Vertical Crustal Movement in Area of *Istra* and *Kvarner* at the Territory of Republic of Croatia

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ABSTRACT

In this work, vertical displacements and deformations of Earth's crust caused by tectonic plate's movements or local geodynamic processes with consequences of smaller or larger earthquakes in area of Istra and Kvarner at the territory of Republic of Croatia are presented. Although, divergence, convergence and transformation along Eurasian and African tectonic plate border are not present, significant vertical displacements caused by earthquakes with intensity of 5-8 degrees according to MSK-64 scale were notified. Consequences of earthquakes and geodynamic processes at micro locations are given with exact numeric values of vertical displacements obtained by least squares adjustment of precise levelling data with accuracy of ±1mm/km from two epochs, in year 1971 and 2000. The analysis of earthquakes frequency and it's correlation with vertical displacements in discrete points in area of interest are given as well.

KEYWORDS: tectonic plate, kinematic model, earthquake, correlation.

INTRODUCTION

The theory of tectonic plates is contemporary theory which in relative simple way explains almost every important occurrences and processes at Earth's surface (formation and evolution of continents and oceans, movements of Earth's crust, volcanic and seismic processes etc.).

Fundamental assumption, on which this theory is based, is that Earth's crust isn't continuous, homogenous, firm and solid envelope around Earth's body. It is a layer which is broken at specific number of structure parts of irregular shape and size called tectonic plates. Impact zones of tectonic plates are areas of distinct tectonic activity with respect to volcanic and seismic processes. Considering mutual interaction of tectonic plates, three impact zones are distinguished (Kious and Tilling 2001):

- divergence or dissention which occurs like a consequence of mutual dissention of tectonic plates, new crust is formed by volcanic activity,
- convergence occurs like a consequence of subduction of one tectonic plate under the other one and degradation of existing crust occurs by its indentation into Earth's body,
- transformation or sliding based on forces which lead to mutual motion of boundary plates.

The main cause of tectonic plate motion is convection. Convection is natural process of circular motion of rock masses in Earth's mantle and astenosphere which occurs like a consequence of a transport of high amounts of heat from Earth's hot interior towards cooler surface. In that process, tectonic plates have a passive role because all of the processes which occur at tectonic plates boundaries are consequence of astenosphere activity (area between 100 and 200 km beneath Earth's surface) (Shahabpour and Trurnit 2001).

Tectonic plate sliding and motion can be also caused by Earth's gravity, Earth's rotation and friction which is consequence of tide waves as a result of Sun and Moon influence (Whiple 2004).

TECTONIC PLATE MOTION

Displacements, that are movements of tectonic plates, can be defined by geometrical principles knowing the time component. Considering the time component, individual tectonic plates can be introduced like firm and solid bodies with no possibility of changing its shape so the spatial relationship between material points changes only between points on boundary plates. When determining tectonic plate's displacements and movements, the body of Earth can be approximate by ideal sphere.

Relative movement of tectonic plate is known when direction and size of plate's displacement in observed time are determined as well (Becker & Faccenna 2007). Usually, tectonic plate motion is described by rotation vectors where Earth is a ideal sphere with radius R. Tectonic plate rotates around instantaneous rotation axis by angle velocity ω. Figure 1 shows the position of imaginary tectonic plate on Earth' sphere, its current rotation axis and rotation vector Ω.

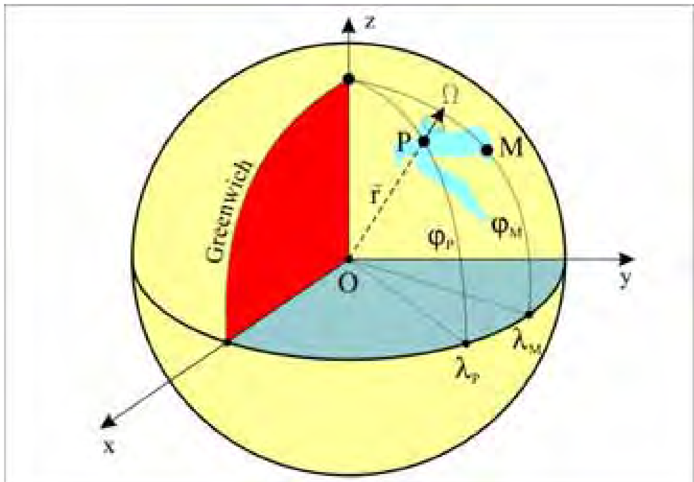

Figure 1: Imaginary tectonic plate rotation vector

Tectonic plate rotation axis goes through the center of the sphere and at surface has the position at point $P(\varphi_P, \lambda_P)$. Plate motion is observed in spatial rectangular coordinate system (*xy* plane is equatorial plane and *xz* plane is Greenwich meridian plane). Rotation vector components at spatial coordinate system are (Rožić 2001; Calais 2007):

$$\vec{\Omega} = \begin{bmatrix} \Omega_x \\ \Omega_y \\ \Omega_z \end{bmatrix} = \Omega \begin{bmatrix} cos\,\varphi_P \quad cos\,\lambda_P \\ cos\,\varphi_P \quad sin\,\lambda_P \\ sin\,\varphi_P \end{bmatrix} \tag{1}$$

where Ω represents angular rotation velocity given by:

$$\Omega = \sqrt{\Omega_x^2 + \Omega_y^2 + \Omega_z^2} \tag{2}$$

Position vector of point $M\ (\varphi, \lambda)$ or $M\ (X, Y, Z)$ is given by (Rožić 2001):

$$\vec{r} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = R \begin{bmatrix} \cos\varphi \quad cos\lambda \\ \cos\varphi \quad \sin\lambda \\ \sin\varphi \end{bmatrix} \tag{3}$$

Linear velocity vector $\vec{v}$ (vector product of rotation vector $\vec{\Omega}$ and position vector $\vec{r}$) is given by:

$$\vec{v} = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = R \begin{bmatrix} w_x \sin\varphi - w_z \cos\varphi \sin\lambda \\ w_z \cos\varphi \cos\lambda - w_x \sin\varphi \\ \cos\varphi(w_x \sin\lambda - w_y \cos\lambda) \end{bmatrix} \tag{4}$$

Combining (1) for Ω_x, Ω_y i Ω_z into (4), finally, linear velocity vector is given by:

$$\vec{v} = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = R \begin{bmatrix} \cos\varphi_P \sin\lambda_P \sin\varphi - \sin\varphi_P \cos\varphi \sin\lambda \\ \sin\varphi_P \cos\varphi \cos\lambda - \cos\varphi_P \cos\lambda_P \sin\varphi \\ \cos\varphi_P \cos\varphi \sin(\lambda - \lambda_P) \end{bmatrix} \quad (5)$$

Velocity vector $\vec{v}$ can be determined for position r_t of any observed point of tectonic plate, for any moment of time t due to initial time epoch t_0 and initial position vector of that point $\vec{r}$.

For global motion of tectonic plates, motion models are developed based on defining rotation motion vector due to pole position i.e. current position of rotation axis. Some of the most important tectonic plate motion models are: P071 (Jordan and Minster 1978), RM2 (Jordan and Minster 1978), APKIM (Drewes 1998), REVEL (Sella *et al.* 2001), PB2002 (Bird 2003), NUVEL (DeMets *et al.* 1990; Argus and Gordon, 1991; DeMets 1993; DeMets *et al.* 1994), ITRF2000 (Altamimi *et al.* 2002, 2003; Hofmann-Wellenhofand Moritz 2005b; Kreemer *et al.* 2006) and last one ITRF2005 (Altamimi 2006; Altamimi *et al.* 2007).

Kinematic and dynamic processes, in interior of tectonic plates, are modeled in a different way using geodetic positioning methods for periodical monitoring of exacts points at Earth's surface.

Kinematic Height Models

In the last chapter is shown that Earth's surface changes under the influences of many geodynamic processes and that measurements and measurements derived variables (coordinates, heights) are also functions of time.

In case of height displacements, when point heights $P_i(h_i)$ are determined several times, heights can be expressed like functions of time (Figure 2):

$$h_i = h(t) \quad (6)$$

Expanding (1) in Taylor series and keeping members of first order, expression (1) becomes:

$$h_i = h_0 + \left(\frac{dh}{dt}\right)\Delta t + \cdots \quad (7)$$

where $\Delta t = t_i - t_0$ and h_0 is height at t_0.

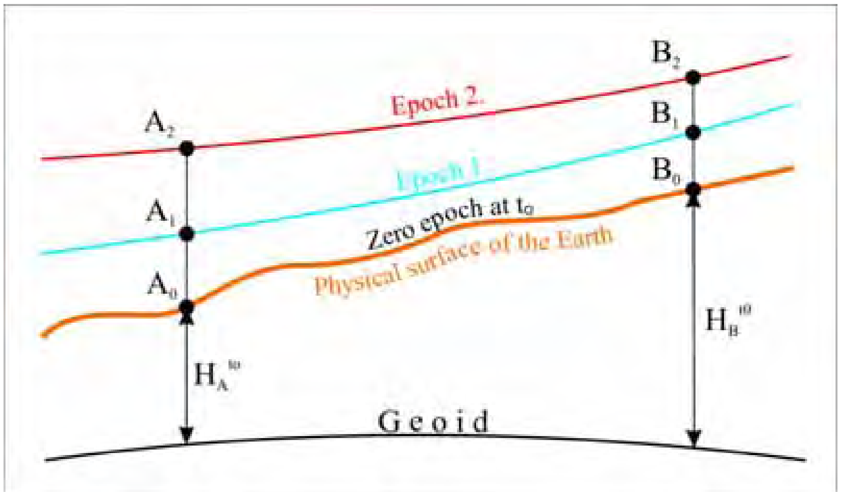

Figure 2: Heights of benchmarks A and B in dependency on time

Introducing substitution $a_i = \Delta t = t_i - t_0$ and $v_h = \left(\frac{dh}{dt}\right)_0$ into (7) linear equation follows:

$$h_i = h_0 + a_i v_h \tag{8}$$

Vertical velocity of benchmark motion is given by:

$$v_h = \frac{h_i - h_0}{t_i - t_0} \tag{9}$$

If for each benchmark, exist more than one observation, least square adjustment of indirect measurements can be applied. In that case, observation equations are given by:

$$\bar{h}_i = h_i + v_i = h_0 + a_i v_h \tag{10}$$

or in explicit form:

$$v_i = a_i v_h + (h_0 - h_i) \tag{11}$$

where a_i represent coefficients of design matrix *A* and expression in brackets, vector of reduced observations $(-l)$.

It's clear that coefficients of observation equations represent time epoch differences and reduced observations represent benchmarks height differences.

Motion velocity of each benchmark can be computed from:

$$v = \frac{a^t l}{a^t a} \tag{12}$$

Reference standard deviation and reference standard deviation of unknown are calculated according to (Feil 1997):

$$m_0 = \sqrt{\frac{v^t v}{n-u}} \quad m_v = m_0\sqrt{q_{xx}} \tag{13}$$

Expression (7) defines a simple motion kinematic model of point (benchmark) and represents linear motion. Adjusted value of point velocity can be easily used to predict the benchmark height for any time epoch.

EARTHQUAKES

An earthquake is the result of a sudden release of energy in Earth's crust that creates seismic waves. At Earth's surface is manifested by shaking or displacing the ground (URL-1). Parameters of an earthquake are: focus or hypocenter (initial rupture point in Earth's interior), epicenter (projection of hypocenter at Earth's surface), intensity (earthquake's effect at Earth's surface at observed area in epicenter) and magnitude (quantity of released energy by earthquake in hypocenter).

Intensity of an earthquake is measured using Mercalli-Cancani-Sieberg (MCS) or Medvedev-Sponheuer-Karnik (MSK-64) scale or European Macroseismic Scale (EMS). All scales have twelve divisions and there's no need for recalculation from one scale to another. The magnitude of an earthquake is measured using Richter scale (URL-2; URL-3).

Almost all of the earthquakes occur at two tight seismic belts at Earth's surface: Circum-Pacific belt (also known as Ring of Fire) with 80% quantity of released energy of and Mediterranean trans-Asiatic seismic belt (Figure 3) with 15% quantity of released energy. The rest of the world with 5% of released energy has no significant earthquake activity (URL-4).

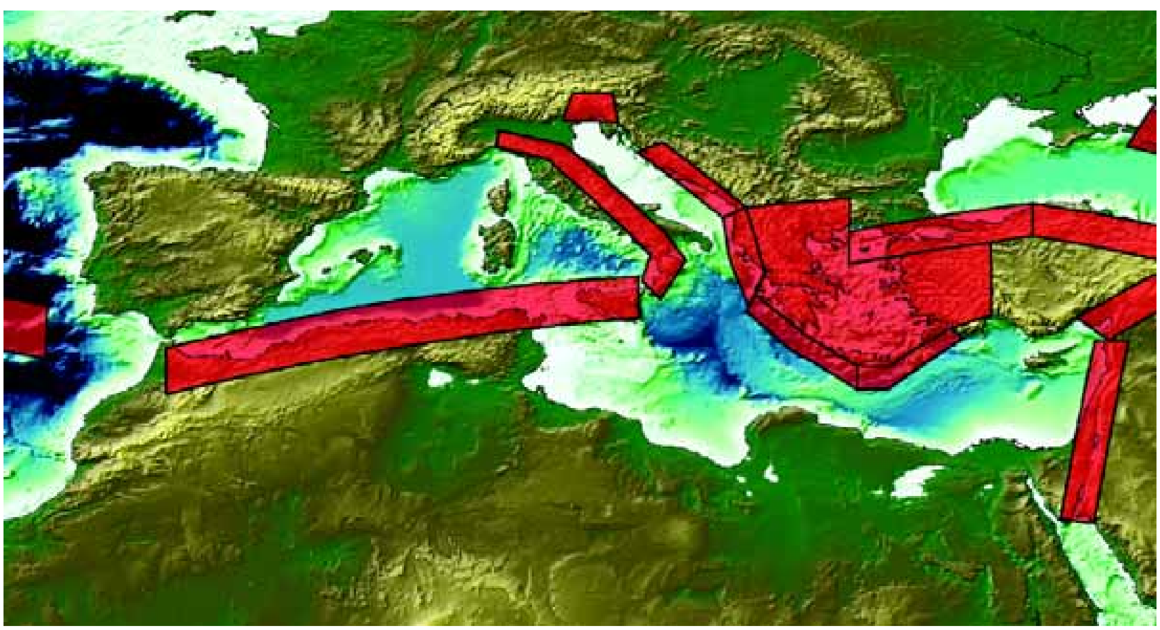

Figure 3: Mediterranean trans-Asiatic seismic belt (URL-5)

Earthquakes at the Territory of Republic of Croatia

Republic of Croatia, as a part of Mediterranean trans-Asiatic seismic is a significant seismically active territory, especially coastal area, north-western part and southern Dalmatia. Information about seismic activity in Croatia reaches year 361. In year 361 town Cissa (today's Caska) at island Pag was completely destroyed and sunk into sea. In year 1667 town Dubrovnik, situated in southern Dalmatia was completely destroyed as well. Both of mentioned earthquakes had intensity of X according to MCS scale. At the territory of Republic of Croatia, from year 361 to 1996, 21 earthquakes of intensity IX according to MCS scale had happened (URL-4). Figure 4 shows earthquakes epicenters and magnitude according to Richter scale, from B.C. to year 2008.

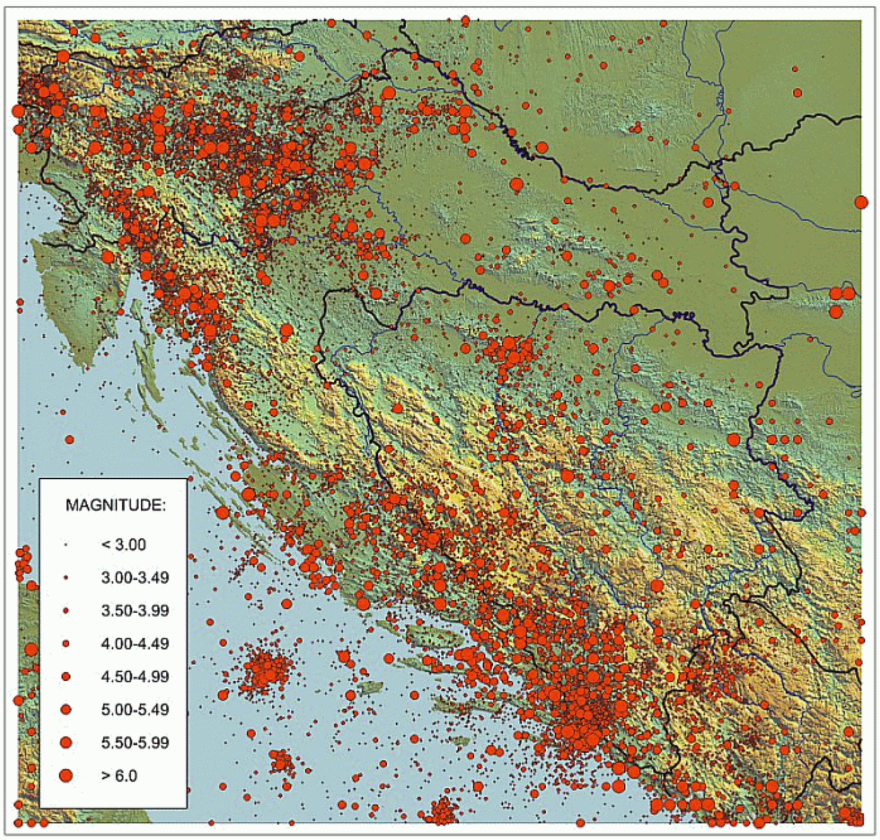

Figure 4: Earthquake epicenters and magnitude from B.C to 2008 at the territory of Republic of Croatia (URL-6)

APPLICATION OF KINEMATIC HEIGHT MODEL

It is well known that the Earth isn't invariable celestial body cause of exposure to many influences of different forces so the consequences are deflected in positions of permanent height marks (benchmarks) that is movements and displacements. Movements and displacements define of benchmarks define deformations of specific, smaller or larger part of Earth's crust. Deformations can be plastic or elastic. After elastic deformations, parts Earth's crust return in initial state but isn't a case when speaking of plastic deformations.

In this work contribution to usage of geometrical levellling (due to epoch 1971) data and new data (due to epoch 2000) for interpretation of elastic deformations of Earth's crust (in vertical sense) are given. It is impossible to, mathematically define a regularity in Earth's crust movement but it is possible to determine its existence and character.

Kinematic height model is applied to 214 identical benchmarks from leveling line no10 (NV010) which connects benchmark MCXVI (Bakar) with fundamental benchmark FR1209 (Brajkovići) and has length of 152 km (Figure 5). Kinematic height model is based on least square adjustment of indirect measurements. Most probable values of benchmark heights from epoch 1971 (II leveling network of high accuracy) and epoch 2000 (data are taken from Geoservis Pula company, Croatia) are considered as measured data.

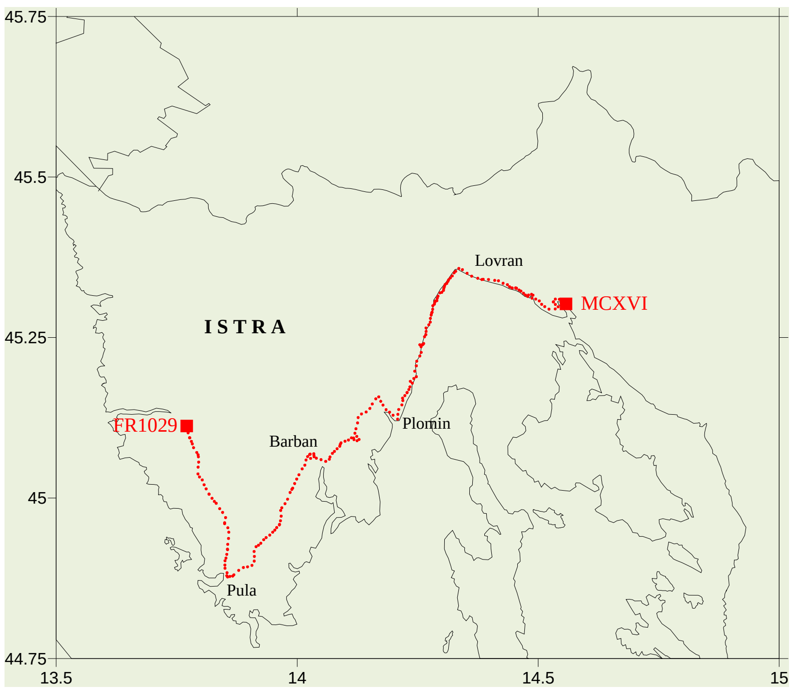

Figure 5: Leveling line no. 10 (NV010)

Epoch 1971 of measurements is taken as initial epoch for t_0 and velocity of vertical motion is set as unknown. Leveling measurements in epoch 2000 are performed by precise digital levels (Sokkia SDL30 and Zeiss DiNi12) with coded leveling rod. The purpose and goal of these measurements were detection of significant vertical displacements of benchmarks in levelling line no 10 (NV010). For these reasons, strict procedure of performing high accuracy leveling was not respected so leveling rod reading (back and front) are taken from middle. Each levelling side was measured in two directions and if measurements didn't match accuracy of precise levelling criteria (±2mm/1km), measurements were repeated. All measured height differences are corrected for normal orthometric correction (OC) and included in lest square adjustment with weights defined through length of leveling sides.

It is important to say that in period from year 1997 to 2003 during reconnaissance of benchmarks in leveling line NV010, all of 216 benchmarks stabilized and measured in II high accuracy leveling were found.

For epoch 2000, 943 height differences for 215 leveling sides were included with reference standard deviation of adjustment of 0.010 m.

As there are no tectonic plate boundaries along Adriatic cost at tested area (Kvarner and east coast of Istra; not excluding Adriatic micro tectonic plate boundaries), expected displacements in mentioned time period have small, but significant amounts, primarily caused by local seismic activity, illustrated in Figure 6.

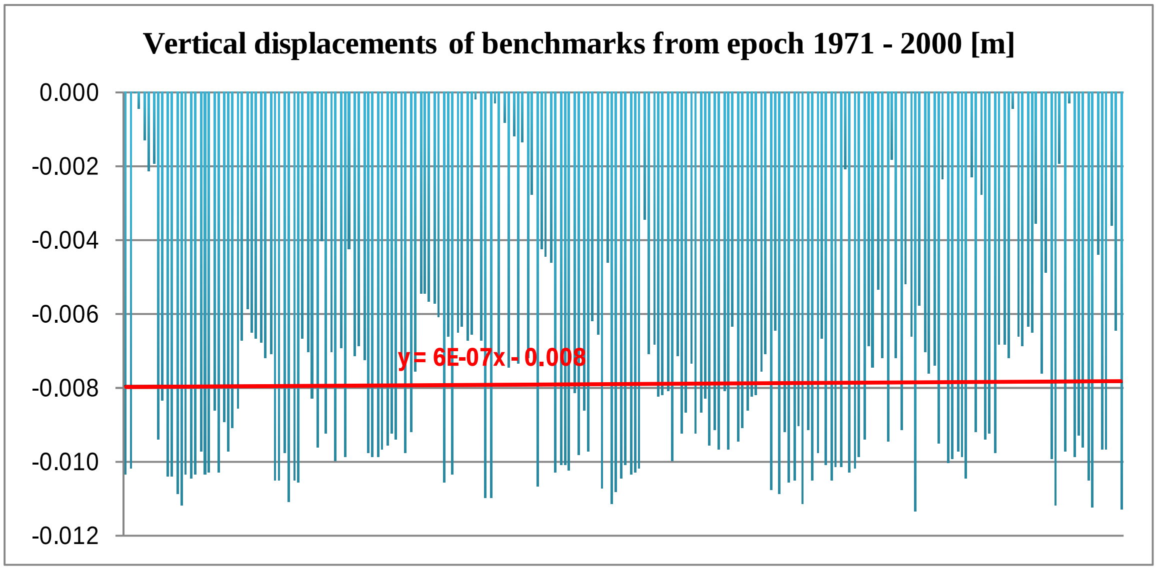

Figure 6: Vertical displacements of benchmarks from epoch 1971 - 2000
(all displacements have negative sign)

Differences of most probable height values between epochs 1971 and 2000 are in interval from 1 to 12 mm which point to trend of benchmarks height growth that is heaving of mentioned part of the Adriatic coast. Regardless of unevenness of leveling methods, this differences in period of 30 years point to presence of vertical displacements cause by tectonic activities.

Significant vertical displacements of Earth's crust are visible along Plomin-Barban road, in Lovran and Pula with interval from 2 to 5 mm (Figure 7).

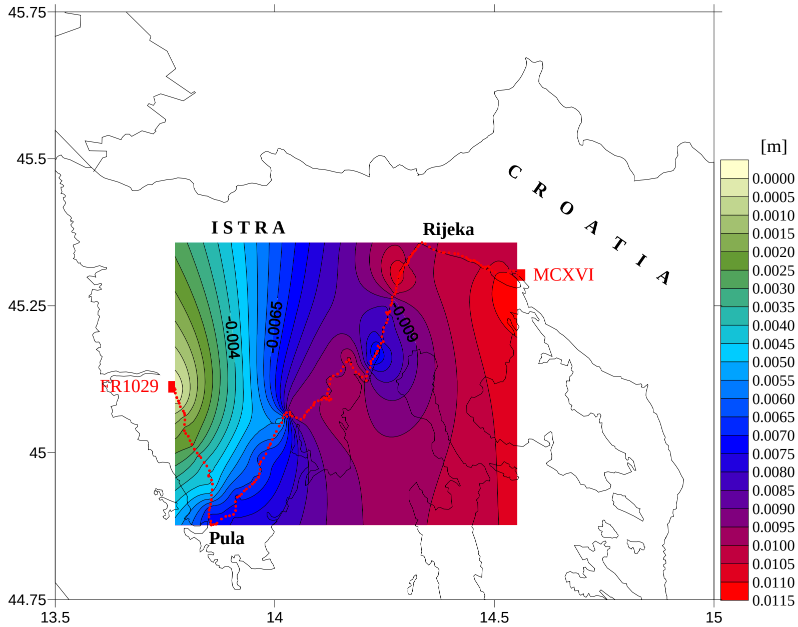

Figure 7: Vertical displacements of benchmarks from epoch 1971 – 2000 at eastern coast of Istra and Kvrner

Correlation between Seismic Activity and Vertical Benchmark Displacements

To correlate seismic activity and vertical displacements of benchmarks in leveling line NV010, seismic map according to MSK-64 scale, of former Republic of Yugoslavia was used. Seismic map was vectored and overlaid with benchmark positions and vertical displacements (Figure 8).

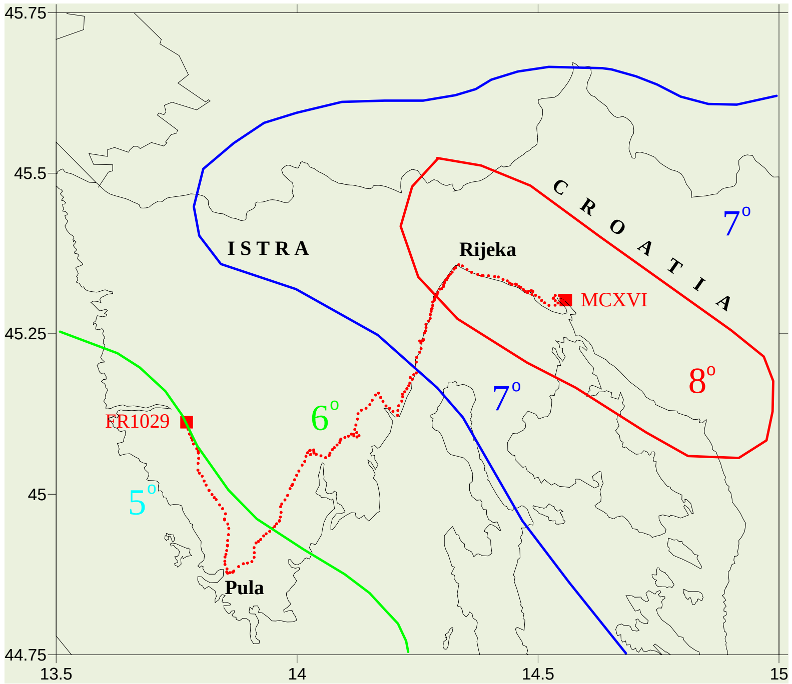

Figure 8: Vectored seismic map of former Republic of Yugoslavia at tested area (green line represents border area of earthquake intensity V, area between green and blue line of earthquake intensity VI, area between blue and red line of earthquake intensity VII and area inside red polygon of earthquake intensity VIII according to MSK-64 scale

Quantity of benchmarks in different seismic areas according to MSK-64 scale is given in Table 1.

Table 1: Benchmarks in seismic areas according to MSK-64 scale

Earthquake intensity according to MSK64 scale	Number of benchmarks
V	62
VI	73
VII	53
VIII	25

Correlation coefficient s calculated using Pearson's correlation method by exact expression (URL-7):

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{(n-1)s_x s_y} \quad (14)$$

Where x_i and y_i represent correlated data, $\bar{x}$ and $\bar{y}$ mean values of correlated data, s_x and s_y simple standard deviations of correlated data.

Pearson's correlation coefficient *r* = *-0.75* indicates to high correlation between benchmark vertical displacements and seismic activity at tested area.

CONCLUSION

The confirmation of Earth's physical surface variability due to geodynamic processes (seismic activity) in area of Istra and Kvarner is given through correlation between vertical displacements of benchmarks with earthquake intensity by Pearson's high correlation factor of $r = -0.75$. Mean value of vertical displacements of approximately 8 mm in period of 30 years indicates to a need for continuous leveling measurements with purpose of detecting vertical displacements, its connection to geodynamic processes and mutual interpretation of results. Once again, and in this article, the importance of cooperation between geoscience branches is pointed out.

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