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GROUND SURFACE MOVEMENTS IN THE AREA OF SALT EXPLOITATION IN TUZLA (BOSNIA AND HERZEGOVINA)

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Abstract: This paper focuses on surface movements determined by geodetic methods and occurred as consequence of brine extraction from Tuzla salt deposit (Bosnia and Herzegovina). Previous studies were mainly focalized on vertical movements, but important information about behavior of the deposit is also available from horizontal movement data. In the case of Tuzla salt deposit the geometry and spatial location of leached/empty spaces are unknown and the comparative analysis of vertical and horizontal movement could be really significant. The spatial identification of points with high values of vertical and horizontal movements depends on the geometry of empty spaces. Horizontal movements investigation has been carried out analyzing data collected by several geodetic measurements. The results obtained by the correlated spatial analysis of vertical and horizontal movements, can identify basic geometric characteristics of the leached/empty spaces. The discussed temporal intervals are two characteristic periods, reffered to the capacity of the deposit exploitation. Movement rates per year and correlation between horizontal and vertical movements are considered as indicator parameters defining the character of ground deformation. Spatial analysis of these coefficients values has identified high risk areas, and gives additional information in thegeological structures definition.

Key words*:* Tuzla (Bosnia and Herzegovina), geodetic measurements, horizontal and vertical movements, subsidence, correlation and spatial analysis, salt deposit exploitation.

1. Introduction

The salt exploitation in Tuzla has been performed since more than 500 years ago, causing ground subsidence and destruction of entire urban settlements. Subsidence was particularly intense in the period 1960-1983, during chemical industry development. The largest subsidence has been recorded in the central part of the town, that in the period 1947-1991 sank of more than 12 m. The most intense sinking rates have been recorded in the 1983 and amounted to 1,1 m/y.

Subsidence and surface deformation caused destruction of about 2700 residential units, approximately 67,000 m^2 of industrial areas, and about 130,000 m^2 of health, educational and sports facilities areas. About 15000 inhabitants had to move out of the vulnerable areas. In order to revalue the damaged area, two artificial lakes have been created after the 2005.

Investigation of salt deposit conditions and properties in the degraded areas, and its relation with the geological pattern of the area, represents a specific and tricky problem. Due to the complex geological and hydrogeological conditions and to the exploitation methods, subsurface behavior of geological series is uncertain after extraction termination.

Uncontrolled brine pumping exploitation at the mining districts of Hukalo and Trnovac stopped in April 2007, but nowadays surface movement and deformation are still present.

The topographical measurements from the 1956 to the 2003 were performed to determine the point's coordinates and horizontal movement. These

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measurements produced also very accurate elevation values. Each measurement series determined and analyzed the elevations, in order to collect several points with known vertical movements.

With the purpose of reducing risk in the Tuzla extraction areas, a systematic scheduled monitoring of deposit and ground surface has been carried out after the termination of exploitation. This monitoring has been performed with GPS static surveys in order to evaluate ground surface movement in the brine pumping area. GPS measurements provided greater accuracy and reliability in determining the horizontal/vertical movements.

Changes in the horizontal movement intensity in a certain direction are an indicator of buildings vulnerability, because they indicate the presence of horizontal deformation (stretching or compacting). Therefore, horizontal movements registered in the exploitation period have been analyzed, providing additional information for monitoring and risk assessment.

Horizontal movements analysis has been performed for certain time periods. In particular the analysis concerns data until the year 1991. Geodetic measurements data for the period 2005-2009 have not been fully processed yet, so this paper does not analyze horizontal movements for this period.

2. Review of existing geodetic measurements data

Systematic geodetic measurements began in the 1956 and, with some interruptions, last until today. Geodetic monitoring program of ground surface movement in Tuzla was elaborated by Fejtulah Smailbegovic. According to this program, in a wider area than the one of exploitation wells, a large number of geodetic points were created, approximately 1250 benchmarks. These points have been related to the trigonometric, polygon and levelling networks.

Surveyed stabilized points (a local coordinate system has been adopted), made an irregular network with different mutual distances. In the deformation areas, there is a relatively small number of points with great mutual distances.

Several points were destroyed during the time, but part of them has been renovated in the vicinity of previous positions, in order to continue the monitoring. During the geodetic campaigns, changes have occurred in the measurements area, survey methods and equipment, as well as the time interval between each measurements series. Several phases distinguished the geodetic measurements methodologies.

Between the 1956 and the 1991 surveyed points were located over the area affected by movements. Monitoring campaigns have been carried out every year so there are 35 measurements series.

Points height has been determined by means of precise levelling method. Height accuracy expressed by the mean square adjustment, amounted to 2 mm/km.

The point’s coordinates have been determined on the basis of traditional topographical measurements such as trigonometric and polygonal networks.By the mid 70's length in polygon network were measured using tape.For this period, the accuracy of determining the coordinate differences in polygon network, expressed by mean square error, was 3-4 cm.

After the mid-'70s, the length in the polygon network were measured by EOD. Since the 1985 final points coordinates have been determined by the method of least square adjustment.

Since the 1991 the volume of measurement has been reduced and just points located in the smaller part of the influence zone have been surveyed. By the 2003 measurements were performed in 4 series: 1993, 1999, 2002, 2003, organized by Tuzla Municipality.

In the final stage of classical dry exploitation as well as for the end of salt wells activities, in addition to the Municipal measurements, measurements were also carried out by the Salt Mine Company, which monitored the Tusanj sinking mining shaft,. During the sinking of Tusanj mining shaft, in the period April 2002 - June 2004, five series of measurements were carried out with a time gap from five to eight months. These measurements were restricted to the immediate area of the salt mine Tusanj.

During the stoppage of uncontrolled leaching exploitation in the area of Hukalo-Trnovac were also carried out geodetic measurements for movement evaluation of a small number of points. The points were located in the mining districts of Hukalo and Trnovac and in locations around the Tusanj mine shafts. These measurements were realized within the Salt Mine Company monitoring. Time interval between adjacent series is uneven and varies from

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three to eight months. The first measurement has been carried out in March 2006 and lasted until today, with time step of several months.

Considering the surveyed area, the measurement methods and the results processing, as well as characteristics of the exploitation phases, this work could not include all existing geodetic data. As a representative, data until 1991 have been considered, from the two characteristic periods of exploitation respectively.

A special segment of geodetic measurements are those arisen from the joint project between CIRSA (Centro Interdipartimentale di Ricerca per le Scienze Ambientali, University of Bologna), the Province of Ravenna (Italy) and the Municipality of Tuzla, which continued through the NATO DEMOS project (Development of a Monitoring System to Counter manage the risks of Subsidence deformation on the Population of Tuzla, Project no. 983305).

3. Ground movements in the period 1956-1991

Detailed information about the movement's extent and intensity in the zone of exploitation influence could be acquired from geodetic measurements data of the 1991. Although a huge database is available, there is just a small number of points with continuous movements monitoring in both vertical and horizontal planes. In particular for 45 points elevation for all years until 1991 has been determined, but there is not any point with continuous determination of x-y coordinates. Vertical movements for the period 1956-1991 have been determined for about 420 points, while the horizontal movements evaluation for the same period was possible for just 43 points.

The maximum measured subsidence from the 1956 to the 1991 amounts to 9,113 m (polygon point number 75), although it is nowadays bigger because in the zone of maximum subsidence there is not any point left. Besides this point, on another 7 points, measured subsidence exceeds 8 m.

Maximum horizontal movements were measured for the polygon point PG49 in the amount of 6,68 m and trigonometric point TT25 in the amount of 5,67 m. The position of points presenting maximum movement is shown in Figure 3. Based on known subsidence values at 420 points a digital model of subsidence is generated by Golden Software Surfer (method of interpolation "Natural Neighbor").

Figure 1 shows 3D subsidence model which illustrates the overall subsidence values.

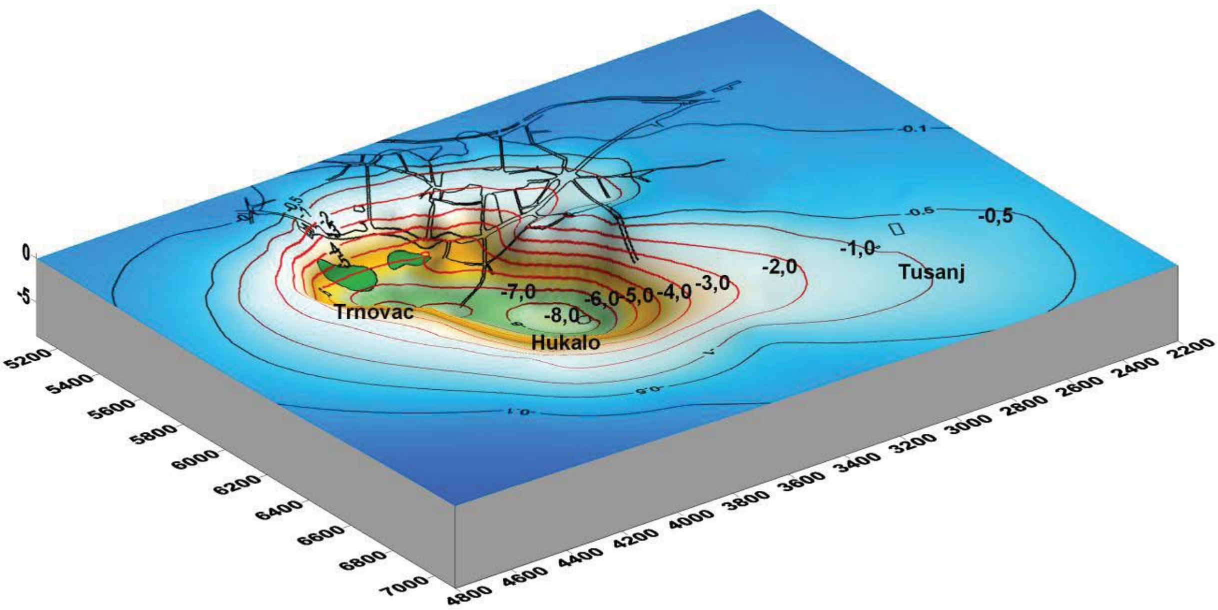

Fig. 1. Surface subsidence 3D model until the year 1991 (local coordinates)

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Figure 2 shows subsidence isolines (magenta color) and horizontal movement vectors. In order to focalize into the general direction of horizontal movements, figure 2 also shows horizontal movement of all points regardless to the time intervals. The overall movements have been determined as the sum of periodic movements between adjacent series of observations. In figure 2 the thicker polyline (cyan color) marks a zone of change in the horizontal movement direction. This line has been moved to the south-southwest of the maximum subsidence zone. In addition to movements this figure shows exploitation wells location. Figure 3 shows the movements by polylines (red color), which generally oscillate around total movement vector. Slightly larger deviation from the general direction is observed for points located in the Lake 1 area, where, during the entire observation period, maximum subsidence was registered.

Spatial distribution of movement in relation to the geological and structural-tectonic features of the area has been also analyzed. As shown in figure 2, thicker (cyan color) polyline marks zone of horizontal movement direction changes. Structural-tectonic features of the wider area have enabled formation of Tuzla salt deposits in the southwest limb of anticline Dolovi. The deposit stretching NW-SE, dipping to the northwest and southwest (generally towards the west). Horizontal movements of greater intensity generally have direction NE-SW, i.e. in the dip direction of the deposit, as shown in figure 2.

The line or zone of changes in horizontal movement direction, in case of inclined solid mineral deposits exploitation, is parallel to the deposit boundary and shifted from the points with maximum subsidence in the rise layer direction. South and southwest of the cyan color line, the layers of anticline Jala-Požarnica are interrupted, tensioned in direction of layers' strike and have a steeper dip, so these isolines are at the shorter distance. Northeast of this line, southwest limb of anticline Dolovi has a gentle dip of layers, and the isolines are on wider distances. Spatial distribution and direction of horizontal movements fully match the structural tectonic characteristics of the deposits.

Figure 4 shows detailed geological map with both subsidence isolines and horizontal movement vectors. On the geological map of the city of Tuzla and the wider environment (Fig. 4) this direction is presented by axis of shallow syncline Gradina-Trnovac-Tušanj. It could be concluded that this

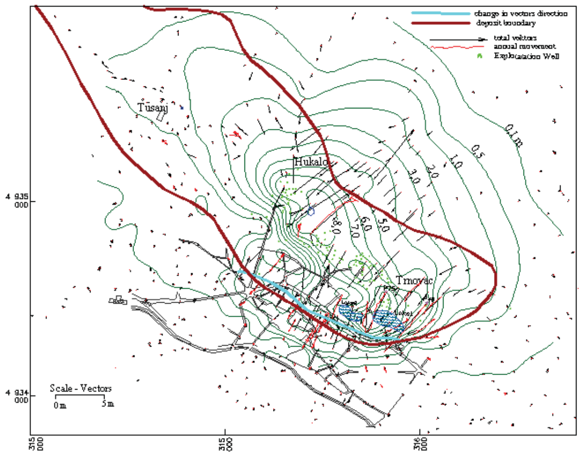

Fig. 2. Spatial distribution of horizontal and vertical movements until the year 1991 (UTM coordinates)

folding structure is of special significance for ground subsidence and determines trends and directions of horizontal movements.

It is noticeable that there is some specific spatial distribution of movements around a central line direction of north-south, which on the geological map presents the Hukalo fault.

4. Movements in the characteristic periods

For the analysis of known horizontal movements distinguished are two representative periods. The first period is characterized by increased brine production and increased average subsidence speed (1977-1984) and the second by reduced brine production and reduced average subsidence speed (1984-1991). An additional reason for the analysis

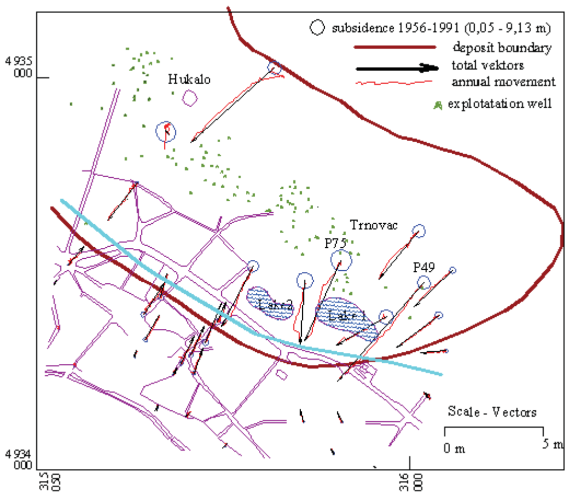

Fig. 3. The points with known movements for period 1956-1991. The circle size is proportional to the total subsidence of points. The line (cyan color) approximately indicates the line of vector direction change (UTM coordinates).

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of movements in these two periods is relatively large set of points with known movements in both periods.

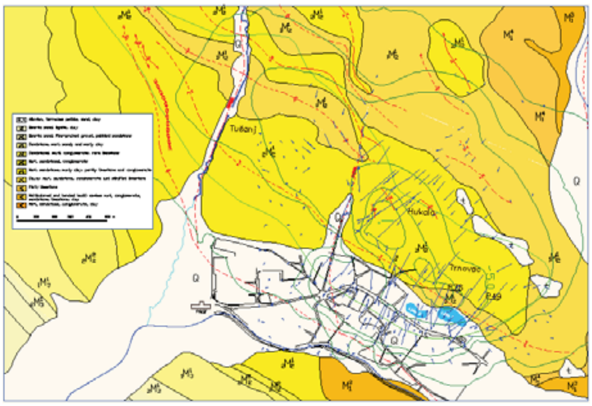

Fig. 4. Geological map of Tuzla and wider area.

There are total 83 points for which could be determined the horizontal and vertical movements in both periods. Maximum subsidence the first period (4,197 m) was registered in the point 75. For the second period maximum subsidence (1,584 m) was registered in the point 50. For these periods spatial movement distribution and both horizontal and vertical movement relation were analyzed.

In figure 5 are shown the subsidence isolines for the both periods; the first (blue) and for the second period (red line). There are relatively few points with known subsidence for both periods and the figures show approximate spatial distribution of subsidence. It can be seen that, for both periods, two "subsidence center" were formed. On the mining district Hukalo isolines are of the same shape, and mining district Trnovac subsidence center, in the second period, has been shifted to the south (Lake 1).

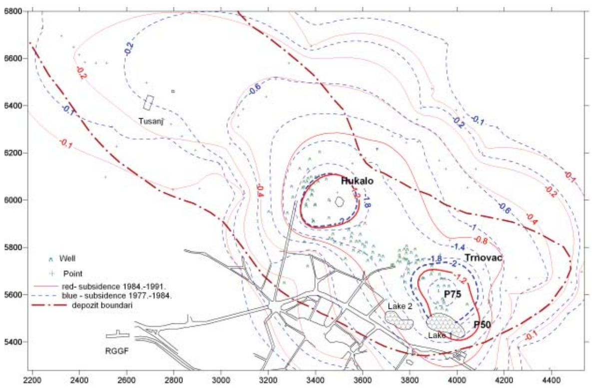

Fig. 5. Subsidence isolines for the period 1977-1984 (blue) and 1984-1991 (red), generated on the basis of the common points (local coordinates).

If isolines are generated on the basis of all the points with known subsidence for the period considered, we get slightly different subsidence contour for both periods.

There are 157 points with known subsidence for the first period, and 170 points for the second period. The maximum subsidence is 2,319 m at the point P603. The point P603 does not have known subsidence the first period, and it is likely that for the first period maximum subsidence rate is not registered. This is pointed out also by the mutual position of points with maximum subsidence rates and horizontal movements.

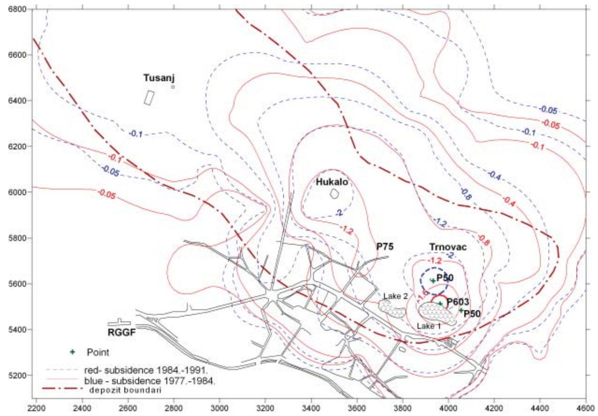

Fig. 6. Subsidence isolines for the period 1977-1984 (blue) and 1984-1991 (red), generated on the basis of all points with known subsidence (local coordinates).

For the first period, maximum subsidence rate and horizontal movements were registered in the point 75, which is not in accordance with spatial arrangement of points with extreme movement values for the case of Tuzla salt deposit. Distance between the points in certain areas is quite large and there is a discontinuity in determining of individual points movement.

Figure 7 shows horizontal movements greater than 0,5 m for the same periods. Maximum movement of the first period is in the point 75 (2,10 m). For the second period, the maximum movement of 0,87 m is at the point 510. It is obvious that almost all points have smaller movements in the second period. At the mining district Hukalo is generally the same direction of movement, while on the mining district Trnovac there is a significant change in direction. This is probably the consequence of intensive exploitation at the mining district Trnovac in the period 1977-1984, resulted as an empty space of larger dimensions in this area.

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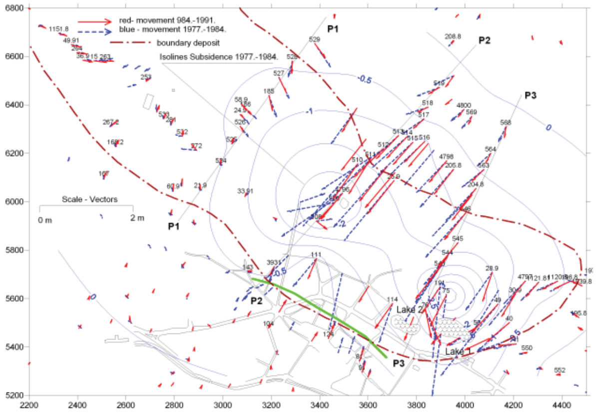

Fig. 7. Horizontal movements of the points (local coordinates).

It could be also noticed that the direction of moving lines change (green line), which is located south of the maximum subsidence did not significantly changed its position in relation to the whole period (fig. 7), because of a small number of points are not fully defined.

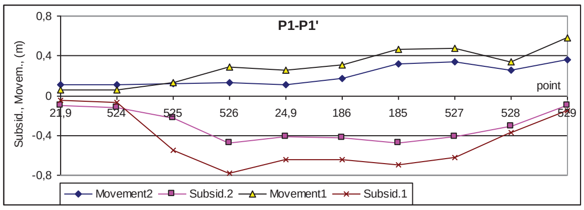

Fig. 8. Movement and subsidence for period 1977-1984 (1), and period 1984-1991 (2) for points 21,9 (T21), 524, 525, 526 ..... 529 (line P1-P1' – fig. 7).

Correlation between vertical and horizontal movement in certain directions could be followed in diagrams of horizontal and vertical movement of several points, according to the periods under consideration. The points are grouped in three directions (Fig. 7), the approximate direction of horizontal movements.

The group directions are marked as P1-P1', P2-P2', P3-P3'. The figures 8, 9 and 10 show intensities of horizontal and vertical movements of the points

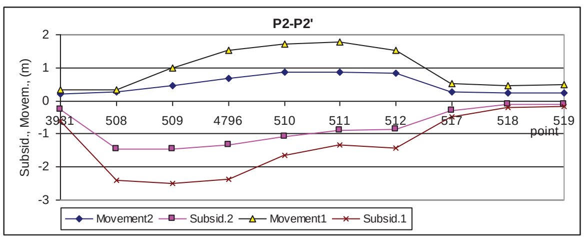

Fig. 9. Movement and subsidence for period 1977-1984 (1) and period 1984-1991 (2) for points 3931, 500, 509, 4796 ..... 519 (line P2-P2' – fig. 7).

mentioned directions. It could be seen that the points, with greater intensity movements, have the same trend of change both the horizontal and vertical movement. Deviations occur at points of lower intensity movement that are on greater distance of exploitation wells, i.e. deposit boundary. Only the points that are in the zone with the same direction of horizontal movement are analyzed, as the points in the southern part of the zone are not observed in both considered periods.

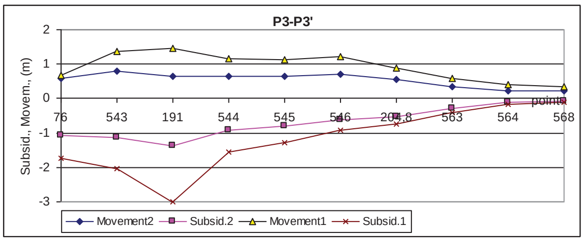

Fig. 10. Movement and subsidence for period 1977-1984 (1) and period 1984-1991 (2) for points 76 (PG76), 543, 191, 544 ..... 568 (line P3-P3' – fig. 7).

The graphs show that the decrease of subsidence rate is followed by decrease in horizontal movements, but the reduction intensity changes depending on the spatial position of points. There is regularity in the change/decrease of movements intensity for the points in P1-P1' and P2-P2' direction. On P3-P3' direction, for the points that are in the zone of intensive movements in the mining district Trnovac, there are larger differences in the intensity change of movements by time periods. Such relations between horizontal and vertical movements are a consequence of the exploitation method and complex geological and structural-tectonic conditions of the area.

5. The analysis of horizontal and vertical movement by periods

The aim of the analysis is to determine the relationship between the intensity of the points vertical and horizontal movements for the periods discussed. For a total of 83 points are, in both periods, known both horizontal and vertical movement greater of 0.05 m. In the classical measurement uncertainty of coordinates ranging was 3 to 4 cm, and due to the impact of errors excluded from analysis are the points with movement less than 0,05 m. For this set of points counted is relations of movements from the two periods, which are identified as coefficients:

K1 = horizontal movement for the period 1977-1984/subsidence for the period 1977-1984

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K2 = horizontal movement for the period 1984-1991/subsidence for the period 1984-1991
Ks = subsidence for the period 1984-1991/subsidence for the period 1977-1984
Km = horizontal movement for the period 1984-1991/horizontal movement for the period 1977-1984
By analyse of these coefficients could be determined whether there is a trend of decrease/increase in movement (horizontal and vertical - Km, Ks), as well as whether it changed the intensity ratio of the horizontal and vertical movements (K1, K2) for the periods discussed. The statistical parameters are assigned for the coefficients in a given set of points (Tab. 1):

the above conclusions on the constant relation of horizontal and vertical movement at times. Together with these coefficients are presented both horizontal and vertical movements of the points. It is evident that there are a relatively small number of points with large differences in the values of K1 and K2. For most points the values are about 1. Larger values of coefficients appear in points with small movements or subsidence. This means that, in the peripheral parts of the zone of influence, the horizontal movements by intensity are greater than the vertical.

Values of the parameters: mean, median, quartile, for the coefficient Ks and Km (columns 4 and 5) also are slightly different, which means that the in-

Table 1 – Coefficient values

Parametar	K1 = Mov1/Sub1	K2 = Mov2/Sub2	Ks = Subs2/Subs1	Km = Mov2/Mov1
1	2	3	4	5
Number of values	83	83	83	83
Minimum	0.135	0.187	0.317	0.339
Maximum	3.853	3.797	1.942	2.514
Range	3.717	3.610	1.625	2.175
Mean	1.089	1.062	0.836	0.899
Median	0.932	0.963	0.680	0.660
First quartile	0.669	0.697	0.615	0.558
Third quartile	1.201	1.184	0.978	0.940
Standard error	0.079	0.068	0.039	0.059
Standard deviation	0.724	0.621	0.361	0.544
Coefficient of variation	0.665	0.585	0.431	0.605

Column 2 and 3 show that the statistic parameters differences have very small values for the coefficients K1 and K2, respectively, the same ratio of horizontal and vertical movements in both periods. This means that, regardless intensity change, retains the same intensity ratio of the horizontal and vertical movements. Coefficient of variation has a significant value, because the value of K1 and K2 range in a wide interval. Figure 10 shows that it is evident that there are points with low values of horizontal movement and great value of subsiding rate and vice versa, so that the relation of these values vary in wide diapason. From the average value and median for the K1 and K2 it is noticeable that there are a considerable number of points with greater intensity of the horizontal then vertical movements. The points are situated in the zone of intense subsidence, which means that there are major changes in the intensity of horizontal movement, and thus the large horizontal deformation.
In figure 11 it is shown comparative values of K1 and K2 coefficients for the points and illustrates

tensity ratio of the horizontal and vertical movement by periods has not changed. Average values

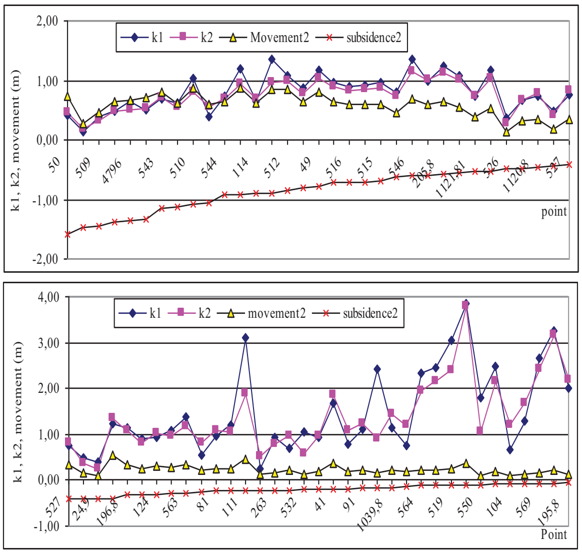

Fig. 11. Coefficient values K1 and K2 for observed points, together with their movements, 4796 ..... 519 (line P2-P2' – fig. 7).

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and median are less than 1, which means that, in the second period, intensity of both horizontal and vertical movement generally decreased (fig. 12).

By spatial analysis of these coefficients zones of varying degree of decrease (change) intensity of movement could be defined. In figure 13 it is shown the spatial distribution of different values of the coefficient Ks. Figure 14 shows the spatial distribution of different values of the coefficient Km.

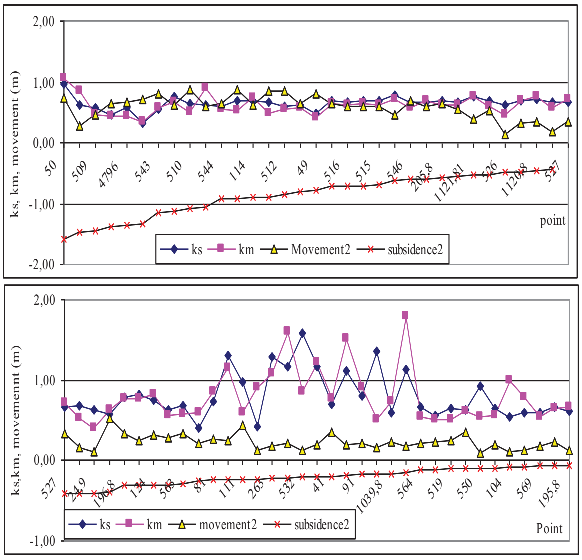

Fig. 12. Coefficient values Km and Ks for observed points, together with their movements.

It is noticeable that, in the second period, both vertical and horizontal movements increased at the area of salt mine Tušanj, where classic mine exploitation was carried outs.. In addition, most of the points have coefficient values (both Ks and Km) less than 0,75. These are the points located in the zone where, in the period of intensive exploitation, were registered maximum movement/subsidence.

6. Conclusion and recommendations

For the most observed points, the relationship between horizontal and vertical movements slightly changed over time. Also, for the most points is the same ratio of intensity decrease/increase both horizontal and vertical movement. Considerable discrepancy was determined only in the zone of intensive brine exploitation at the mining district Trnovac.

The general conclusion is that for most of the points is intensity both horizontal and vertical movement decrease in the second period, at reduced volume of brine exploitation. The excep-

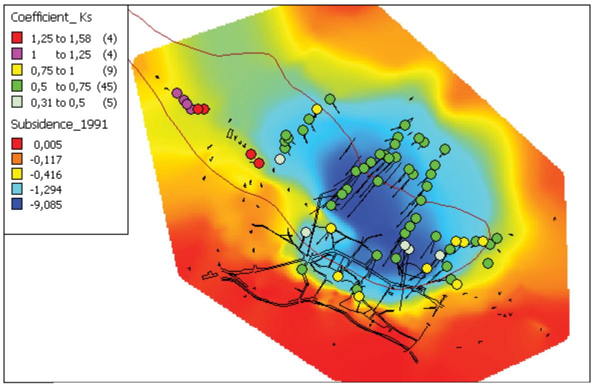

Fig. 13. Spatial distribution of the points with different coefficient values Ks.

tions are points which are located in the area above the pit Tušanj. This indicates possible appearance of processes in massif that does not correspond with the deposit exploitation capacity. During this period there was not increased production of rock salt in the pit Tušanj. Future monitoring should also include the area of the pit Tušanj and pay special attention to monitoring of the massif behavior in this area.

The results of analysis showed that there is a strong interdependence of horizontal and vertical movement. These results provide additional information about the process of massif moving and the surface terrain in the zone of Tuzla salt deposit leaching influence. Future analysis of data monitoring at the risk assessment should include also a spatial analysis of horizontal movements.Proposed GPS measurements, in the future monitoring, will enable monitoring of horizontal movement with estimate of higher accuracy.

This paper has shown that geological and structural-tectonic structure of the salt deposit and wider environment has a significant impact on the spatial distribution both horizontal and vertical movements.

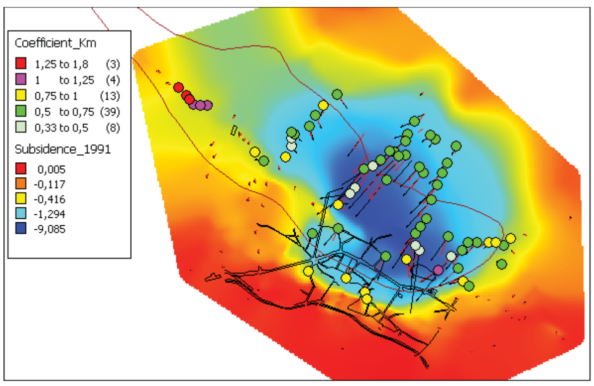

Fig. 14. Spatial distribution of the points with different coefficient values Km.

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There is no doubt that the massif consolidation, caused by long-term exploitation, will continue in the future, which will be reflected by further horizontal and vertical ground movement.

In future studies of massif consolidation and movement on the surface, great attention should be paid to morpho-genetic analysis of the area, surveying the range and type of engineering geological conditions, their individual components and their interrelationship: including details of geological structure, especially shear zones, engineering geological properties of rock Massif, defining the intensive degradation zones, determination of the discontinuities in the overlying strata, mass loss in the deposit etc.

Certainly it should also contain and determine all surface manifestation of deformation induced by subsidence (slide, creep, damages on buildings and infrastructures, etc.), that are as following processes present in the city.

Permanent survey and risk monitoring is necessary in order to develop an urbanization that follows and respects the minimum ecological norms and the acceptable risk level. The data gathered would be used to rank all geohazards for further urban planning and activities within this area.

Acknowledgments

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