at 275A, 272C, and 19 indicate trend of horizontal movement. These trends indicate the northward movement to the mouth of the Tamagawa River where the new land was formed by the latest soil deposits.

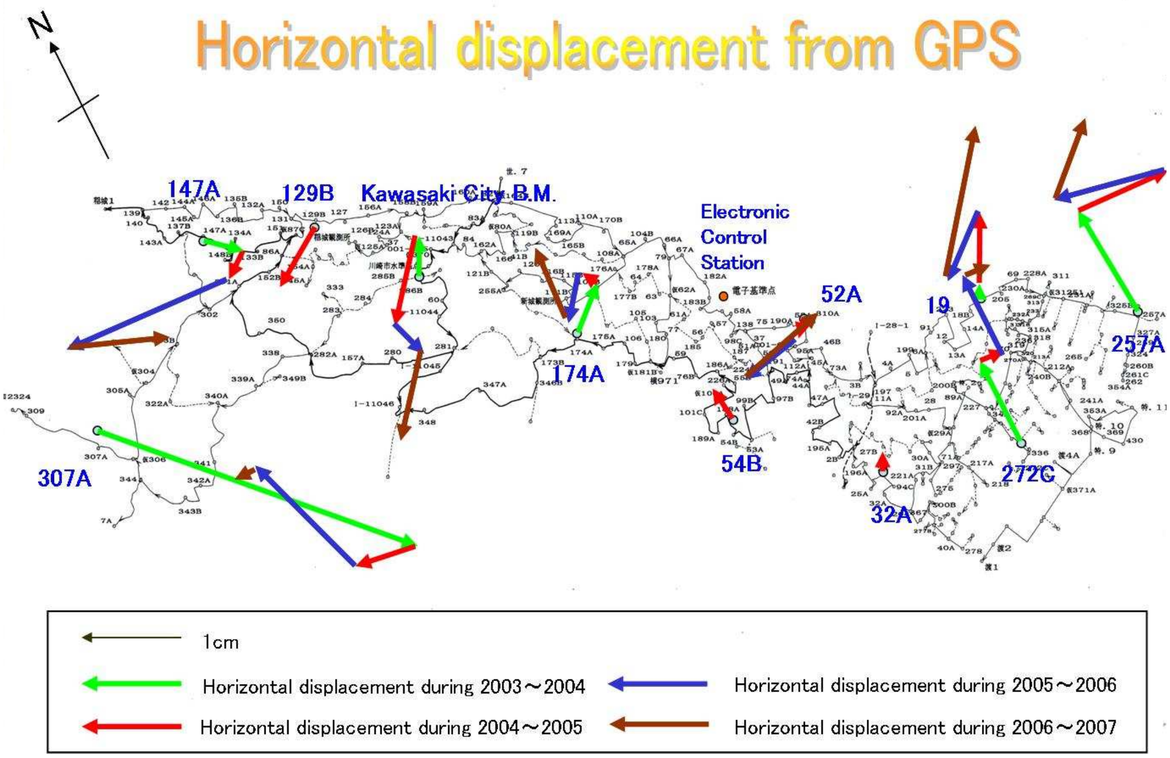


Figure 3: Successive displacement vector in Kawasaki from 2003 to 2004, from 2004 to 2005, from 2005 to 2006, and from 2006 to 2007.

3. DETECTION OF GROUND DEFORMATION IN THE INTERVAL C270 OF THE TAIWAN HIGH SPEED RAILWAY CALIBRATION

The Taiwan high speed railway of 350km length is constructed by the Taiwan High Speed Rail Corporation (THSRC).The work is divided into three parts, civil construction, track establishment, and control communication. Further civil construction is divided into 12 civil work intervals and 4 control ranges. During the whole civil work, we had directed much attention on the ground subsidence along the railway, especially segment C270 of 42.8km.

3.1. Vertical Movement of GPS Point on the Viaduct in the C270 Interval

The ground subsidence along the Taiwan High Speed Railway had been discussed since the Taiwan High Speed Rail Cooperation(THSRC) published in 2001 the following report:

THSRC: Resident engineer's preliminary report on ground movement in West Taiwan and implications for contract C270,September 2001.

This report discussed ground subsidence, especially in C270 referring to the literature published in 2000 by the Water Resources Bureau of the Ministry of Economic Affairs (MOEA/WRB).

Considering importance of these reports, a special plan was proposed in December, 2003, to carry out precise leveling and GPS survey on the viaduct in C270. Precise leveling should be carried out referring to the manual of the first order leveling in Taiwan with allowance of discrepancy of 2.5mm $\sqrt{Skm}$ (S is the length of leveling rout in km unit) between forward and backward survey. GPS should be carried out on every survey points with 2 km interval with observation period of over 3 hours.

These works were carried out on March, 2004 and September 2004, respectively. A special device for GPS observation were developed, and installed on the viaduct. Orthometric heights were determined referring to the Taiwan first order bench marks near C270. Analyses of GPS observation were carried out with the aid of Bernese4.2 and of GAMIT10.1 as a check. Three dimensional position determination was carried out referring to IGS stations such as WUHN(China), USUD(Japan), NTUS (Malaysia) , and GUAM(USA).

Vertical ground deformation was deduced by precise leveling and GPS observation for the period from March, 2004 to September, 2004. The results are shown in Figure 4. We find maximum subsidence near the station MC231094. Generally we find similar trend derived from leveling result and GPS result. Most remarkable discrepancy between two surveys is 3cm, while this may due to the lack of observation time. We may cancel out this kind of discrepancy by application of longer observation time.

3.2. Comparison of the new Results of Ground Subsidence with the old one

THSRC Report (2001) gives the figure in which contour line of equal ground subsidence rate is illustrated. From this we find yearly rate of ground subsidence along the interval C270 as follows:

Around TK210	-	1 cm / year
Around TK233 ~ TK237	-	6 cm / year
Around TK245	-	5 cm / year

THSRC Report(2001) gives the subsidence rate of -10 cm / year ~ 11cm□year along the C270 during the period from 2000 to 2001.

New GPS survey and precise leveling were carried out on March, 2004. Some observation points are the same ones for November, 2003. Thus we can deduce vertical deformation during the period from November, 2003 to March, 2004.

The above mentioned old results of subsidence are summarized in Figure 5. Considering these results, we may obtain the following conclusions on the trend of subsidence in C270;

1 - Trend of subsidence rate along the interval C270 during June, 2003 -November, 2003, and the one during November, 2003-September, 2004 are quite similar each other. This indicates that latest subsidence rates obtained from repeated GPS observation and precise leveling on the viaduct in C270 may be quite the same one as obtained from former precise leveling on the ground.

2- Center of maximum subsidence may migrate from time to time, while annual rate of subsidence does not change almost throuout whole period of railway construction.

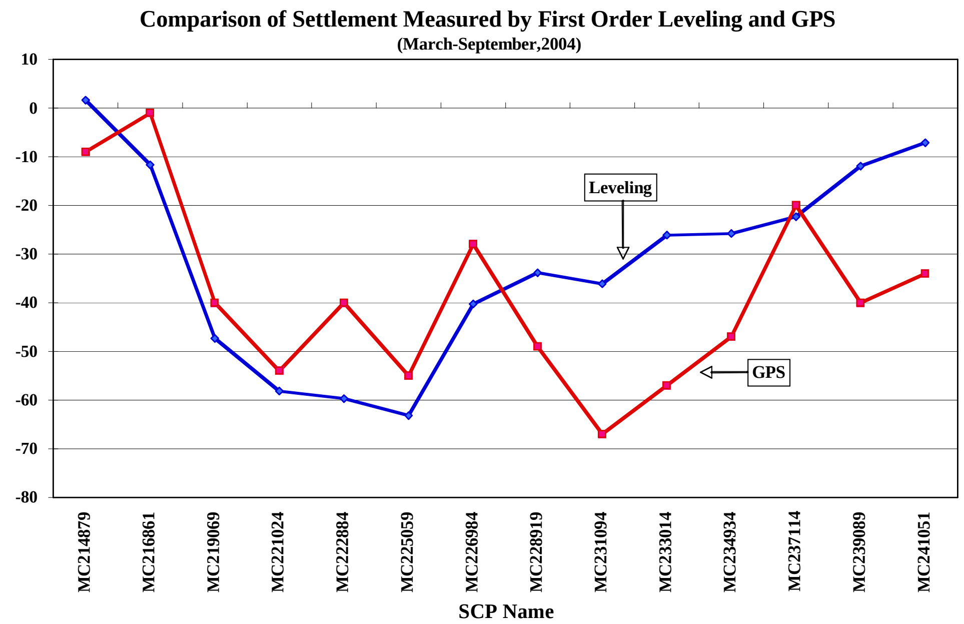


Figure 4 - Vertical deformation of survey points on the viaduct, C270 interval (1).
Period: March, 2004 ~ September, 2004

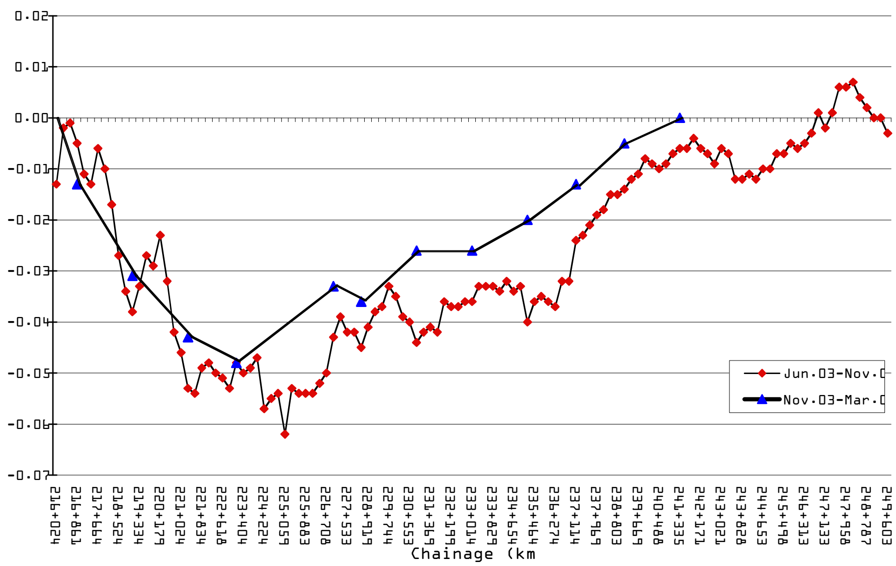


Figure 5: Vertical deformation of survey points on the viaduct, C270 interval (2).
Period: June, 2003 ~ November, 2003(red)
Period: November, 2003~March, 2004(blue)

3.3. Horizontal Movement of Survey Point on the Viaduct in C270

We can deduce the horizontal movement of survey points on the viaduct in C270 from the results of 24 hour GPS observation that were carried out in March, 2004 and September, 2004, respectively by means of academic software such as Bernese4.2 and GAMIT10.1. The results are indicated in Figure 6(a) and Figure 6(b). The westward movement of 10~20mm is remarkable. The results obtained from two different software's coincide each other within accuracy of several mm, while result from GAMIT may be more stable rather than the one from Bernese.

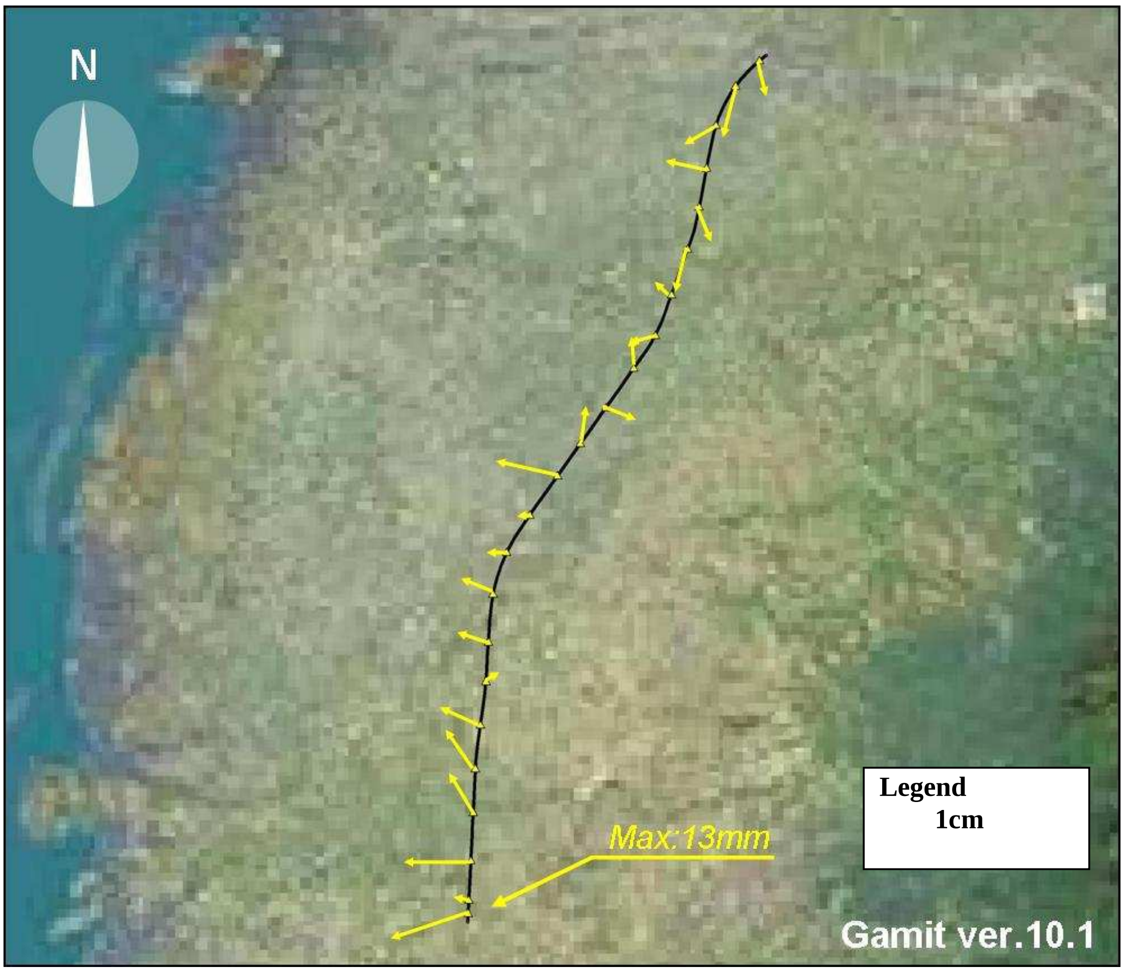


Figure 6(a): Horizontal movement of survey points on the viaduct, C270.
The results obtained from GAMIT10.1 are shown.

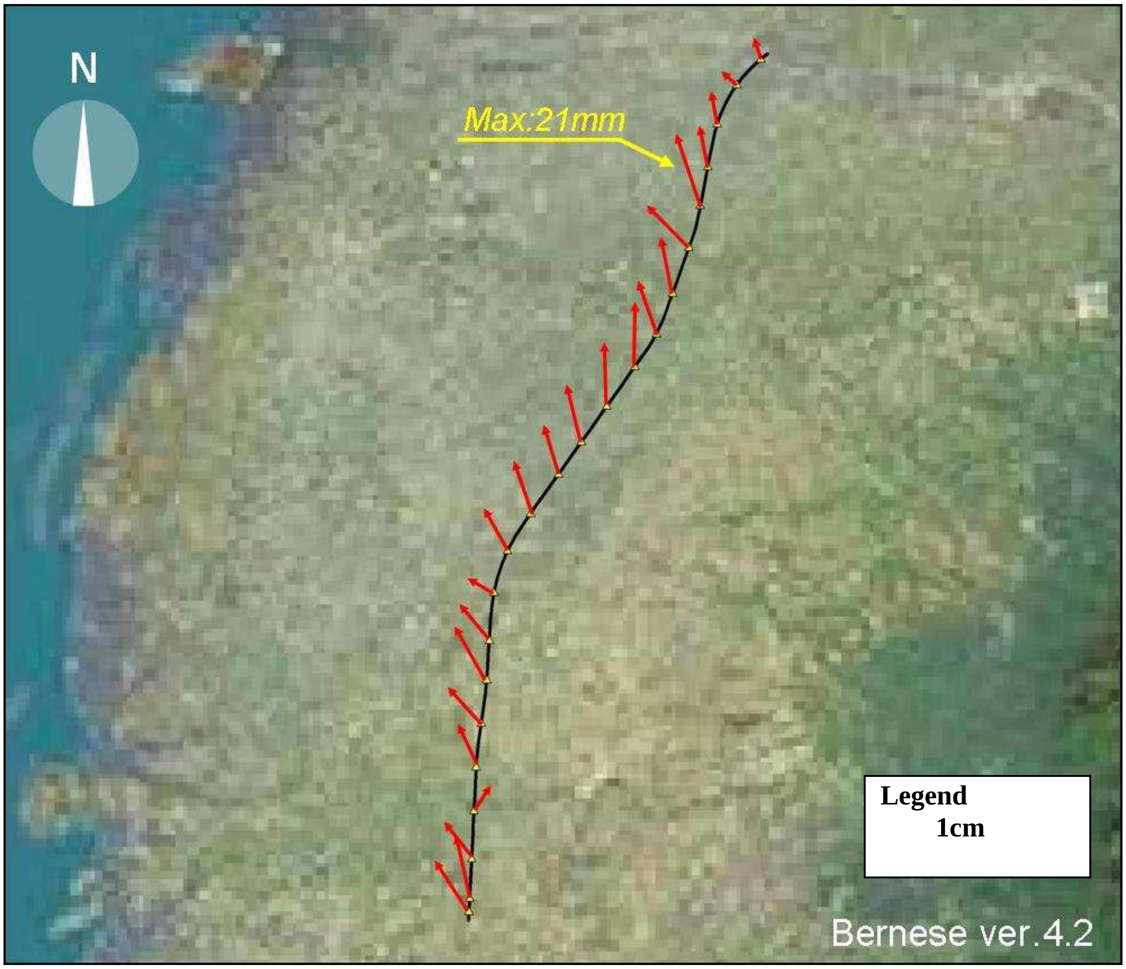


Figure 6 (b): Horizontal movement of survey points on the viaduct, C270.
The results obtained from Bernese 4.2 are shown.

4. CONCLUSIONS

Until now ground deformation was usually monitored by the performance of precise leveling, while test observations of GPS have been carried out directly in Kawasaki, Japan, for monitoring ground subsidence, and also on the viaduct along high speed railway in Taiwan in order to investigate viaduct deformation caused by the ground subsidence. Here we give summary of the results of this kind of test observations were carried out in March, 2004 and September, 2004, respectively. We find ground subsidence of 10cm/year at the most and also horizontal movement of 2~3cm along the railway. Thus we find GPS survey is useful not only for detecting the vertical subsidence but also for horizontal movements.

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