GPS Network for Monitoring Land-Subsidence in Metropolitan Region of Recife, Brazil

Verônica Maria Costa Romão, *UFPE Recife*
Antônio Simões Silva, *UFV Viçosa*
Tarcísio Ferreira Silva, *UFPE Recife*

Conteúdo [esconder]

1. Introduction

The metropolitan region of Recife (RMR) has a population around 3 million inhabitants over an area of 2.740 km2, that includes 14 cities, with Recife as the main city of Pernambuco State, situated in northeast of Brazil (Figure 1). The rapid growth of the population in Recife and the scarcity of rain in the interior regions of the state during the last years have led to continuous shortages in water supply, for private as well as for public and industrial use. So the demand for water in the RMR is not totally supplied by the water authority of the Pernambuco State that provides about 12m3/s of water, corresponding to 75% of all demand for the region (Cabral et al., 2000).

As a consequence, since 1998 about 4000 deep wells have been established in the region. Schematically, in Figure 2 this is seen in a quarter of Recife (Casa Amarela), where the black points represent the constructed wells for water extraction.

Figure 1 : Location of the State of Pernambuco and Recife, in Brazil

Figure 2 : Schematic large number of wells for pumping water in the Casa Amarela quarter of Recife

This uncontrolled, extensive ground water extraction from aquifer storage probably has created subsidence along the coastal area, where the population density is significantly larger than for any other quarter in Recife, and the water demand increases with the summer tourism. A supposed land subsidence associated with overdraft of aquifers in RMR is now being jointly investigated by a research group from the Federal University of Pernambuco and the University of Hannover that for over 25 years has cooperated with universities and organizations in Brazil through several common projects related to satellite positioning (Romão 2001). The Polytechnic University of Catalunha is also participating in this project with numerical studies, based on finite elements, which include geological profiles in a simulation by using the computational software Code-Bright for a prediction of future subsidence processes (Cabral et al. 2002).

Figure 3 :
Area of study in Boa Viagem beach, in Recife

Several methods have been applied to monitor ground subsidence in many parts of the world. Investigations on integrating other techniques with GPS have increasingly been carried out, as reported in many research papers (Bitelli et al. 1999; Chang 2000; Aguirre et Gemael 2001; Borre et al. 2001; Ge et al. 2001; Sato et al. 2002).

In this paper, it is proposed a methodology of using the combined GPS and leveling approaches to monitor the possible phenomenon of subsidence in the area of highest risk in Recife.

2. Study Area

The main urban district in Recife lies along the Boa Viagem beach, where a central area with about 3 km2, was chosen for the pilot project of this study, as shown in Fgure 3 by hatched lines.

Three kinds of information helped to select this area for investigation:

- **high concentration of wells for pumping water;**
- **accentuated tourism, specially in the summertime that increases the demand for clean water; and**
- **available data bank with geotechnical, hydrological and hydro-geological information, which were used to perform numerical simulation with the Code_Bright software.**

3. Previous Projects

Figure 4 : Local GPS reference network in Recife

From previous joint projects, actives local GPS reference networks for precise real time positioning were implemented in Brazil. The first was developed in April 1999 in Pontal do Sul, Parana State, which was used for several marine applications (Krueger et al. 2001). In November 2000, a second network was operated during three weeks, for an urban area of Recife, with four GPS reference stations. Besides these four stations, the station RECF of the Continuous Brazilian Monitoring Network (RBMC) (Fortes et al. 1997) was also included, as seen in Figure 4.

Investigations on multi-station approach positioning under the particular equatorial ionospheric conditions, as well as its use for real time cadaster surveys and geodetic control surveys were carried out. The results showed that such local reference network is feasible to provide precise real time positioning over baselines up to 40 km, when data communication aspects are overcame (Willgalis et al., 2001; Willgalis et al., 2002), and when the effects of the distance and station dependent errors are corrected or eliminated (Seeber, 2001).

Based on these experiences and results, a GPS reference network will be established, including the RECF and the 3aDL stations from project above mentioned. Besides investigating the reference network establishment approach, the combination of GPS and levelling measurements on object-points will be studied, in order to investigate the feasibility of using GPS to monitor possible phenomenon of subsidence in Recife. This methodology is described bellow.

4. GPS Monitoring Network

4.1 Monitoring network set up

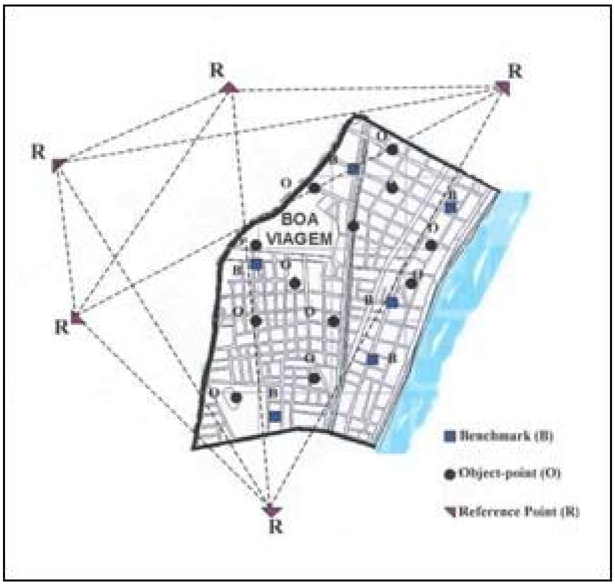

Figure 5 : GPS monitoring network

A local GPS reference network with five stations (R), including RECF and 3aDL stations, should be set up at the external study area (Figure 5), in stable places with distances between 9 and 15 km. In addition to these stations, six existing benchmarks (B) located inside the area are included to complete a field of eleven reference stations of a monitoring network. In these benchmarks GPS and leveling heights information will be available.

Twelve new well distributed control points in the area, spaced one to each other between 0,3 to 0,5 km, will be established to form the so-called field of object-points (O), in which the expected vertical displacements will represent the land subsidence for the investigated area. On the object-points, GPS and leveling observations will be also surveyed. In this form, the total monitoring network is composed of 23 stations (Figure 5).

Some of the benchmarks are located in less suitable sites for GPS signal reception. In this case, eccentric stations up to 30 m away from the benchmarks must be implemented.

4.2 GPS and leveling observations

For this investigation four epochs of GPS and leveling observations are planned, separated in time by six months each. For logistical and financial reasons, the GPS observations should be carried out in four hours sessions with five two-frequencies receivers. The permanent RECF station will be simultaneously connected to any others four stations during the surveying. By this way, the complete net will be observed in about 10 sessions, which corresponds to about two weeks of measurements. Precise leveling lines will be surveyed to connect the six benchmarks to the excentric stations and to the surrounding object-points.

4.3 Data processing and analysis

In order to identify unstable reference stations, caused by unsuitable monumentation markers or by the proximity of these stations to the deformation area, a least squares minimally constrained free adjustment must be applied (Niemeier, 1985, Silva 2002), before the computations and the analysis for any possible displacement in the object-points are performed. All GPS observations of the monitoring network will be calculated using the scientific GEONAP software (Wübbenna 1991).

The computations for each k-epoch (k = 1, 2, 3, 4) can be carried out by a free least square adjustment, in which the coordinates of all points of the monitoring network are expressed as unknowns in the Gauss-Markov-Model (Niemeier 1985; Pelzer 1985; Koch 2000; Hekimoglu et al. 2002):

$$l_k + v_k = A_k x_k \quad (1)$$

where k indicates a specified epoch. The stochastic model is given as

$$D\{l_k\} = Q_{l_k} = P_k^{-1} \quad (2)$$

Here D $\{l_k\}$ is the dispersion of the n x 1 observation vector l_k, v_k is the n x 1 residual vector, A_k is the n x u design matrix, is the u x 1 unknown vector, P_k is the n x n weight matrix of observations, and Q_{ik} is the n x n cofactor matrix.

After the condition $v_k^T P_k v_k$ = *min* is satisfied, the least-squares estimator of the unknowns can be obtained with

$$\hat{x}_k = (A_k^T P_k A_k)^+ A_k^T P_k l_k \quad (3)$$

The dispersion of, which describes the precision of the estimated unknowns, is expressed as

$$Q_{\hat{x}\hat{x}} = (A_k^T P_k A_k)^+ \quad (4)$$

where the upper + indicates a pseudo-inverse of the normal equation. The difference vector d of the estimated unknown vectors for two epochs (e.g. k = 1 and k = 2) and their cofactor matrix are expressed as

$$d = \hat{x}_2 - \hat{x}_1 \quad (5)$$

$$Q_{dd} = Q_{\hat{x}_1\hat{x}_1} + Q_{\hat{x}_2\hat{x}_2} \quad (6)$$

At this point, a global congruency test must be applied, in order to verify whether the difference vector d is significant. In other words, with this test any significant coordinate differences between the two epochs is detected. The congruency test quantity T is calculated from the equations (5) and (6) as

$$T = \frac{d^T Q_{dd}^+ d}{h\, s_0^2} \quad (7)$$

Here h represents the rank of the cofactor matrix . The estimated variance factor is given as

$$s_0^2 = \frac{v_1^T P_1 v_1 + v_2^T P_2 v_2}{f} \ , \quad (8)$$

where f = f1+ f2 is the summation of the degrees of freedom for the two epochs. Under the assumption that the coordinates are the same for the two epochs, the null-hypothesis is stated

$$H_0 : E\{\hat{x}_1\} = E\{\hat{x}_2\} \quad (9)$$

The test statistic follows the F-distribution on the basis of the probability relation

$$P\left\{\frac{T}{s_0^2} \leq F_{h,f,1-\alpha} \middle| H_0\right\} = 1 - \alpha \quad (10)$$

The null-hypothesis is rejected, when the statement T > $F_{h,f,1-\alpha}$ is satisfied. In this case a deformation is assumed. In the next step it is necessary to localize which point(s) has(have) contributed to the deformation. This investigation can be made using Gauss elimination method or others methods that can be found e.g. in Niemeier (1985), Silva (1995), and Hekimoglu et al. (2002).

The global congruency test will be applied for verifying the occurrence of deformation in the study area as well as for investigating the stability of the reference stations. Then the results of the first epoch (k = 1) will be compared with the results obtained for the project in November 2000, in order to identify any instability in the RECF and 3aDL stations.

The results of the GPS height differences will be compared with the leveling height differences between the two epochs, with the presumption that ellipsoidal height differences and orthometric height differences are regarded as equivalent. In addition the local geoid can be regarded as constant over the area of investigation.

4.4 Numerical simulation

A simulation based on the Code_Bright program, developed at the Polytechnic University of Catalunha, which uses finite elements, was recently applied at the study area surrounding a deep well. According to Cabral (2002), a flow of 5,0 m^3/h during 30 months and geological profiles were regarded in this simulation. At the end of the simulated period a subsidence of about 3 cm was detected.

5. Concluding Remarks

The results of the previously described projects, developed in Brazil, and several investigations in other parts of the world have demonstrated that GPS technology applied for a network concept can offer high accuracy by using differential carrier-phase measurements, correcting or eliminating residual systematic errors and adopting precise ephemeris, which enables the detection of ground subsidence at a level about few centimeters.

The comparis on between both kinds of height differences can be a good indicator of the feasibility of using GPS for ground subsidence detection.

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