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CURVATURE AND RADIUS OF CURVATURE VARIATION IN THE CHARACTERIZATION OF AN AREA AFFECTED BY ANTHROPOGENIC MINING ACTIVITIES

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Abstract: *This study analyzed the curvature and radius of curvature in order to characterize an area affected by anthropogenic coal mining activities. The study took place in an area located in Jiu Valley, Romania. 16 control points were considered (CP1 – CP16), for which the quota values were determined (X,Y,Z system) at the moment of analysis (T1) in relation to a reference moment (T0). The differences in quota were calculated (XYZ) between moments T1 and T0. Curvature (Curv) and radius of curvature (RadC) values were calculated. Strong correlation was recorded between Curv and Z(T1-T0), r = -0.847***, between Curv and Dg (diving the ground), r = 0.847***, and between Curv and Ls (land slope), r = 0.891*** (*** p < 0.001). Weak correlation was recorded between RadC and Y(T1-T0), r = 0.586***. Spline type mathematical models described the variation of curvature, and Radius of curvature in relation to the control points (XYZ values), under conditions for curvature, respectively for radius of curvature. According to the multivariate analysis, the PCA diagram resulted, in which PC1 explained 50.737% of variance, and PC2 explained 49.263% of variance. The cluster analysis generated the dendrogram in which the control point CP16 was positioned separately, and the other control points were grouped in a cluster based on similarity (Coph.corr = 0.998). The ranking of the control points, in relation to the values recorded for the Curv and RadC parameters, was done in the form of Scaling dendrogram.*

Keywords: *Coal mining area; curvature; ecological systems; mathematical models; radius of curvature*

1. Introduction

The settlement of coal mines generated complex effects on the environment, with direct influences on the relief, soil and vegetation [1]. The authors recorded how the subsidence affected the degree of soil coverage with vegetation, the water regime on the soil surface, the vegetation and overall led to a reduction in the quality of environmental factors.

Mining represented a sector of the economy that provided jobs, and provided and continues to provide energy resources and raw materials for society [2], [3]. The authors also communicated how mining, in addition to positive effects, also presented negative effects on the environment.

Underground coal mines have generated cumulative spatio-temporal effects on the environment [2]. Effects of mining have been recorded on the aquifer layer on an extensive scale, as a result of the direct and indirect effects of underground mining operations [4].

The ecology of the land surface has recorded variations in time and space as a result of the impact of coal mine subsidence [5]. The authors of the study evaluated the physical, chemical and hydrophysical properties of the soil based on a number of approximately 3000 soil samples, taken from 60 sampling points.

The underground exploitation of coal generated extensive changes of the geomechanical nature of the rock mass [6]. The authors considered that studying the processes that lead to deformations of the earth's crust,

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associated with mining activities, can ensure the sustainability of mining operations in relation to the environment. The authors studied the parameters of the horizontal deformations of the earth's surface and the comparative analysis of the values of the parameters with objectives of interest (e.g. the positioning of some pipelines). Underground mining has the effect of moving and deforming the land following the extraction of the useful mineral substance [7].

These areas of land affected by underground mining will have to be monitored over time in order to protect the surface and existing constructions on it in order to make forecasts over time of this phenomenon and the sustainable development of these areas, which are generally mono-industrial areas and disadvantaged areas [8].

Determining real forecasts in time can make investments in these areas constantly and with maximum efficiency. Land subsidence under the influence of underground exploitations is monitored over time by determining some parameters that define the phenomenon as well as through the characteristic curves that will be realized following topographical observations carried out in alignments and tracking stations that were placed on the surface covering the underground exploitations [9].

The present study evaluated the curvature and radius of curvature of the land, associated with the phenomenon that affected the surface of the land, as an effect of coal mining in the Jiu Valley area, Romania.

2. Materials and method

In relation to the purpose of the study, changes to the land surface were evaluated in the Jiu Valley area, Romania, figure 1.

The monitoring station for the phenomenon of land subsidence under the influence of underground mining in the case of the Petroşani Mining Basin, covered the perimeter of Livezeni mine, an area in that the phenomenon manifested itself significantly, with implications in the protection of the constructions carried out on the surface and on the constructions planned to be carried out.

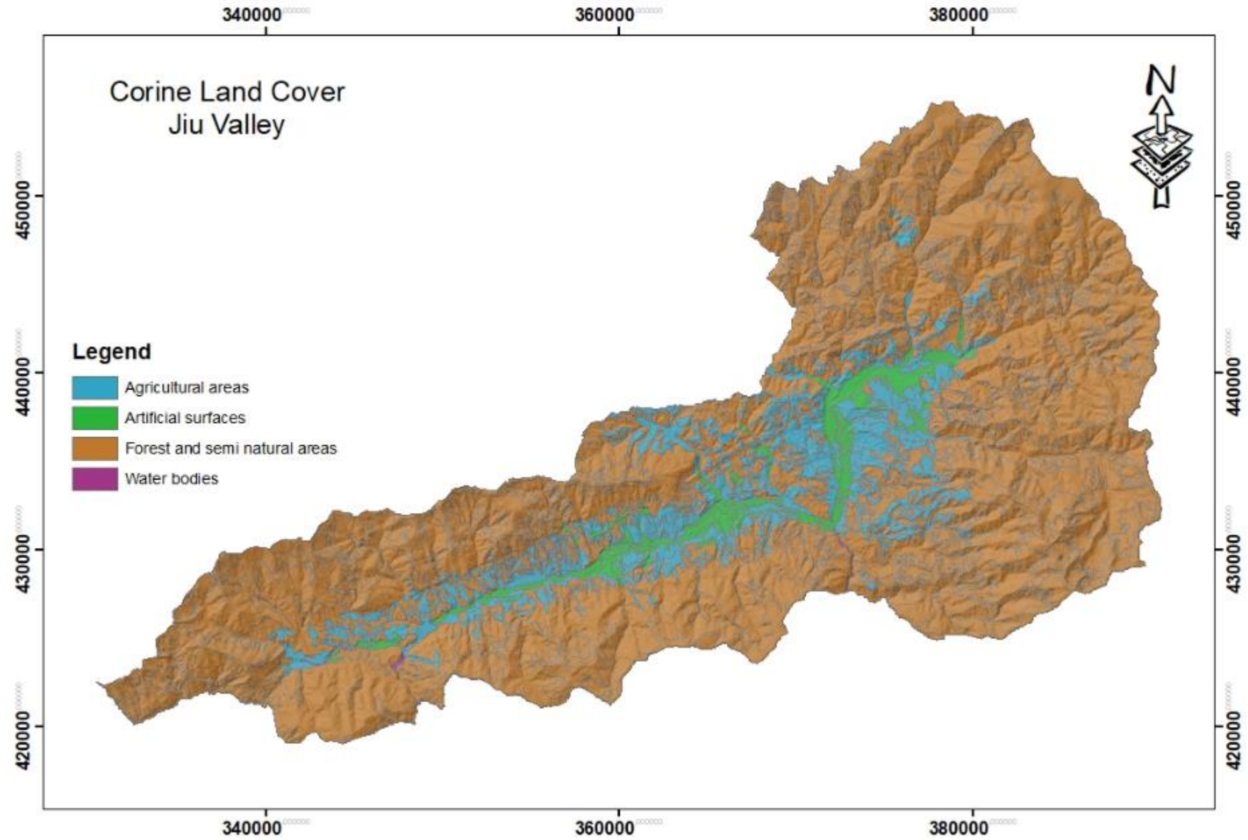

Fig.1. The study area, Jiu Valley, Romania

The area considered for monitoring and study was in Maleia zone in the study area. According to the specialized literature [10], [11], [12], which provided a series of parameters to describe the phenomenon of changing the earth's crust, Radius were selected for the present study of radius of curvature (RadC), equation (1), and Curvature (Curv), equation (2).

The radius of curvature is determined by the succession of deformations in time, and the curvature of the surface is the inverse of the radius of curvature, and was defined as the inverse of the ratio between the angle of convergence of the tangents in the neighboring points and the distance between them.

$$R_i = \frac{d_{i-1,i+1}}{\frac{S_{i+1}-S_i}{d_{i,i+1}} - \frac{S_i - S_{i-1}}{d_{i-1,i}}} \quad \text{or:} \quad R_i = \frac{d_{i-1,i+1}}{\Delta I_i} \tag{1}$$

$$C_i = \frac{1}{R_i}[km^{-1}] \quad \text{or:} \quad C_i = \frac{\frac{S_{i+1}-S_i}{d_{i,i+1}} - \frac{S_i - S_{i-1}}{d_{i-1,i}}}{d_{i-1,}d_{i+1}} \tag{2}$$

16 control points (CP1 to CP16) were used with XYZ coordinate values at T1 (actual time) and T0 (reference time) presented by [11].

Appropriate software was used to analyze the results and generate some graphic representations [13], [14].

3. Results and discussion

Curvature (Curv) and Radius of curvature (RadC) were calculated in relation to the values of the coordinates of the control points at the moment T1 (current time) and the moment T0 (reference time). The results are the values presented in table 1.

Table 1. Calculated values for the coordinates of the control points, curvature and radius of curvature, area located in Jiu Valley, Romania

Control point	Different XYZ coordinate values (moments T1 and T0)			Curvature	Radius of Curvature
	$X_{(T1-T0)}$	$Y_{(T1-T0)}$	$Z_{(T1-T0)}$	(Curv)	(RadC)
CP1	0.0031000	-0.0037000	-0.0128000	0	0
CP2	0.0035000	-0.0055000	-0.0181000	0	0
CP3	-0.0027000	-0.0140000	-0.0766000	-0.0006013	-1663.0531385
CP4	0.0007000	-0.0326000	-0.1280000	0.0136276	73.3807045
CP5	0.0026000	-0.0156000	0.9214000	-0.0835935	-11.9626513
CP6	0.0053000	-0.0067000	-0.0365000	0.0530850	18.8377198
FP7	0.0000000	0.0000000	-0.0001000	-0.0087576	-114.1865069
CP8	0.0135000	0.0103000	-0.0737000	0.0037720	265.1104388
CP9	0.0090000	-0.0068000	-0.0659000	-0.0022557	-443.3189514
CP10	-0.0004000	-0.0008000	0.0005000	-0.0000732	-13659.1407419
CP11	0.0056000	-0.0001000	-0.0346000	0.0024905	401.5240584
CP12	0.0065000	-0.0160000	-0.1007000	-0.0009545	-1047.6682898
CP13	-0.0234000	-0.0056000	-0.0288000	-0.0002389	-4185.2018811
CP14	0.0030000	0.0005000	0.0192000	0.0001234	8105.5649623
CP15	-0.0016000	-0.0118000	-0.0298000	0.0002789	3585.5318707
CP16	-0.0051000	0.0214000	-0.0590000	0.0000088	113481.7811205

The correlation analysis was done to evaluate the interdependence between the values of the coordinates (XYZ), curvature (Curv), radius of curvature (RadC) and other parameters that described the land sinking phenomenon communicated in previous studies [11], [15]. The result was the correlation matrix in map format, figure 2.

Curvature (Curv) showed a strong correlation with $Z_{(T1-T0)}$, r = -0.847***, with the Dg parameter, r = 0.847, and with the Ls parameter, r = 0.891***. Radius of curvature (RadC) showed weak correlation with $Y_{(T1-T0)}$, r = 0.586*.

Very strong correlation was recorded between Dg and $Z_{(T1-T0)}$, r = -1***, and between Td and Dd, r = 1***. Moderate correlation was recorded between Ls and $Z_{(T1-T0)}$, r = -0.7**, and respectively between Ls and Dg, r = 0.7**.

The variation of the values of the curvature (Curv) and radius of curvature (RadC) parameters was analyzed in relation to the control points.

The curvature (Curv) variation in relation to the $X_{(T1-T0)}$ values at the 16 control points (CP1 to CP16) was described by a Spline model. The statistical values resulting from the analysis are presented in table 2, and the graphic distribution is presented in figure 3. The errors related to the Spline model were described by equation (3).

$$\bar{\varepsilon} = \left(\sum_{i=1}^{n} \varepsilon_i\right) / n = \left(\sum_{i=1}^{n} \left|\frac{ys_i - y_i}{y_i}\right|\right) / n \tag{3}$$

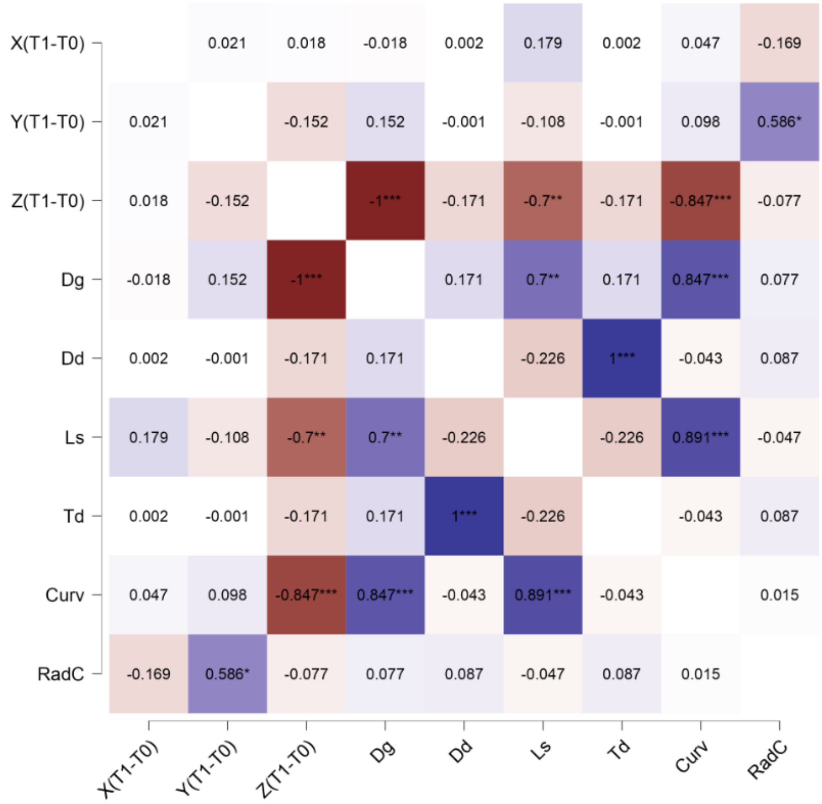

Fig. 2. The matrix of correlations between XYZ coordinates and parameters that described the phenomenon of land subsidence

The variation of Radius of curvature (RadC) in relation to $Y_{(T1-T0)}$ associated with the 16 control points (CP1 to CP16) was described by a Spline model.

The statistical values resulting from the analysis are presented in table 3, and the graphic distribution is presented in figure 4.

Table 2. Statistical values that described the variation of Curvature (Curv) in the study area, located in Jiu Valley, Romania

Trials data		**Curvature (Curv)**			
No	x_i	y_i	y_{si}	e_i	$I_{i/1}$
PC1	0.00310	0.00000	0.00116	0.00000	1.00000
PC2	0.00350	0.00000	0.00253	0.00000	2.17933
PC3	-2.70E-03	-0.00060	-0.00062	0.02636	-0.53235
PC4	0.00070	0.01363	0.01224	-0.10178	10.55896
FP5	2.60E-03	-0.08359	-0.07936	-0.05065	-68.45510
FP6	5.30E-03	0.05309	0.04957	-0.06625	42.75684
FP7	0.00E+00	-0.00876	-0.00702	-0.19799	-6.05857
FP8	0.01350	0.00377	0.00377	-0.00069	3.25144
PC9	9.00E-03	-0.00226	-0.00222	-0.01379	-1.91892
PC10	-4.00E-04	-0.00007	-0.00099	12.51216	-0.85318
PC11	0.00560	0.00249	0.00622	1.49661	5.36341
PC12	6.50E-03	-0.00095	-0.00159	0.66873	-1.37393
PC13	-2.34E-02	-0.00024	-0.00024	0.00000	-0.20607
PC14	3.00E-03	0.00012	-0.00690	-56.90924	-5.95118
PC15	-1.60E-03	0.00028	0.00037	0.31312	0.31591
PC16	-5.10E-03	0.00001	0.00001	0.06105	0.00805

$\bar{\varepsilon} = -2.64140$

Table 3. Statistical values that described the variation of Radius of curvature (RadC) in the study area, located in Jiu Valley, Romania

Trials data		**Radius of curvature (RadC)**			
No	**x_i**	**y_i**	**y_{si}**	**e_i**	**$I_{i/1}$**
PC1	-0.00370	0.00000	-3150.70000	0.00000	1.00000
PC2	-0.00550	0.00000	-1463.00000	0.00000	0.46434
PC3	-1.40E-02	-1663.10000	-242.94000	-0.85392	0.07711
PC4	-0.03260	73.38100	71.59600	-0.02433	-0.02272
FP5	-1.56E-02	-11.96300	-800.77000	65.93722	0.25416
FP6	-6.70E-03	18.83800	-346.51000	-19.39420	0.10998
FP7	0.00E+00	-114.19000	-356.31000	2.12033	0.11309
FP8	0.01030	265.11000	901.70000	2.40123	-0.28619
PC9	-6.80E-03	-443.32000	-239.38000	-0.46003	0.07598
PC10	-8.00E-04	-13659.00000	-4849.00000	-0.64500	1.53902
PC11	-0.00010	401.52000	-965.16000	-3.40377	0.30633
PC12	-1.60E-02	-1047.70000	-859.36000	-0.17977	0.27275
PC13	-5.60E-03	-4185.20000	-1431.40000	-0.65799	0.45431
PC14	5.00E-04	8105.60000	2666.40000	-0.67104	-0.84629
PC15	-1.18E-02	3585.50000	2566.30000	-0.28426	-0.81452
PC16	2.14E-02	113480.00000	113310.00000	-0.00150	-35.96344

$\bar{\varepsilon} = 2.74269$

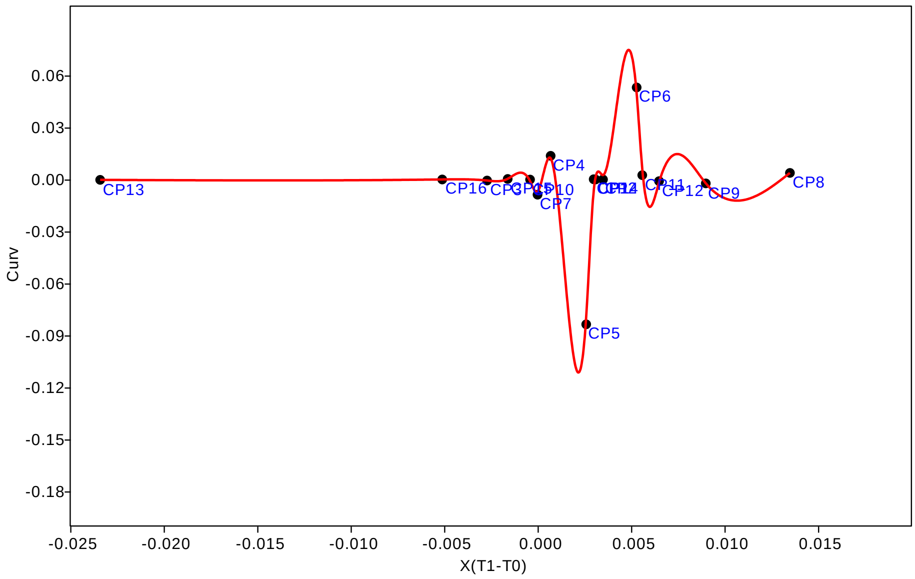

Fig. 3. Graphical distribution of curvature (Curv) for the study area, located in Jiu Valley, Romania

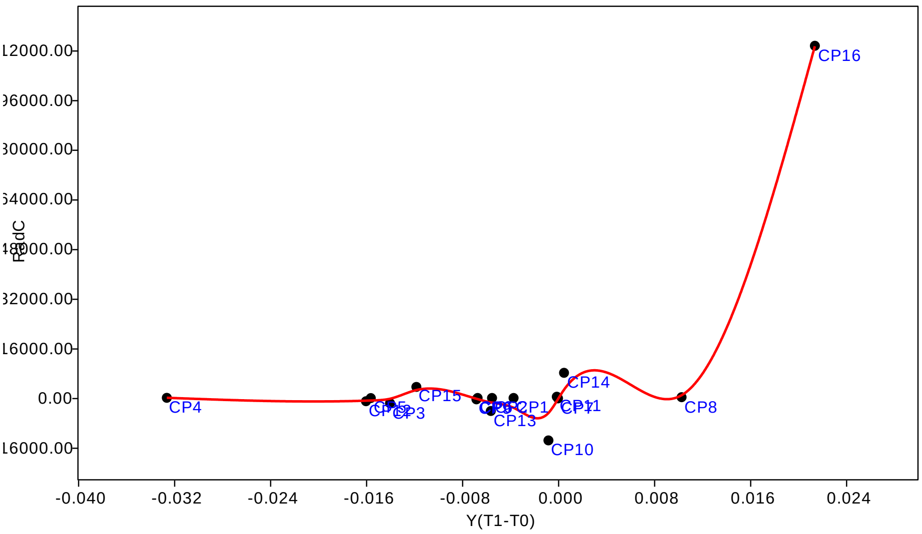

Fig. 4. Graphical distribution of the radius of curvature (RadC) for the study area, located in Jiu Valley, Romania

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The multivariate analysis was applied to generate the PCA diagram, to find out the distribution of control points in relation to the two parameters (Curv, RadC), as well as to find out how the main components explained the presence of variance, figure 5.

From the analysis of the distribution of the control points, it was observed the positioning of two points outside the safety zone, 95% confidence (CP5, and CP16). Control point CP5 presented the maximum deviation in the description of curvature (figure 3), and CP 16 presented the maximum deviation in the description of RadC (figure 4).

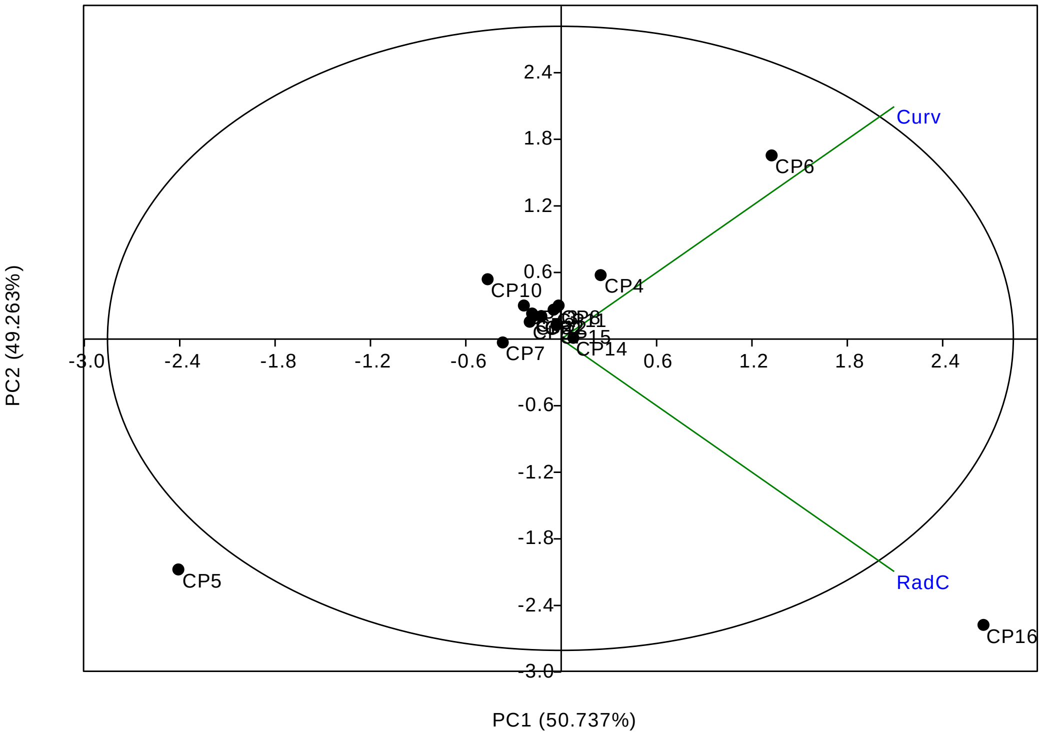

Fig. 5. PCA diagram, for the description of the obtained results

Cluster analysis was used to generate the control point association dendrogram (CP1 to CP16). The result was the dendrogram from figure 6, under statistical safety conditions (Coph.corr. = 0.998). The separate positioning of the control point CP16 was found and the grouping of the other control points within a cluster.

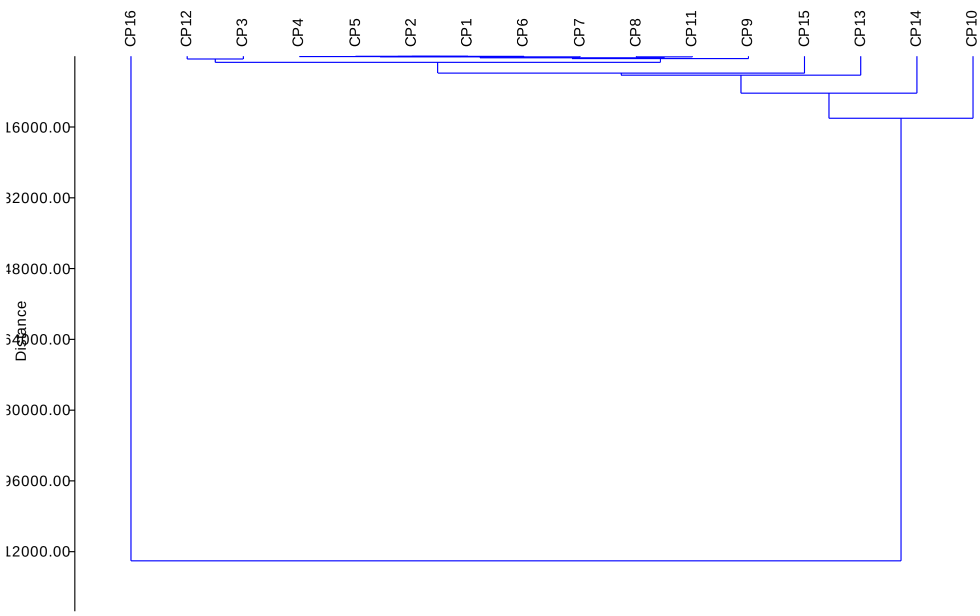

Fig. 6. Dendrogram of association of control points,
in relation to the values generated for Curv and RadC parameters

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The ranking of the control points, in relation to the values recorded for the Curv and RadC parameters, was done. Figure 7 resulted, in which the 16 control points are hierarchically positioned on the y axis (Event). It was established that the control point CP16 is positioned in the middle of the series of control points. The control point CP16 presented an independent position also within the Cluster analysis dendrogram (figure 6).

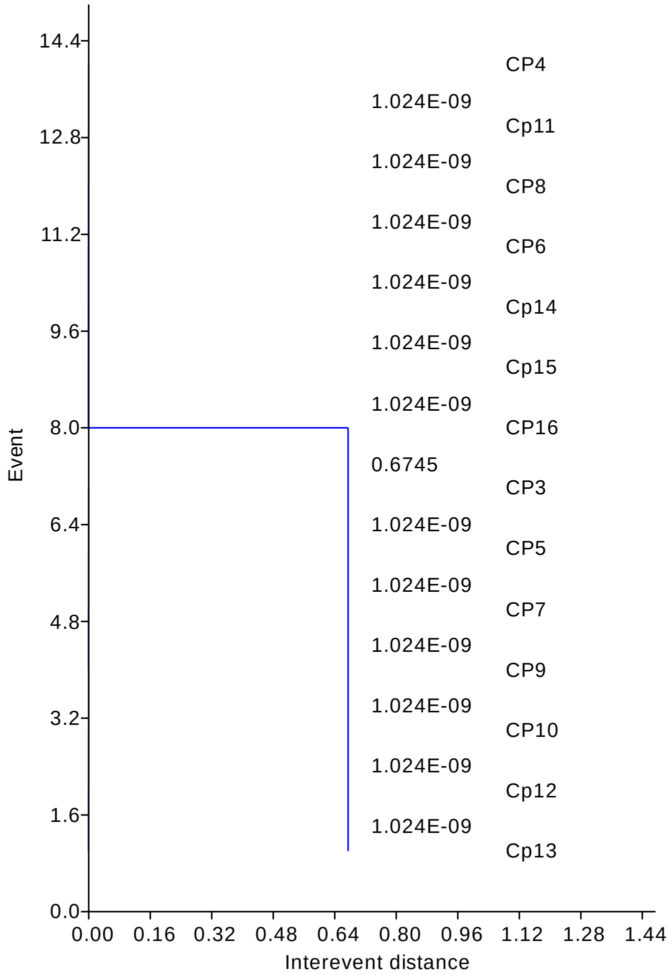

Fig. 7. Scaling dendrogram

The alteration of ecosystems, through the settlement of mines, subsidence zones with variability in time and space, and a series of associated processes regarding the soil and vegetation, requires a differentiated ecosystem management for the recovery of the affected lands [7], [1]. Marian and Onica (2021a) [8] considered it important to permanently monitor these areas, and to make forecasts in real time.

Determining the parameters that define the phenomenon of subsidence and describing the characteristic curves was considered important to characterize the affected areas and for preventive purposes in relation to predictable events [9].

In relation to plant nutrition were considered appropriate [3]. Such practices presuppose the consolidation of the land, and depending on the functionality of the soil, various ameliorative and fertilizing products were considered appropriate for the soil, the cultivation of plants with a good adaptation, such as local populations [16], [17], [3].

Different models have been found useful in describing areas affected by subsidence and predicting associated phenomena [4], [5].

Changes in soil structure, associated with mine settlement processes, represent an important factor in soil productivity in the affected areas [5], [18], [19], [20]. The authors considered important the prompt monitoring and interventions, in good time, of the affected areas (cracks with dimensions up to 6 m), and the selection of appropriate vegetation on the surface of the land, represent useful methods for controlling the affected surfaces.

The present study contributes to the evaluation of the areas affected by mining operations over time, by describing the curvature (Curv) and the radius of curvature (RadC) and finding some Spline models that described these parameters.

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4. Conclusions

Curvature parameters (Curv) and radius of curvature (RadC), associated with subsidence phenomena generated by mining operations in the Valea Jiului area, Romania, were described based on 16 control points and the associated XYZ values.

Curvature (Curv) showed a strong correlation with $Z_{(T1-T0)}$, r = -0.847***, with the Dg parameter, r = 0.847, and with the Ls parameter, r = 0.891***. Radius of curvature (RadC) showed weak correlation with $Y_{(T1-T0)}$, r = 0.586*.

Spline models were found that described with high fidelity the variation of curvature (Curv) in relation to the values $X_{(T1-T0)}$ at the 16 control points (CP1 to CP16) , and a radius of curvature (RadC) in relationship with $Y_{(T1-T0)}$ associated with the 16 control points (CP1 to CP16).

Multivariate analysis facilitated the generation of distribution diagrams and association of control points in relation to analyzed parameters (Curv, RadC). The points with independent positioning in relation to the analyzed parameters were identified. The hierarchy of the control points was obtained, in the form of Scaling dendrogram.

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