Report on Previous and Plan of Future Geodynamic Research in the Historical Centre of Old City of Dubrovnik

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Abstract. Dubrovnik, the Croatian and the world cultural monument of the highest category, that has been included in UNESCO’s World Heritage List since 1979, is placed in seismic very active area. Throughout the history, the buildings in the city suffered a large amount of damage caused by natural disasters and by human action. The most critical of all these causes were earthquakes. Monitoring of the displacements in vertical direction in order to determine possible deformations of the historical centre of the Old City of Dubrovnik started with project network making in 1982. A comprehensive analysis of deformations has been made using PANDA scientific software. In 1995 and 1996 the larger Dubrovnik area was hit by more than 150 earthquakes of VII and VIII degrees on the MCS scale. Series of aftershocks that followed lasted for more than two years. In the course of this period more than 3000 earthquakes were registered. The region around Dubrovnik is very active in seismically-tectonic sense. The main cause of earthquakes are tectonic movements of the Adriatic micro-plate which pushes forward parts of the Adriatic structural unit. In this paper the report on geodetic measurements during the eighties and nineties in the past century will be made. The results of the analysis will show the need for further research, i.e. geodetic observations of the historical centre and much wider area around the city of Dubrovnik. Further observations must be expanded with the precise horizontal, GNSS and gravimetric measurements. The research should be done in an interdisciplinary way. The reconstruction plan for the previously established network, as well as the plan for the future research work will be presented in this paper.

Keywords: displacement measurements, Dubrovnik, earthquakes, geodynamic measurements, levelling network.

1. Introduction

Old City of Dubrovnik [Figure 1.1], the Croatian and the world cultural monument of the highest category that has been included in UNESCO’s World Heritage List since 1979 [URL 1], is placed in seismic very active area. Throughout
the history the buildings in the city suffered a lot of damage caused by natural disasters and by human action. Earthquakes were among the most important of all these causes, yet with the most severe consequences. There were more than 5000 earthquakes, the most notable was the one in 1667 that destroyed almost the whole city, killing more than 5000 people and also marked the declining power of the former Republic of Dubrovnik [URL 2]. The power of the earthquake was X degrees on the Mercalli–Cancani–Sieberg (MCS) scale. In 1979 the Dubrovnik was hit by another strong earthquake of IX degrees on the MCS scale, which marked the beginning of permanent seismic survey in the city and aseismic rehabilitation of the facilities in the historical centre under the UNESCO protection.

In addition to natural disasters and the effects of weather, deterioration of the Old City of Dubrovnik was contributed by the bombing and destruction of the City during the Croatian War for independence at the end of 1991. Damage caused to the buildings brought concern among the general public and it became necessary to repair the damages that according to estimates amounted to over two and a half billion dollars.

Monitoring of the vertical displacements to determine possible deformations of the historical centre of the Old City of Dubrovnik started with project network making in 1982. This project was realized in the field in 1983 with stabilization of benchmarks. From 1983 till 1994 seven series of measurements were carried out using precise levelling method. A comprehensive analysis of deformations has been made according to Hannover method, using PANDA scientific software.

After the last conducted series of measurements, in 1995 and 1996 the larger (15 km in radius) Dubrovnik area was hit by more than 150 earthquakes of VII
and VIII degrees on the MCS scale. Series of aftershocks that followed lasted for more than two years. There were more than 3000 registered earthquakes, of which 1350 had been located [URL 3].

2. Geodynamic aspect of Old City of Dubrovnik and its surrounding area

Dubrovnik was founded on the two main settlements - Laus and Dubrava (area 3 and 1 in Figure 2.1 - left) that were connected in 11th century by filling marshy valley between the Gruz Bay in the north and the Old Port in the south and by the construction of today’s main street Placa, i.e. Stradun (part 2 in Figure 2.1 - left). Placa street (Stradun) is running through the centre of the city from the Pile Gate to Luza Square. Its walls Dubrovnik was given in the 12th and 13th century. In figure 2.1 (right) seismic microzoning is shown, and it is notable that the whole Old City of Dubrovnik is placed in a very unpleasant area regarding the possible magnitudes of earthquakes. As shown in figure 2.1 (right) the maximum earthquake magnitudes that can occur are between 8 to 10+ MRC degrees [URL 4]. Old Town and the boardwalk were built on the ground, the composition of which consists of mud and sand, and they are both concurrently located on a seismically active area, where the Adriatic micro plate underlines the Dinarides [Marjanović 2009].

Figure 2.1 The structure parts of the ground of historical centre of Old City of Dubrovnik (left), and its seismic microzoning (right).

Causes of the earthquakes are tectonic movements whose starting point is situated in the moves of the Adriatic micro-plate. Additionally, the micro-plate pushes forward parts of the unit Adriatic. Due to the resistance to these moves a relatively wide space of noticeable compression along the touch of units the Adriatic and the Dinaric is formed. Seismically-tectonic profile has been done on the basis of the interpretation of a deep seismic reflexive profile. Firstly, positions of certain faults in space are observed, then leaps of rocks' complexes in their zones. The highest leap is present along the fault Ploče-Dubrovnik. Its largeness is about 4 km in the under surface part of the Earth's crust. In profile added
focuses of earthquakes are joined to the certain zones of fault. The occurrence of earthquakes in depths between 5 and 15 km has been distinguished. The highest concentration of earthquakes' focuses is placed in depths between 3 and 20 km [URL 4].

The region around Dubrovnik is very active in seismically-tectonic sense. Relatively high concentration of earthquakes and particularly the phenomenon of high intensity earthquakes indicate to permanently present tectonic activity. According to the geologic classifications this region is located in the area of contact between the regional structural units the Adriatic and the Dinaric. The fault Ploče Dubrovnik stretches along the direct borders of these units. Between the island of Mljet and Dubrovnik's seabed the unit Adriatic adjoins the Adriatic micro-plate. In seismically-tectonic sense the whole area of contact of these units is the most active in the structural system.

3. Displacements measurements

The primary task of geodetic measurements of vertical displacements consist of determination of the height changes of the observed object as related to its surroundings and/or height changes as the functions of time [Pelzer 1987]. This definition supposes continuous observation of objects, which was technically not possible in the 1980s. Therefore 115 benchmarks were embedded into the objects in the town, i.e. they make levelling network composed of many closed figures.

3.1. Levelling network established in the 1980s

Levelling network in the area of the old city was designed so that its benchmarks primarily serve as a permanent base points for monitoring vertical displacements. The plan of the city that was made in 1972 by the Institute of Art History, was used for the design of the network. The plan was developed based on the polygon network of Dubrovnik and measured contours of blocks in scale 1:1000, later supplemented by the details obtained from and given by the same Institute. The basic levelling network consists of 13 closed polygons and a series of benchmarks stabilized in the pilot objects selected according to the agreement with the representatives of the Institute of Cultural Monuments Protection in Dubrovnik. A total of 115 benchmarks were stabilized [Figure 2.1]. and are designated by the capital letters and numbers:

- A benchmarks outside the city walls (in total 14 benchmarks),
- B benchmarks inside the city walls (in total 60 benchmarks),
- C benchmarks of additional profiles (in total 24 benchmarks),
- D benchmarks in pilot objects (in total 17 benchmarks).
Stabilization of the benchmarks has been done in the first half of May 1982. Benchmarks in the form of brass rods, 6 cm long and 1 cm in diameter with a hole in them, are embedded into objects to the plane of the wall, for about 1.30 m above the ground. The height above the sea level is defined with the hole in the middle of the bar, which during the observation also serves to set shorter levelling rod. Benchmarks are set to be invisible, i.e. in the plane with the wall of the facility where they are located. From 1983 to 1994 seven epochs of measurements were carried out:

1. First epoch of measurements was carried out in February 1983.
2. Second epoch of measurements was carried in March 1984.
3. Third epoch of measurements was carried out in March 1985.
4. Fourth epoch of measurements was carried in April 1987.
5. Fifth epoch of measurements was carried out in April 1988.
6. Sixth epoch of measurements was carried out in April 1990.
7. Seventh epoch of measurements was carried out in June 1994.

A longer time period can be noticed between 6 and 7 epochs of measurements, which was caused by the Croatian war for independence. In the period from 1994 until today no measurements have been made. Taking into account that in 1995 and 1996 the area near Dubrovnik was hit by more than 150
earthquakes of VII and VIII degrees on the MCS scale that were followed by more than 3000 aftershocks; the fact that no measurements were taken afterwards is quite unsatisfactory.

3.2. Field measurements procedures

Measuring conditions were specific and extremely unfavourable. Very short lines of sights in combination with large height differences dominated in the field. This has resulted in increased number of level stations and thereby always with a possibility of reduced measurement accuracy.

Very often the lines of sights were passing near the ground and buildings, where the refraction influence is the biggest. Due to the terrain configuration and specific urban architecture, this was not possible to avoid. For example, one of the cross sections was 330 m long with height difference on the south side compared to the central part it is about 25 meters, while in the northern part it is about 35 meters.

Given the specific field conditions (overcoming larger height differences over short distances), a measurement procedure has been specially adapted. For the determination of height differences between benchmarks a pair of levelling staves of various types was used. When the observation of the benchmark was performed, a special short levelling rod (length 0.90 m) with centimetre division on invar bar was used. It was hung on the benchmarks in the objects. The levelling rod was secured at the benchmark using iron groove which was corresponding to the hole. Observations at the connecting points have been done using standard 3-meter invar levelling rod. The entire levelling network is dependent to a stable benchmark RDCLXXII, which was taken as errorless [Kapović et al. 1998]. Height differences between benchmarks were measured by means of differential levelling method, double-run levelling (forward and backward). The measurements were made using level Leica NA2 with optical micrometre Leica GPM3. According to ISO 17123-2 achievable accuracy (1 km double run levelling) is 0.3 mm / km by using parallel plate micrometre GPM3 [URL 5]. It should be noted that in each epoch of measurements special care has been dedicated to taking care of the technical requirements, i.e. not to change them, so the same instruments, methods of levelling, levelling staves and other accessories were used.

The results of the aforementioned measuring conditions were 4300 m levelling lines in the area of 25 ha. Due to the unfavourable terrain conditions, 4300 m levelling lines were required to set up with 270 level stations. The average length of the line of sight was 8 meters [Kapović et al. 1998]. According to the optimal length of the line of sight for differential levelling of 27.5 m [Kapović 1993], it can be concluded that these conditions were extremely unfavourable.

By reason of all these problems, great attention was paid to develop the network project with optimal geometry (with the proper selection of the position of network points in geological terms and their stabilization), in order to achieve high precision and reliability of the network. This was essential for making accurate conclusions about the actual behaviour of the monitored structures.
4. Data processing and results analysis

In vertical network adjustment, 118 benchmarks were included (115 benchmarks of epochs A, B, C and D with benchmarks R_{130}, R_{DCLXXIV} and R_{DCLXXII} and 149 height differences), i.e. there were 117 unknowns and 149 measurements which should have been adjusted. The adjustment of the levelling network was carried out with multi-surveying customised, scientific software package PANDA. Height differences for the adjustment process were taken as the arithmetic average of the two measurements (double run measurements). Statistical tests show that there were not any blunders among the observations. Since the goal of the task is to determine the vertical displacements, i.e. the change in height above the sea level of all the benchmarks from one epoch to another, the levelling network relies on a single benchmark R_{DCLXXII} as the error less. This is the benchmark of the precise levelling network on the building in the Old port [Figure 2.1], with its height above the sea level being H = 3.6060 m. Its height is obtained from tide gauge measurements and the measured height differences related to the R_{DCLXXII}. The approximate values of unknowns, i.e., the height of nodal benchmarks are determined based on the height of benchmark R_{DCLXXII}. For all seven epochs of measurements the same approximate values of unknowns were taken, i.e. the approximate heights of the points were taken from the first epoch of measurements. The benchmark R_{DCLXXII} in the Old port is connected with benchmark R_{DCLXXIV} which is located on the side west of the Pile Gate. This benchmark is associated with benchmark R_5 located in the area Boninovo.

The obtained quality analysis from the adjustment process [Table 4.1] shows that the average standard deviation of measurements is around 1 mm for all epochs of measurements except epoch 6. In epoch 6 average standard deviation is 2.54 mm. Achieved standard deviation per 1 km levelling is 3 mm/km except epoch 6. In epoch 6 standard deviation per 1 km levelling is nearly 8 mm/km. These results show that extremely difficult field conditions have the impact on collected data. Nevertheless, the quality of collected data is very satisfactory. Only in epoch 6 the measurements were of lesser quality. The reason for that fact remains unknown.

<table>
<thead>
<tr>
<th>1.96 $\sigma$ = 95%</th>
<th>Epoch 1 (mm)</th>
<th>Epoch 2 (mm)</th>
<th>Epoch 3 (mm)</th>
<th>Epoch 4 (mm)</th>
<th>Epoch 5 (mm)</th>
<th>Epoch 6 (mm)</th>
<th>Epoch 7 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. st. dev.</td>
<td>0.57</td>
<td>0.35</td>
<td>0.49</td>
<td>0.39</td>
<td>0.76</td>
<td>1.29</td>
<td>0.49</td>
</tr>
<tr>
<td>Max. st. dev.</td>
<td>1.67</td>
<td>1.06</td>
<td>1.10</td>
<td>1.16</td>
<td>2.27</td>
<td>3.80</td>
<td>1.29</td>
</tr>
<tr>
<td>Average st. dev.</td>
<td>1.12</td>
<td>0.76</td>
<td>0.80</td>
<td>0.83</td>
<td>1.62</td>
<td>2.54</td>
<td>0.92</td>
</tr>
<tr>
<td>St. dev. of st. dev.</td>
<td>0.22</td>
<td>0.13</td>
<td>0.13</td>
<td>0.14</td>
<td>0.27</td>
<td>0.49</td>
<td>0.20</td>
</tr>
<tr>
<td>St. dev. / km</td>
<td>3.48</td>
<td>2.14</td>
<td>2.52</td>
<td>2.35</td>
<td>4.60</td>
<td>7.91</td>
<td>2.86</td>
</tr>
</tbody>
</table>
4.1. Visualisation and interpretation of the achieved results

In order to analyse the behaviour of the network benchmarks, and thus the whole network, it is necessary to determine the vertical displacements of the benchmarks for all epochs in relation to the first epoch of measurements, i.e. the first epoch was taken as a reference. Adjusted heights from least square adjustment were taken for the purpose of determining the vertical displacements between all epochs of measurements.

Determined vertical displacements are shown in table 4.2, with only basic statistical information.

<table>
<thead>
<tr>
<th>Table 4.2 Basic statistical data of determined vertical displacements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical displacements (mm)</td>
</tr>
<tr>
<td>Epoch 2-1</td>
</tr>
<tr>
<td>Max “−” value</td>
</tr>
<tr>
<td>Max “+” value</td>
</tr>
<tr>
<td>Average</td>
</tr>
<tr>
<td>St. dev.</td>
</tr>
</tbody>
</table>

For the purpose of the best possible interpretation of the results, the visualisation of displacements between the first and other epochs of measurements has been done. Figure 4.1 shows the 3D surface of the entire network as a result of the first epoch of measurements.

Figure 4.1 3D surface of 1st epoch of measurements.

Figure 4.2 shows the visualisation of displacements that has been obtained as a difference of adjusted benchmark heights of the entire network for sixth and seventh epoch of measurement. Determined vertical displacements were obtained relative to the first epoch of measurement, i.e. 6-1, 7-1.
From the presented results, it is evident that in the first three series of measurements no significant displacements of surface occurred. However, from the fourth series of measurement, displacements of the benchmarks up to 4.8 mm were determined. The largest displacements were determined at the benchmarks built in pilot objects after sixth and seventh epoch [Figure 4.2], and it can be concluded that there was the subsidence of these objects.

5. Future plans

The results of the analysis show the need for further research, i.e. geodetic observations of the historical centre and much wider area around the city of Dubrovnik. Further observations must be expanded with precise horizontal,
GNSS and gravimetric measurements. The research should be done in interdisciplinary way.

The established levelling network from 1982 needs to be expanded. The problem this network has is that the area that it covers isn’t stable enough and it is located on a seismically very active area. So it is necessary to expand it to the east, west and north side of the Old City of Dubrovnik, to a more stable ground with a couple of more levelling lines and benchmarks. In that way, a more comprehensive deformation analysis could be done. The main problem with the current network is that it relies on the benchmark RDCLXXII stabilized in the Old Port that is placed on the filled ground and in the area where the strongest earthquakes can occur. From the fifth epoch of measurements benchmark RDCLXXIV was connected with benchmark R5 located in the area Boninovo, on the east side of the Old City, 1.5 km distant from benchmark RDCLXXIV. The levelling network should also be expanded to the north and west side of the Old City, so in the future the whole levelling network can rely on more benchmarks that are placed on a more stable ground and in a distant area.

Furthermore, the relative gravity measurements should be included in this project, using the calibrated high order Gravimeter Scintrex CG-5 [Figure 5.1], (the standard which is required to achieve the specified Geoid Model accuracy) [Bašić & Bjelotomić 2014] at new benchmarks explained above and at main nodal leveling network points (A benchmarks outside the city walls) along with the GNSS measurements. The main purpose of including the gravity measurements is using the potential differencies beside only differential levelling heights, and in that way not to depend on levelling lines in the future.

Figure 5.1 Relative gravimeter Scintrex CG-5

The GNSS measurements will be carried out either with the fast static or with the kinematic method for determination of ellipsoidal height for each gravity
In the future, the differential levelling measurements must be complemented with measurements for determination of the horizontal displacements using GNSS measurements. Since Dubrovnik is located on a seismically active area where the Adriatic micro plate underlines the Dinarides, GNSS measurements are necessary for better understanding and interpretation of the determined displacements. GNSS has become one of the most used methods in applications that require high positioning precision such as velocity field estimation and computation of plate tectonic models. Also, coordinates of geodetic points on Earth’s surface change with time due to plate tectonics and therefore are dependent of epoch of their determination [Marjanović et al. 2012]. The Adriatic microplate is a plate or a lithosphere block which includes the area of the Adriatic Sea, eastern part of Italy, the river Po valley and the area of western Dinarides. The microplate is situated on the border between two major tectonic plates, Euro-Asian and African plate. The main cause for the deformation processes in the whole area is the moving of African plate in north direction [Krijgsman 2002]. The results of determination of horizontal and vertical movements of the Adriatic microplate on the basis of GNSS measurements that were carried out in the period between 1994 and 2005 within the frame of the 21 measuring campaigns organised at the research territory, [Marjanović et al. 2012] should also be analysed for better interpretation of determined displacements of the Old City of Dubrovnik. At the beginning of December 2008 the CROPOS (CROatian POsitioning System) was launched. The system has 33 reference GNSS stations working 365/24/7 and apart from applying CROPOS for the state survey and cadastre, CROPOS data can also be used for further geodynamic research of the Old City of Dubrovnik. Thus, more precise and reliable horizontal and vertical movements of the Adriatic microplate can be obtained [Pavasović 2014].

6. Conclusion

This paper, shows the results of the monitoring project of the vertical displacements of the Old City of Dubrovnik during the eighties and the nineties of the past century. Since Dubrovnik is located on a seismically active area where the Adriatic micro plate underlines the Dinarides, and considering the fact that after the last epoch of measurements the larger Dubrovnik area was hit by more than 3000 earthquakes, it is very important to continue with this monitoring project.

Having analysed the results of measurements of vertical displacements of the Old City of Dubrovnik, the conclusion reached is that, although undoubtedly some displacements occurred in amount from -4.8 mm to 4.3 mm, they were largely unified, i.e. they were with the same character in terms of positive or negative displacements and with similar amounts. Some displacements that occurred and should be paid more attention to, took place at two pilot objects. At present, these displacements do not represent a problem for the objects in Dubrovnik, but monitoring displacements should be carried out, especially if we...
are familiar with the fact of the ground on which the city is located. Hence, it is necessary to react if some kind of bigger displacements occur in the future.

The results of the analyses show the need for further research, i.e. geodetic observations of the historical centre and much wider area around the city of Dubrovnik. Further observations must be expanded with precise horizontal, GNSS and gravimetric measurements, and in that way not to depend on levelling lines only. The research should be done in interdisciplinary way.

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References


Kapović, Z. (1993). Determination and Analysis of Bridge Displacements and Deformations with Special Emphasis to Temperature Influence, PhD. Thesis, Faculty of Geodesy, University of Zagreb, Zagreb.


Izvješće o prethodnim i plan budućih geodinamičkih istraživanja u povijesnoj jezgri Staroga Grada Dubrovnika


Ključne riječi: Dubrovnik, geodinamička mjerenja, mjerenje pomaka, nivelmanska mreža, potresi.

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