Assessment of Satellite Based and Terrestrial Measurement Techniques in Monitoring Vertical Deformations

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SUMMARY

Monitoring and analyzing deformations of large structures is included in the main interest of Geodesy Science. In deformation monitoring, terrestrial techniques such as precise levelling and/or space-based techniques such as GPS (Global Positioning System) are most commonly used measurement methods.

In this paper, the subject is vertical deformation analysis of a large viaduct across a lake. The viaduct is a very attractive test object with its geological and geotechnical conditions for deformation research. With the aim of determining the deformations of this engineering structure, a control network was established and four campaign GPS measurements were carried out. GPS measurements were supported by Precise Levelling Technique. Because of that the height component is the least accurately determined GPS coordinate, due to geometric weakness of system and atmospheric errors.

Analysis were done according to three different approaches; at first two approaches, deformation analysis using the height differences provided from the precise levelling measurements and from the GPS measurements were carried out separately. Then, as the third approach, the combined deformation analysis using the data from both measurement techniques was done. In combining process of heterogeneous data of two techniques, the stochastic information of the measurements was determined by the help of Helmert Variance Component Estimation technique.

In here, the details about the computation algorithms of all these three approaches will be explained. The results will be given both in numerically and graphically. Interpretations about the results are going to be held in the conclusion part of the paper too.

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1. INTRODUCTION AND BACKGROUND

Technologic developments affect engineering applications as well as all fields of human life. Using the products of developed technology, very large sizes of structures are constructed to serve humanity today. However, monitoring these structures against destructions of natural effects, such as atmospheric and environmental factors and periodically occurred disasters such as earthquakes, landslides etc. is very important to being sure on safety of them. Because, when a long period of time is considered, the defects of these effects might be much more serious. According to this necessity, much related to human health, monitoring deformations of these engineering structures and analyzing of them constitutes a main investigation area of geodesy science.

There are several methods to use measuring the deformations of structures. These methods can be grouped into two as geodetic methods and non-geodetic methods. The major motivation of this study as the subject of this paper is geodetic methods. Until 1980's the deformations of large engineering structures were monitoring using conventional geodetic methods, which includes precision distance-angle measurements and levelling measurements. After starting to use Global Positioning System (GPS) with geodetic aims in the world wide, this satellite based positioning system has also become a dominant technique in deformation measurements branch of geodesy.

GPS technique has benefits of high accuracy and simultaneous 3-D positioning; however there are handicaps about vertical positioning using this technique. Because, the height component is the least accurately determined GPS coordinate, predominantly due to inherent geometric weakness and atmospheric errors (Featherstone et al 1998). In most cases of deformation monitoring studies related to large engineering structures, the required accuracy level is considerably high such as millimeter. GPS measurement technique satisfies the accuracy requirements for determination of 2D deformations; on the other hand, the required accuracy in vertical may not be satisfied by using this technique, because of the insufficiencies mentioned above. Therefore, using GPS measurement technique in deformation measurements with millimeter level accuracy requires some special precautions that increase the measurement accuracy in GPS observables via eliminating or reducing some error sources such as using forced centering equipments, applying special measuring techniques like rapid static method for short baselines or designing special equipments for precise antenna height readings (Erol and Ayan 2003).

In some cases, even these special precautions might be insufficient to reach the necessary accuracy level; at that time to support GPS measurements with a precise conventional method such as precise levelling measurements would be very useful as an improving solution.

All these summary information, given here until now, is to imply the necessity and reason of this study. The aim of this study is analyzing the vertical deformations of an engineering structure using GPS and Levelling measurements data. During the analysis, three different approaches were applied. In the first and second approaches, height differences from precise levelling measurements (ΔH) and from GPS measurements (Δh) were used in the analyzing algorithm separately, but in the third approach the combination of height differences (Δh and ΔH) were used in the deformation analyzing procedure. In combining process of two observables groups ($\underline{\Delta h}$ and $\underline{\Delta H}$), Helmert Variance Component Estimation Technique is used during the determining the weights of observables as the stochastic part of the model. The theory, application steps and results will be explained among the details of following sections.

2. THEORY OF DEFORMATION ANALYSIS

The conventional deformation analysis is managed in three steps in geodetic networks. In the *first step*, the measurements, carried out in t_1 and t_2 measurement epochs, are adjusted separately according to free adjustment method; outliers and systematic errors are detected and eliminated in this step. In the *second step*, global test procedure is carried out and by this test it is ensured that if the network points, assumed as stabile, stayed really stabile in the $\Delta t = t_2 - t_1$ time interval or not. In the global test, after the free adjustment calculations of the networks (epochs) separately, the combined free adjustment is applied to both epoch measurements. During the combined free adjustment computation, the positions of the assumed stabile points, are given as one-single group of points for both epochs, on the other hand the positions of the deformation points in the t_1 instant are assumed as if one group of points and the positions in the t_2 instant are assumed as another group of points. In addition to this, in combined free adjustment, the partial-trace minimum solution is applied for the stabile points ($tr(Q_{stabile,stabile}) = min$) (Ayan 1982; Ayan et al. 1991, Erol and Ayan 2003).

After determining a group of stabile points as the results of global test, the deformation points are handled one by one and it is inspected that if their positions are changed or not (Ayan 1982, Ayan et al. 1991, Erol and Ayan 2003).

2.1 Deformation Analysis Using Height Differences

2.1.1 Deformation Analysis with Levelling Measurements

To test the changes of heights in points of a control network, measurements are carried out in durations of t_1 and t_2. The network is adjusted separately by using these measurement groups. During these calculations, free network adjustment method is used and it is assumed that all of the point heights are changed. To use the same point heights as the approximate values in both adjustment computations is purposed. In the calculations, outliers are eliminated and calculations are repeated. It is aimed that the measurement precision and network geometry are to be the same during the both period (Erol and Ayan 2003).

The second step of analysis is called as global test. With this test, it is determined if there is any vertical displacement in a point or a group of point in the $\Delta t = t_2 - t_1$ interval. For carrying out the global test, the free adjustments of the measurements in duration of t_1 and t_2 and thereafter the combined free adjustment of two groups of measurements are employed.

$$\Omega_1 = \underline{v}_1^T \underline{P_1} \underline{v}_1 \qquad S_{01}^2 = \frac{\Omega_1}{f_1} \tag{1}$$

$$\Omega_2 = \underline{v}_2^T \underline{P_2} \underline{v}_2 \qquad S_{02}^2 = \frac{\Omega_2}{f_2} \tag{2}$$

$$\Omega_G = \underline{v}_G^T \underline{P_G} \underline{v}_G \qquad S_{0G}^2 = \frac{\Omega_G}{f_G} \tag{3}$$

In the equations, f_1 , f_2 , f_G demonstrate the degree of freedom after the first, the second and the third adjustment computations correspondingly. As it is understood, equation 1 belongs to free adjustments computations of the first epoch, equation 2 belongs to free adjustments computations of the second epoch and equation 3 belongs to the combine free adjustments.

From these results that are found out in equation 1, equation 2, and equation 3, the test value T_G is determined as given below.

$$\Omega_0 = \Omega_1 + \Omega_2 \qquad f_0 = f_1 + f_2 \qquad r = f_G - f_0 \qquad T_G = \frac{(\Omega_G - \Omega_0)/r}{(\Omega_0 / f_0)} \tag{4}$$

This test value is independent from the datum and fit to the F-distribution with in an assumption. T_G test value, is compared with the critical value, chosen from the Fisher-distribution table according to r and f_0 degrees of freedom for S=1-α=0.95 confidence level. There after, if $T_G < F_{r,f_0,1-\alpha}$, it is accept that the H_0 null hypothesis that is implied with $H_0 : d = \underline{H}_2 - \underline{H}_1 = 0$ is true for the points of which heights assumed as if not changed.

On the contrary, if $T_G > F_{r,f_0,1-\alpha}$, it is said that the points, which had been chosen as stabile were changed their heights. Then, the combined free adjustment and global test are repeated again and again as all of the points, which had been assumed stabile, are being leaved out from the assumed stabile points list one by one, because each of them might be responsible for the deformation of the network composed by stabile points. By this way, the real stabile points, which are not changed their positions during the Δt time interval, are determined (Erol and Ayan 2003).

The following step of the analysis is the localizing of height changes. For doing this, T_H test values are calculated for the every network points, except the stabile points, and they are compared with F critical value that is given from the Fisher distribution table again (Erol and Ayan 2003).

$$d = H_2 - H_1 \qquad S_0^2 = \frac{\Omega_0}{f_0} \qquad T_H = \frac{d^T\, Q_{dd}^{-1}\, d}{r\, S_0^2} \qquad Q_{dd} = Q_{H_1H_1} + Q_{H_2H_2} \tag{5}$$

If the $T_H > F_{r, f_0, 1-\alpha}$, it is said that the height of the point changed significantly. Otherwise, it is resulted that d height difference is not a displacement but it is caused by the random measurement errors (Erol and Ayan 2003).

2.1.2 Deformation Analysis with GPS Derived Height Differences

Determining vertical deformations using GPS derived height differences is based on the same calculation algorithm as deformation analysis with precise levelling data, which is explained above very detail. In the algorithm, the ellipsoidal height differences (dh_{ij}), which were derived from the GPS baseline solutions, are used as measurements. Also, the stochastic information of measurements comes from the GPS baseline solutions as m_0 (apriori variance) and $Q_{dh_{ij}dh_{ij}}$ (cofactor value of height difference). From these values, $m_{dh_{ij}}^2 = m_0^2 Q_{dh_{ij}dh_{ij}}$ is calculated as variance of GPS derived height differences. The weight of GPS derived height differences is calculated as $P_{dh_{ij}} = \dfrac{m_{0dh_{ij}}^2}{m_{dh_{ij}}^2}$. In this equation is $m_{0dh_{ij}}^2 = 1$ in the case study.

2.1.3 Combined Deformation Analysis

In this approach, height differences, derived from both measuring techniques, are used together and deformation analysis is applied according to results of evaluation of combined data groups. A very important point that has to be considered in the first step of this approach is that the both measurements groups derived from both techniques do not have the same accuracy. And so, the stochastic information between these measurements groups relative to each other has to be derived. In this study, for computing the weights of both measurement groups derived from GPS measurements and levelling measurements respectively, Helmert Variance Component Estimation (HVCE) Technique have been used.

Variance Analysis was developed at the very beginning of 20^{th} century and firstly was applied to heterogeneous data in 1907 by F.R. Helmert (Grafarend 1984). So far, variance analysis technique has been applied to a lot of fields and the problems related to Geodesy and Photogrammetry Engineering has become the first among these fields. The purpose of variance component estimation is to find realistic and reliable variance components of the measurements to construct correctly the a priori covariance matrix of them. The method divides the measurements into different groups, and then simultaneously estimates the variance components for each group. Before a least square solution is used, the “a priori” covariance matrix has to be estimated (Kızılsu 1998).

Variance analysis technique has an increased importance especially after satellite based measurement techniques have become widely used in geodetic applications. Because, satellite based measurements and terrestrial measurements are used together with in a same project to serve the same purpose. However, with this aim, when combining these measurements is necessary, the correlation between them and different weights of each measurement group causes problems in the computation algorithms. Because of that it is difficult to put together the measurements, which doesn't have the same accuracy. In general, the weights are derived experimentally in the laboratory environments to use while combining these kinds of measurements. However, these experimental processes could be discussed, because, researches are shown that there are considerable differences between the weights, computed according to variance analysis and experimental ones.

A full derivation of the technique and computational model of variance component estimation are given in Welsch 1978, Grafarend 1984. The summary of the mathematical model is given below (Kızılsu 1998).

The Helmert equation,

$$H\sigma^2 = c \tag{6}$$

Matrix expression of equation 6 is:

$$\begin{bmatrix} h_{11}h_{12}...h_{1u} \\ h_{21}h_{22}...h_{2u} \\ .... \\ h_{u1}h_{u2}...h_{uu} \end{bmatrix} \begin{bmatrix} \sigma_1{}^2 \\ \sigma_2{}^2 \\ .... \\ \sigma_u{}^2 \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ .... \\ c_u \end{bmatrix} \tag{7}$$

where,
u is number of measurement groups

$$c_i = v_i{}^T P_i v_i \tag{8}$$

$$h_{ii} = n_i - 2Tr(N^{-1}N_i) + Tr(N^{-1}N_i N^{-1}N_i) \tag{9}$$

$$h_{ij} = Tr(N^{-1}N_j N^{-1}N_i), \quad (i \neq j) \tag{10}$$

N is global normal equation matrix including all measurements, n_i is number of measurements in i^{th} measurement group, P_i is assigned weight matrix for i^{th} group, N_i is normal equation matrix for i^{th} group, v_i is residuals of i^{th} group measurements, and σ^2 is estimate of the true value of the variance factor.

In here, as it is seen that, c is a function of P (weight matrix) and P is also a function of σ^2. And because of this hierarchy, Helmert solution needs an iterative computation.

Step by step computation algorithm of Helmert Variance Component Estimation is as given below:

The First Step : Before the adjustment, a unique weight is selected for each measurement groups. At the beginning, the weights for each measurement groups can be chosen equal $(P_1 = P_2 = ... = P_u = 1)$

The Second Step : By using the a-priori weights, normal equations $(N_1, N_2, ..., N_u)$ for each measurement groups separately and general normal equation (N) are composed. In here, the general normal equation is the summation of normal equations such as $N = N_1 + N_2 + ... + N_u$.

The Third Step : Adjustment process is started, unknowns and residuals are calculated.

$$x = N^{-1}d, \quad (d = A^T Pb) \tag{11}$$

$$\begin{aligned} v_1 &= A_1 x - b_1 \\ &\ldots\ldots\ldots\ldots \\ &\ldots\ldots\ldots\ldots \\ v_u &= A_u x - b_u \end{aligned} \tag{12}$$

The Fourth Step : Helmert equation is generated (Equation 6).
The Fifth Step : Variance components in Helmert equation $(\sigma_1{}^2, \sigma_2{}^2, ..., \sigma_u{}^2)$ and new weights are calculated.

$$P_{i+1} = P_i / \sigma_i{}^2 \tag{13}$$

The Sixth Step : If the variance component $(\sigma_i{}^2)$ for all groups $(i = 1,2,....,u)$ is equal to one, then the iterations will be over. If it is not, then it goes to the second step and computations are carried on using the new weights. The iterations are continued until the variances reaches to one ($\sigma_i{}^2 = 1$) (Kızılsu 1998).

3. NUMERICAL EXAMPLE

3.1 Definition of the Study

In this study, the vertical deformations of highway viaduct, Karasu, were investigated using GPS measurements data and precise levelling data. As the longest viaduct of Turkey (2160m), Karasu is located in the west of Istanbul in one part of the European Transit Motorway.

While it is considered the hydrologic and geologic conditions of the area, where the viaduct was built, it is better understood the reason of choosing this viaduct as the example for investigating the structural deformations of a construction, because this viaduct cross over the lake and piers of the building are in the water.

The deformation measurements of Karasu involved four measurement campaigns. The first campaign was in June 1996, the second in March 1997, the third in October 1997 and the last one was in April 1998. These four campaigns were included GPS measurements and precise levelling measurements. With the aim of investigating the deformations of this structure, a well designed local geodetic network was established, and it was measured using GPS technique according to designed session plan. Also, precise levelling measurement technique was carried out between network points.

The network had 6 reference points, were set around the viaduct and 24 deformation points on the building of the viaduct especially established on the piers (as it is seen in the figure 1(a)) where thought to be most stabile places on the structures.

(a) **(b)**

Figure 1 : In **(a)** one of the 24 deformation points established on a pier of the viaduct is shown, in **(b)** also one of these points is seen during the GPS session.

Viaduct has two tracks and 24 of deformation points, the 12 of them are in the northern track and other 12 of them are in the southern track as it is seen in the figure 2. The constructions of these deformation points were built as appropriate for the forced centering institutions (see

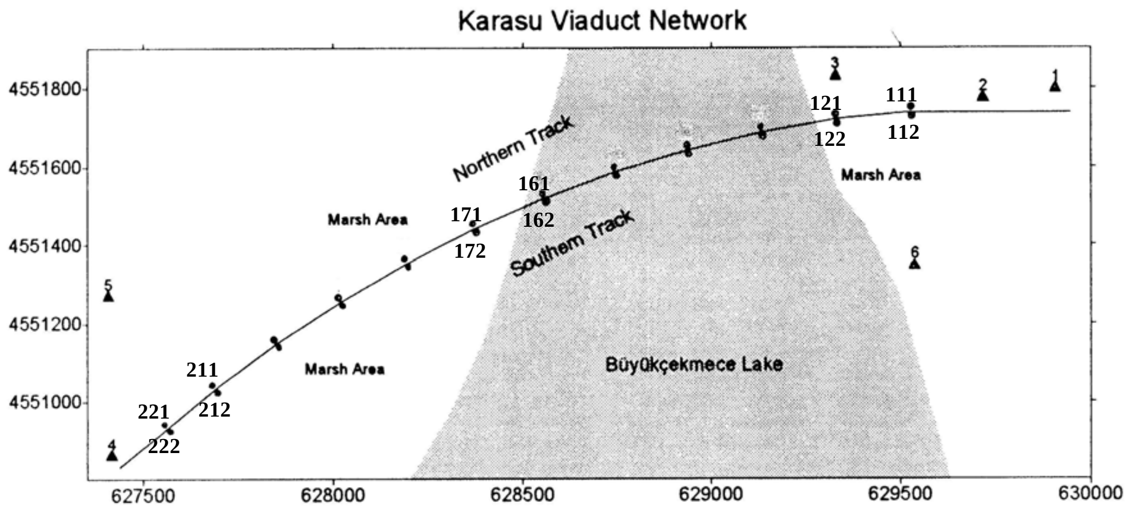
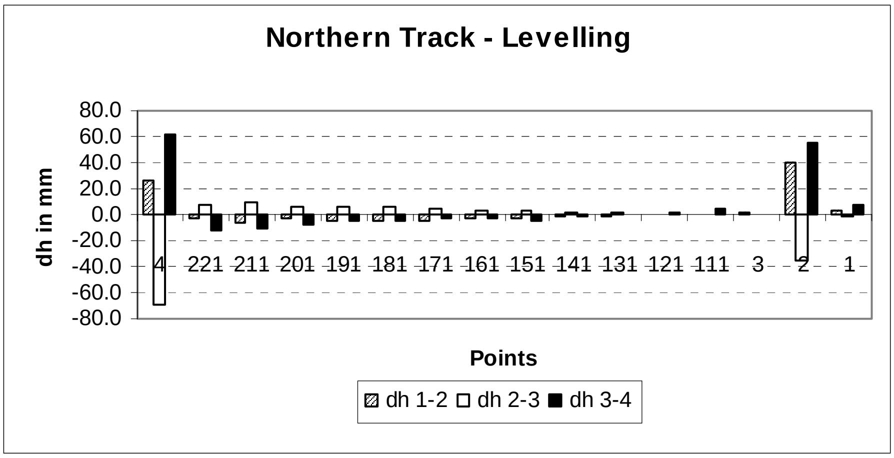


figure 1 (a)-(b)). And reference network points were constructed as pillar and so they also had these instrumentation systems to avoid the centering errors (Erol and Ayan 2003).

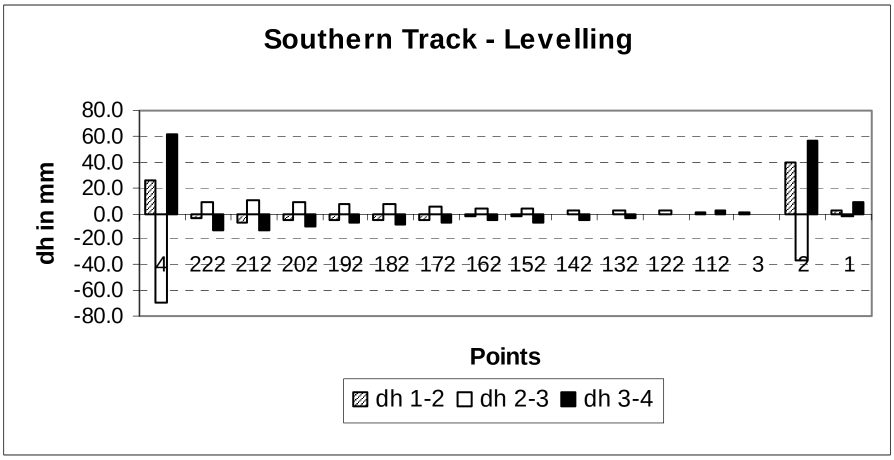
Figure 2 : The configuration of the geodetic network (Çelik et al. 2001).

3.2 Evaluating of Deformation Analysis Approach

Resultant graphics of three deformations analysis approaches are given below.

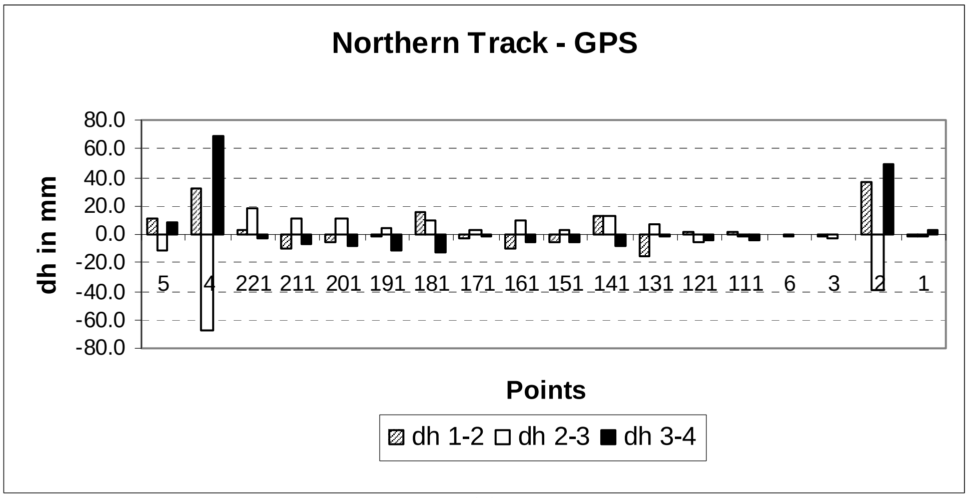


(a)

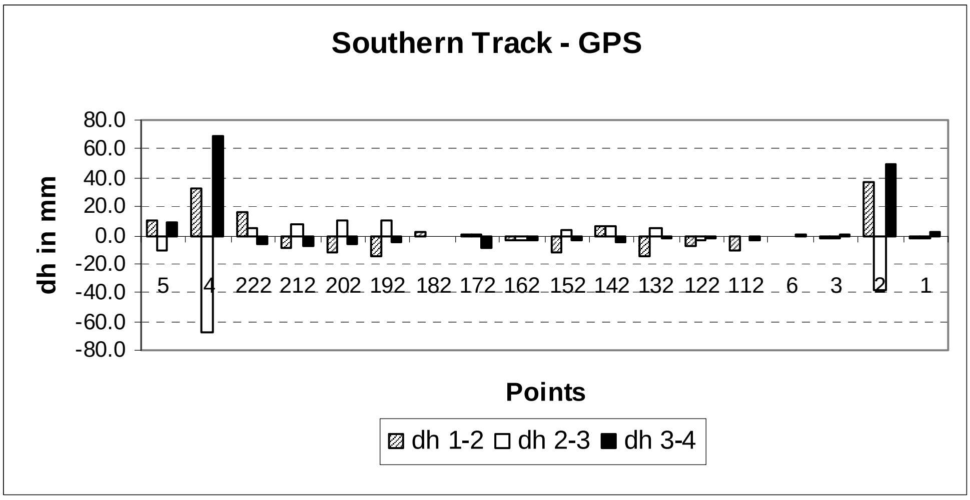


(b)

Figure 3 : Height differences between consecutive epochs for each point in the northern track (a) and southern track (b) of the viaduct according to the **first approach results** (deformation analysis using height differences from levelling measurements)

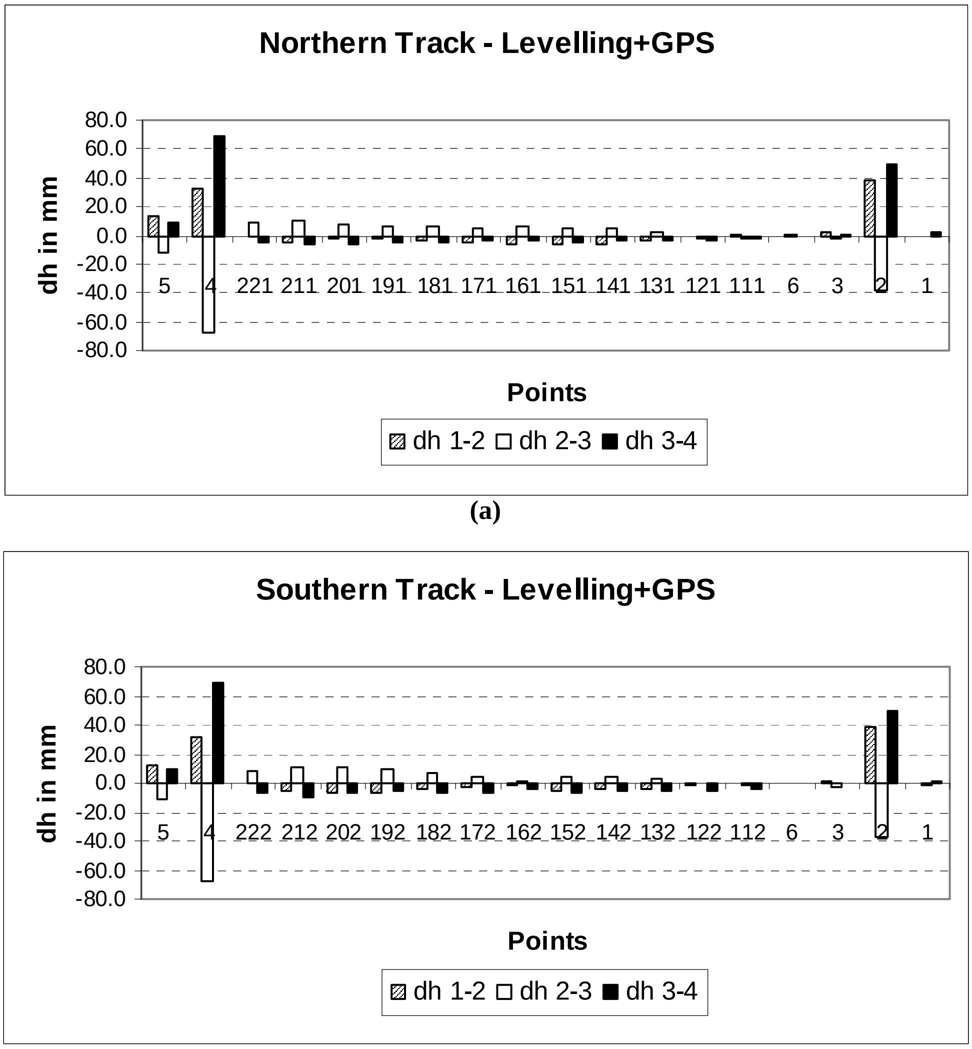


(a)



(b)

Figure 4 : Height differences between consecutive epochs for each point in the northern track (a) and southern track (b) of the viaduct according to the **second approach results** (deformation analysis using height differences derived from GPS measurements)



(a)

(b)

Figure 5 : Height differences between consecutive epochs for each point in the northern track (a) and southern track (b) of the viaduct according to the **third approach results** (deformation analysis using height differences derived from both GPS measurements and levelling measurements)

3.3 Interpreting of the Results

As it is mentioned previously, the deformation analysis was carried out into three approaches. At first data from both measurement techniques were processed for each epoch separately. Thus, the results from independent solutions for each epoch were compared. This was necessary for getting information about the quality of data, revealing possible inherent problems and to get apriori information about instable points and by this way to determine a suitable strategy for analysis.

As the result of this preparation process, it was seen that precise levelling measurements made very beneficial support to GPS measurements. Because by the help of levelling, it is become possible to check the heights from GPS measurements and antenna heights problems occurred during GPS sessions were able to be clarified. This is very considerable contribution of levelling measurements to GPS measurements in deformations monitoring.

After these processes, deformation analyses were carried out by using height differences from levelling measurements, from GPS measurements and also by using combination of height differences from both GPS and levelling measurements respectively. In general meaning, the results were confirmed each other. In the results, it was surprisingly found that the maximum height changes were in point 2 and point 4 (as it is seen in the graphics), which were assumed as stabile at the beginning of the project and even though that their constructions are pillar. According to analysis of precise levelling data, on the contrary of the situation in point 2 and point 4, there weren't seen any changes in heights in the deformation points on the viaduct. On the other hand, according to the second approach (using GPS derived height differences) in some points on the viaduct, height changes were reported.

In the third approach, as a result of the Helmert Variance Component Estimation it was computed that the weight of height differences from levelling equals to 30 times over of the weight of GPS derived height differences. This result was reached in the third iteration step. According to derived weights of the heterogeneous data group, deformation analysis was repeated.

Results of three approaches can be compared according to graphics (see figure 3, 4, and 5). In the graphics, height changes according to consecutive measurement campaigns are seen. The point groups of each track of the viaduct are shown in separate graphics. Therefore, for the result of each approach, there are two graphics as northern track and southern track. As the graphics of the first, the second and the third approaches are compared, it is seen that the results of the third approach is closer to the first approach. This similarity shows that it is not reliable enough to use GPS measurements without special precautions for the GPS error sources, such as multipath, atmospheric effects, antenna height problems etc., in vertical deformation analysis of engineering structures. So, as the result of this study, it is suggested to support GPS technique with levelling measurements in monitoring vertical deformations. According to investigating result of the second approach, it was seen changes in heights of some points on the viaduct. However, while the first and third approaches are considered, it is understood that these changes, seemed to be deformations on the object point of the viaduct according to results of the second approach, were not significant and caused by the error sources in GPS measurements especially antenna height problems.

In general review of graphics, all points including reference and deformation points, have similar characteristic of movements between consecutive epochs. Maximum movements were recorded in point 2 and point 4 and these movements were interpreted as deformation. The movements recorded in deformation points on the viaduct didn't mean deformation since they are not significant regarding to accuracy achieved.

However, at a first glance, it was surprising to found deformations in point 2 and point 4 that had been chosen as reference points, after geological and geophysical investigations, the origin of these results was captured. According to that the area is a marsh area that this characteristic might widen also underneath of these two reference points, 2 and 4. The uppermost soil layer in the region is not seemed to be stabile and the foundations of the constructions of the reference points are not founded as deep as the piers of the viaduct and so they are affected the environmental conditions easily. And these conditions supported the results of the analysis that in the object points on the viaduct, there were not exposed any significant movements. On the other hand, it is possible to mention about the correlation between vertical movements in two reference points, 2 and 4, and wet/dry seasons, because the uplift and sinking movements of these reference points seems very synchronic as related to seasonal changes in amount of water (see the given graphics in figures 3, 4 and 5).

4. CONCLUSION AND REMARKS

In this study, vertical deformations of a large highway viaduct were investigated with three different deformation analysis approaches. The main motivation was testing the performance of GPS as a satellite based precise positioning system in determining vertical deformations as being aware of geometrical weakness of this system and error sources affects its vertical positioning accuracy. To determine the performance of it, the results of analysis of the data derived from GPS are compared with the results of analysis of precise levelling measurements. As the third approach, data groups, ellipsoidal height differences from GPS and orthometric height differences from precise levelling measurements were combined, and they were used in the deformation analysis computations. These heterogeneous data were combined according to HVCE technique in this deformation analysis approach, and as the result of this technique, the weights of precise levelling height differences as proportional to the weights of GPS derived height differences was calculated as 30.

The results of this study, experienced with measurements of Karasu viaduct, are thought to be very important remarks for vertical deformation analysis studies using GPS measurements. As the first remark, GPS measurement technique can be used for determining vertical deformations with some special precautions for eliminating GPS error sources. These include using forced centering mechanisms to avoid centering errors, using special equipments for precision antenna height readings, using special antenna types to avoid multipath effects etc. Also, during the data processes it is necessary to clear the cycle slips from the data, and to consider insufficiencies of the used tropospheric and ionospheric models.

However, even though these precautions, to provide better results in vertical deformation analysis, GPS measurements have to be supported with Precise Levelling measurements. It was seen that precise levelling technique gives more successful and reliable results according to GPS technique in determination of vertical deformations, while the first and the second analysis approaches were compared each other.

And using the combination of GPS measurement technique and precise levelling technique gives better results than using just GPS measurement technique as it can be seen in the third deformation approach. Hence, using the combination of levelling measurements and GPS measurements together in deformation analysis algorithm gives better and more reliable results in vertical deformation analysis. And on the other hand, levelling provides an opportunity to check antenna heights errors and by this way it helps to increases the quality of GPS data, and according to this, using levelling measurements as an auxiliary technique during the deformation measurements in addition to GPS is also be beneficial for the 2D deformation analysis with GPS measurements.

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BIOGRAPHICAL NOTES

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The author graduated from the Geodesy and Photogrammetry Engineering Department of Istanbul Technical University (ITU) in June 1996. In January of 1998, he started to study as Research Assistant in Geodesy Division of ITU. He graduated Geodesy and Photogrammetry Engineering Master Program of Institute of Science and Technology at ITU in June 1999. He studied "Monitoring and Analyzing Deformations of Karasu Viaduct Using GPS Measurements" as his MSc thesis. He attended to Doctorate Program of Geodesy in Institute of Science and Technology of ITU in the year of 1999. Still, he is studying his PhD thesis with the subject of “Deformation Analysis Using GPS and Precise Levelling Measurements” and employed as a research assistant at ITU. His scientific interests include Deformation Analysis, GPS Measurements and Data Processing, Hardware of Computers.

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