EVALUATION OF EROSION ON THE SITE OF THE SALIGNY RADIOACTIVE WASTE REPOSITORY

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Abstract

The completion of the Cernavoda nuclear power plant generated the need to build a low and medium radioactive waste repository. Choosing a location for the repository was not random, potential locations being proposed after a multi criteria analysis. The most important criteria were geological, hydrogeological and economic. Because Dobrogea area met a large proportion of these conditions, the scope of the investigation was narrowed down to that territory. 37 potential locations were analyzed (GEOTEC, 1993) and submitted to a minimal set of specific investigations. Following these studies, it was proposed that the location of the repository should be the Saligny site, situated in the proximity of reactor 1 at the nuclear power plant in Cernavoda.

The next stage consisted of a highly detailed investigation of the site, through engineering works specific of such investments. One of the works aimed at estimating site erosion, a calculation necessary because of the significant period of use of the repository (300 years).

Erosion is the process of chemical and physical degradation of soil and rocks, during which unconsolidated particles are detached and transported by rainfall water and wind. Erosion prediction and measurement methods and models have evolved in time and many are currently based on *in situ* experiments.

For the Saligny site, erosion was estimated using the RUSLE method (Renard *et al*., 1987), but also on the basis of laboratory measurements using the PINHOLE method (Walker & Jermy, 1997).

Keywords: RUSLE, erosion, pinhole, dispersivity.

1. Estimating soil loss through the RUSLE method

Based on the USLE method „Universal Soil Loss Equation" (Wischmeier and Smith, 1965), the RUSLE method "Revised Universal Soil Loss Equation" (Renard *et al*., 1987), estimates soil erosion based on the following formula:

$$A = (R)(K)(LS)(C)(P),$$

where:
A = potential average annual soil loss on the long term (*tons/acre/year*);
R = rainfall/run-off erosivity in a given location factor;
K = soil erodibility factor;
LS = hillslope length and steepness factor;
C = cover management (crop/vegetation) factor;
P = support practice factor.

The rainfall and run-off factors in a given location (R)

The R factor is the average annual rainfall erosion (potential soil to be washed during rainfall and storms). This is a parameter which can be calculated according to the total kinetic energy of the storm, the storm's maximum intensity within a period of 30 minutes (in/hr) and the number of storms each year. Measurements must cover a minimum of 22 years. The calculation formula proposed in 1959 by Wischmeier is:

$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)(I_{30})_k\right]$$

where:
R = the erosive power of the rain (MJ/ha/year);
I_{30} = the maximum 30-minutes rainfall intensity;
j = the counter for each year used to produce the average;
k = the counter for the number of storms in a year;
m = the number of storms in each year;
n = the number of years used to obtain the average R.
E = the total storm kinetic energy in hundreds of ft/tons per acre (MJ/ha), calculated with the following formula (Renard, *et al.* 1987):

$$E = 1099[1 - 0{,}72^{(-1{,}271)}];$$

where:
I = the average rain intensity (mm/h).
Due to the fact that such measurements are not done in Romania, obtaining data for the area of Saligny was not possible. The R factor value has been estimated in accordance with the table drafted by Stone (2005). In this table, the R factor value varies between 90 and 130, depending on the region, rainfall intensity and duration. By analogy with regions similar in terms of climate, for Cernavoda, a region with relatively little rainfall, the R factor was estimated at 90.

The Soil Erodibility Factor (K)

The K factor is a measure of likelihood of soil particles to detach and be transported under the impact of rainfall and surface drainage.

Soils rich in fine-grain material, such as clays, are more resistant to erosion, due to their high cohesion. Thus, for such soils, the K factor ranges between 0.05 and 0.15. Sandy soils also register low values of the K factor (0.05-0.2) because of the high rate of water infiltration. This leads to reduced

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run-off on the slopes, and, therefore, to a reduced level of transport of detached particles.

Silts and clayey soils register moderate values of the K factor, between 0.25 and 0.45, due to moderate susceptibility to the detachment of particles and transport along the slope.

Silts are the most susceptible to erosion, with the highest value for K, exceeding 0.45 and up to 0.65. Particles this size are easily detached and carried down along the slope.

In order to determine the K factor of the soil, 55 undisturbed samples were collected from different areas of the future slopes of the repository.

Laboratory tests have been carried out on these samples, such as: particle grain analysis (silt and clay fractions and sand percentage according to the American standard), organic matter content (in percentage) and the analysis of permeability (cm/s).

Laboratory test results have led to the following conclusions:

- In point of grain size distribution, the samples are loess (clayey silt), according to the Romanian standard, which gives the ground loess characteristics;
- The organic matter content of samples varies between 2.11 and 5.13%;
- The permeability of the analysed samples varies between 0.000203 and 0.00665 cm/s.

According to the grain size distribution, the Saligny site is dominated by the presence of a silty surface layer (loess) with clay content within the range of 18 to 27%.

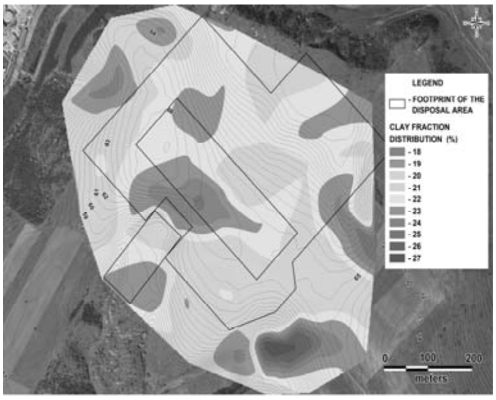

Fig. 1 *Clay fraction distribution on site*

The clay fraction distribution on site (fig.1) cannot be correlated with the ground morphology or the agricultural practices carried out until now. It is noteworthy, however, that the highest rates are generally registered in the valleys and on the plateau. After analyzing the dominant wind directions over the course of a year, to the North and West in the spring, summer and autumn, respectively the West and North in the winter, it appears that these areas are the most exposed to wind erosion. Therefore, the detachment and transport of the silt fraction of these slopes have led to a higher percentage of clay fractions in these areas.

Another parameter used to establish the K factor is organic matter (Figure 2). Its presence in the soil significantly reduces erosion due to the compounds it helps to form. The organic matter soil compounds lead to an increasing cohesion of particles. As a result of this phenomenon, the particles are much harder to detach under the impact of rain drops during the storm. Organic matter also plays a vital role in the development of biological activity, this latter fact enabling a better soil infiltration of rainwater, and thereby reducing runoff on the slope.

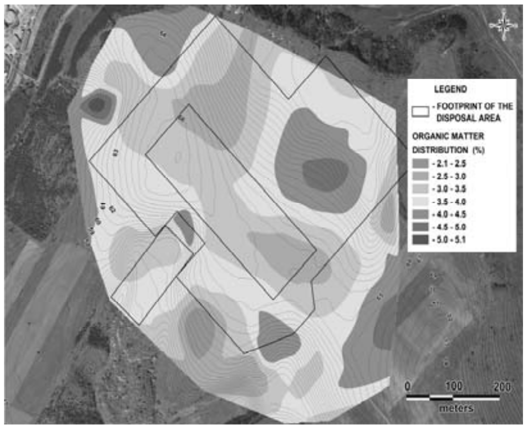

Fig. 2 *Organic matter distribution on site*

As it was to be expected, the peak values of organic matter are concentrated, in general, around the areas with thick vegetation, but also around two areas where the remnants of agricultural crops were buried in the ground during excavation.

Another parameter that is taken into account for the calculation of the K-factor is the ground permeability. The influence of this parameter on soil loss is understandable. The greater the permeability, the lower the risk of slope runoff, and therefore, of particles being transported away. Distribution of permeability on site is shown in fig.3. High permeability values are registered on arable land or land stripped of vegetation, where the percentage of the clay fraction is also low.

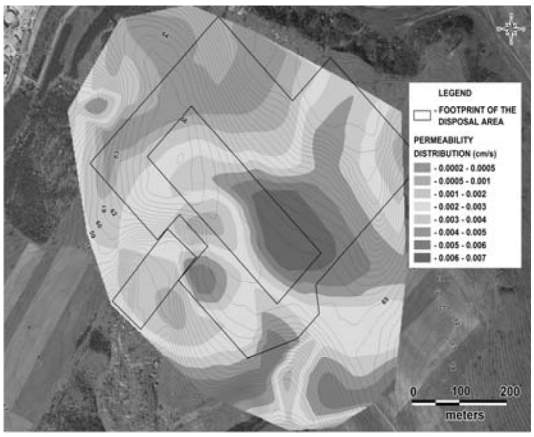

Fig. 3 *Permeability distribution on site*

The diagram developed by USDA (The United States Department of Agriculture) was (fig. 4) was also used to assess the K factor.

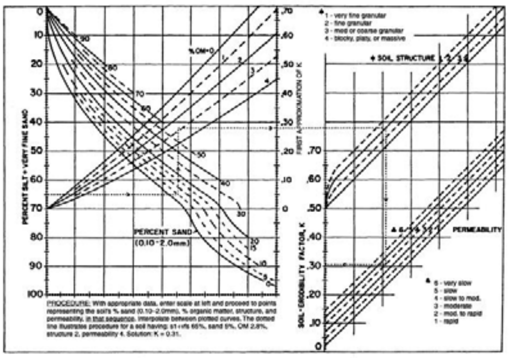

Fig. 4 *USDA nomograph used to calculate soil erodibility (K factor)*

The nomograph helps derive the K factor values, according to the percentage fractions of sand, organic matter, silt, soil structure and permeability.

Using the diagram and laboratory test results, the K factor values were calculated in the 55 sampling points.

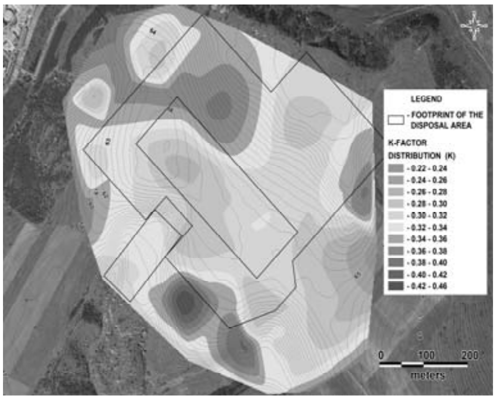

Fig. 5 *K-factor distribution on site*

The Length-Slope Factor (LS)

The effect produced by the morphology of the land is entered in the calculation of soil loss by the LS factor. It incorporates the effect produced by the gradient of the slope and its length. Normally soil erosion is directly proportional to the slope of the land, but also to its length.

As the length of the slope increases, so does the soil loss, due to the gradual increase of material accumulation in the direction of flow, and due to the increase in water flow on the slope. Similarly, erosion increases with the increase of the slope gradient.

The L factor gives the effect of the slope length on erosion. The L factor value is 1 for a slope length of 72.6 feet (22.12 m) at a gradient of 9%. Following that reasoning, the L factor value is lower than 1 for shorter slopes, of 72.6 feet and for bigger lengths, higher values of the factor L. If erosion is caused by uniform flow on slope, then the factor will be equal to 1 along the entire length. Erosion can also be produced by concentrated water streams, the so called rill erosion. In this case, the L factor has a linear increase along the entire length of the slope, on the direction of the slope. The L factor is most often given by both types of erosion, interrill and rill erosion.

L values remain almost constant over the entire length of the slope if the slope is uniform, smooth and linear, but increase when the rill flow prevails.

The S factor (the slope gradient) reflects the effect of the slope on the soil loss. It has the value 1 for a slope of 9%. The value of the S factor is higher than 1 for slopes exceeding 9% and lower for less steep slopes. It is to be noted that erosion increases proportionally with the ratio between slope gradient and slope length. In addition, rill flow erosion is more pronounced on a steep slope.

The estimation of the S factor is very accurate for slope gradients of 3 to 20% and moderately accurate for gradients of 1-3% and 20-35%. For slopes exceeding 35%, the estimate accuracy is quite low because of the instability caused by a very steep slope.

These two factors are accounted for in the soil loss formula as a single factor, the LS factor which quantifies the influence of topographic elements on erosion. After producing the grid slope map, the LS factor was calculated on alignments, using the following formula (Stone, 2000):

$$LS = [0.065 + 0.0456(\text{slope}) + 0.006541(\text{slope})^2] \times (\text{slope length} / \text{const})^{NN}$$

where

Slope = slope steepness (%)

Slope length = length of slope (ft.)

Constant = 72.5 Imperial or 22.1 metric

NN = see table 1 below

Table 1 *NN values (Stone 2000)*

Slope	<1	1≤ Slope <3	3≤ Slope < 5	≥5
NN	0,2	0,3	0,4	0,5

The LS factor values are close to 0 for the plateau area, and increase according to the algorithm described, with a maximum value of 6.3 in areas with a slope higher than 9%.

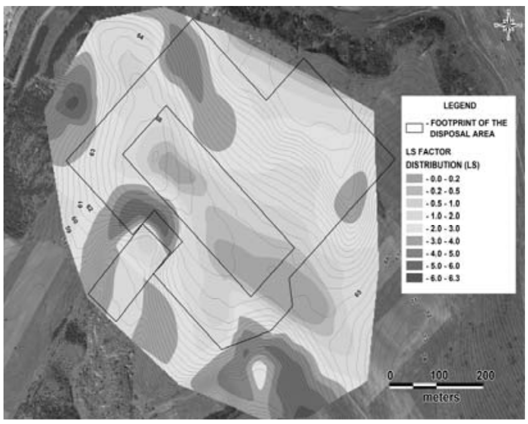

Fig. 6 *LS factor distribution on site*

Cover Management Factor (C)

The C factor is the influence produced by vegetation coverage on soil erosion. It includes both vegetation and biomass.

Basically, the C factor is a comparison of soil loss on a land with a crop and a specific management system, and the corresponding soil loss on fallow land.

Different values of the C-factor for various types of cover layers such as plant debris, broken stone, etc correlated with slope and length of hill are chosen from a table.

Common operations accompanying hillside preparation include the removal of the vegetation layer and of the plant roots, which play a significant part in the fight against erosion. For this initial stage, of barren ground, the C factor will be assigned the value 1. The presence of vegetation, including vegetation residues and anthropic filling means that the C factor value drops under 1. For areas exposed to strong erosion, mechanical protection layer are used, such as faggots or bunches of straw, layers or cushions of broken stone.

By zoning the researched area according to the tree coverage rate (thick or sparse), the type of vegetation - grassland or arable land, the C factor values were derived, and then used to draw up the variation chart (fig. 7). The zoning was done base on the existing orthophotogram, but also after on site observation.

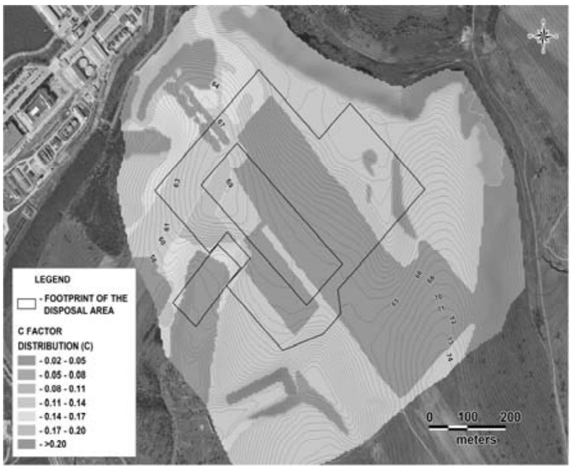

Fig. 7 *C factor distribution on site*

An area of approximately 23.5 ha, accounting for 29.2% of the overall 80.4 ha submitted to investigation, was thus marked off as having a C factor higher than 0.20. This area represents arable land, cultivated each year, or areas with a steep slope, where the runoff along the hillside is high, leading to insufficient water content and poor, underdeveloped vegetation.

Areas where the C factor ranges between 0.08 and 0.20 are also represented by arable parcels have had the advantage of not being included in the agricultural circuit for several years. During this time, mixed vegetation developed here, made up of shrubbery and grass. Aside from these parcels, there are also some pastures in the area.

The areas covered by non-homogeneous waste repositories of the Cernavoda nuclear plant and the areas covered by trees were assigned a C factor ranging between 0.02 and 0.05.

The agricultural practice factor (P)

The P factor depends on the agricultural activities carried out. The ploughing method and crop rotation affect soil erosion. This factor rarely applies to built sites, in this case the P factor is 1.

Soil loss tolerance standards (A)

A tolerable soil loss through erosion is acceptable when the maximum annual amount of eroded soil does not impede on the natural productivity on the long run or on soil stability.

The impact of erosion on a certain type of soil, and therefore, the tolerance level, vary according to soil type and depth. In general, thick soils with a uniform composition, without stone fragments and not previously eroded are deemed to have a higher tolerance limit than thin or previously eroded soils. Soil erosion tolerance rates are described in table 2 (Stone, 2007).

Table 2 *Soil loss tolerance rates*

Soil erosion categories	Potential soil loss (tons/acre/year)
Very low (tolerable)	<3
Low	3 - 5
Moderate	5 - 10
High	10 - 15
Severe	>15

Soil erodibility at the Saligny site was classified and zoned according to the rates established by Stone (2007), according to table 2.

The erodibility zoning map (annual soil loss through erosion) was drafted by multiplying the grids corresponding to the 5 factors.

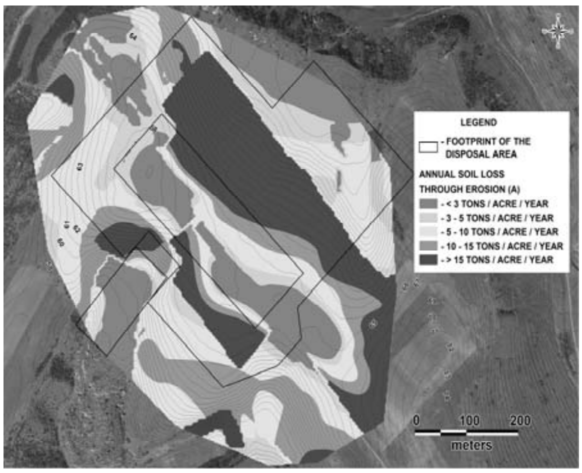

Fig. 8 – *Annual soil loss through erosion (A)*

The map zones the potential annual soil loss through erosion on the long term in the current geomorphological and land use conditions.

Areas with maximum erodibility, higher than 15 tons/acre/year and 37 tons/ha/year, are areas with a steep slope, deprived of trees and with a natural surface affected by agricultural works (ploughing). This category of ground erodibility accounts for circa 9.6 ha, or 23.1% of the overall studied area. The severe and high erodibility areas cumulated account for 41.5% of the overall area, whereas low and very low erodibility areas cumulated, for circa 49.7% of the overall area.

Lack of information and interpretative arguments regarding the accurate implementation of methods to assess erodibility may lead to higher uncertainty in approximating the factors and, consequently, the end result. Compared to the current on site conditions, absolute calculated erodibility values seem to have been overestimated, but the relative erodibility zoning is very reliable.

In order to increase the reliability of results obtained through this method, the data gathered by RAAN-SCN Pitesti during 2000-2004 were analysed. The monitoring of erosion measurement grids, placed on the Northern, South-Eastern and Southern slopes of the Saligny hill showed an alternation of erosion and deposits. Deposits are predominant at the foot of the slopes, with an average rate of circa 1.5 mm/year. The erosion process is more frequent during summer and autumn and is characterized by an average rate of 2.6 – 3.2 mm/year for the three years of measurements.

In order to estimate an average value on the medium term, the technique of Cs-17 profile variation was applied, with Cs resulting from atmospheric deposits. The algorithms that were applied were based on the decrease in time of Cs-137 concentration in the topsoil and on the variation of concentration according to depth.

Estimates based on the decrease, in time, of Cs-137 activity in the topsoil led to erosion rates of 3.1 – 4.5 mm/year for the plateau area (with a gradient of circa 2^0) and 1.3 – 5.0 mm/year for the slopes, where the gradient varies between 6 - 15^0).

Average erosion rates estimated in accordance with the variation in the activity of Cs-137, depending on depth, range between 2 and 8 mm/year on the plateau and between 7 and 15 mm/year on the slopes. The algorithm also allows for the estimation of the deposit rate, which may vary between 7 and 14 mm/year on the site.

The RUSLE equation predictions for the Saligny site are, in general, relatively comparable with estimates based on the Cs-137 concentration or obtained through experiments: 2-3 mm/year for the plateau area and 6 – 12 mm/year for the site slopes. The on site monitoring emphasized the following values: 2.6 – 3.2 mm/year for slopes with a 6-15^0 gradient.

To conclude with, estimated and measured slopes erosion has no impact on the site stability during the operational stage. On the long run, erosion may lead to a change in the site topography. Nevertheless, the changes are not significant in climatic and vegetation conditions similar to the current ones.

2. Dispersivity of soil layers covering the sites slopes – the PINHOLE test

Description of the pinhole test

Soils with a fine-grained particle composition, such as clay, silty clay and clayey silt (loess), having high concentrations of sodium (Na^+), display a high degree of erodibility and dispersion. These phenomena are measured experimentally when water passes through the soil specimen, and not at the surface of the specimen.

The visual inspection of the specimen's resistance to erosion and dispersion is carried out, by assessing the turbidity of the water that has passed through, the volume of water collected in a graded cylinder, as well as on the basis of the final diameter of the hole formed in the specimen.

The pinhole test is deemed to be one of the most reliable physical trials in order to establish dispersivity (Walker & Jermy, 1997). It was developed as a tool to assess the erodibility of fine-grained soils. At this stage, distilled water is passed through a tubular opening with a 1 mm diameter made in a 38±2 mm thick sample (Sherard *et al.*, 1976). The test is carried out on samples with natural humidity. Distilled water acts on the cylinder hole walls exerting pressures of 50, 180, 380 and 1020 ± 5 mm. At the end of each test, the collected outflow, the turbidity of the discharged water and the hole size are recorded. If the discharged water stays clear and the hole does not widen through erosion under a head of water of 380 mm, the sample is non-dispersive. On the other hand, if the discharged water is not clear (but colored with a colloidal cloud) and the hole diameter widens under a water flow caused by a pressure of 50 mm water column, the sample is dispersive. Intermediary soils erode less, under a 50-180 mm water column pressure.

According to ASTM D4647-06 (2006), there are two classification criteria for the dispersivity of fine-grained soils (A and B):

- Method A classifies soils in 6 categories of dispersivity: dispersive (D1, D2), slight to moderately dispersive (ND4, ND3), and nondispersive (ND2, ND1).

- Method B classifies soils into three categories of dispersivity: dispersive (D), slightly dispersive (SD), and nondispersive (ND).

Nevertheless, it should be noted that dispersive soils are rather difficult to identify and it is generally accepted that several types of tests and repetitions thereof are necessary in order to establish dispersivity.

Taking samples from the site

During two on site campaigns, 39 undisturbed soil samples were collected from the slopes of the DFDSMA site. The samples were extracted from the surface using a 70 mm diameter barrel core. The sampling methodology requires the removal of the first 5 to 10 cm of topsoil, and then the sampling. For a better data distribution, the samples were collected, to the extent possible, in a trigonometric network. But the overgrown vegetation and the anthropic intervention, by the storage of filling, made the sampling somewhat difficult to carry out.

Carrying out the pinhole test

As provided for in the working methodology, the following steps were applied in order to prepare the analysed specimen:

- Approximately 150 grams of material from each sample were analysed to establish Atterberg limits and natural water content;
- The rest of the material was worked through a 2 mm sieve, to separate impurities;
- The material in each sample was homogenised and brought to the upper plasticity level through reduction or by increasing water content. The sample water content was then calculated in these conditions.
- A sample 38 ± 2 mm thick was obtained, by compaction in 5 individual layers, of the homogenised material in the cylinder of the pinhole device.
- The sample was placed in between two metal sieves, followed by filters of maximum 5 mm gravel. (fig. 9).

The pinhole test was afterwards carried out. The pinhole device was connected to a tank containing distilled water and with a constant charge. A switch was used to adjust the piezometric head at the entrance of the device at 50 ± 5 mm.

This is measured from the axis of the cylinder.

Water in the device was collected for 5 minutes and the outflow was measured in cm^3/sec. If the outflow thus obtained ranges between 1.00 and 1.40 cm^3/sec and the water is very cloudy, the test normally ends here. But for all samples tested at this gradient, the outflow remained clear. Taking this fact into account, the gradient was increased by upgrading the piezometric charge from 50 ± 5 mm to 180 ± 5 mm. The outflow turbidity for this gradient was significant for some samples, which were classified as ND4 and ND3 (moderately dispersive).

For samples where the outflow was still clear, the piezometric charge was increased to 380 ± 5 mm and even 1020 ± 5 mm. These samples were classified as ND2 and ND1 (non-dispersive). At the end of each pinhole test, the sample was taken out of the cylinder and sectioned lengthwise (fig. 10).

The next step was to analyse the diameter and shape of the canal left by water flowing out. For samples classified as ND4 and ND3, the sample canal diameter reached values as high as 1.5 – 2.5 mm.

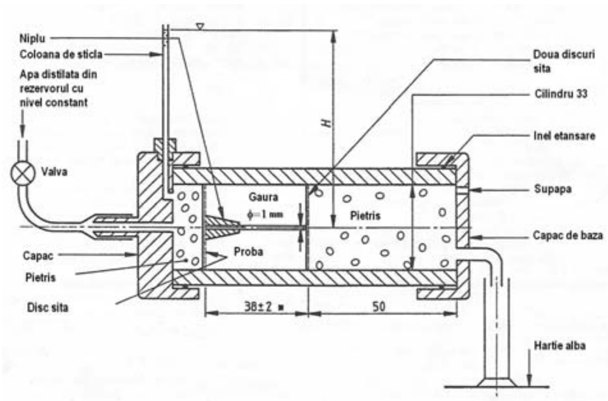

Fig. 9 *The pinhole device*

Fig. 10 presents some of the samples tested. The diameter obtained as a result of the test was compared with the initial diameter of the hole produced by metal rod with a 1 mm diameter. This clue was another criterion to classify the samples into one of aforementioned categories.

***Figure 10** Sectioned sample cylinders*

Interpretation of results

After analyzing the data obtained from testing the 39 samples (discharge turbidity, total outflow, hole diameter), the distribution charter of dispersivity classes was established, according to ASTM D4647-06 (2006) (fig. 11). Given the fact that for the 50 ± 5 mm gradient the discharge collected from all samples was clear, the dispersivity classes that the analysed soils fall into are ND2 and ND1 – nondispersive soils, and ND4 and ND3 – moderately dispersive soils. By overlapping the chart containing the dispersivity distribution and the orthophotogram, it was easily noted that the highest dispersivity areas overlap with arable, intensely cultivated land. The logical explanation would be that mechanical earth works made it easier for water to seep into the ground and, as a consequence, favored physical and chemical disintegration processes.

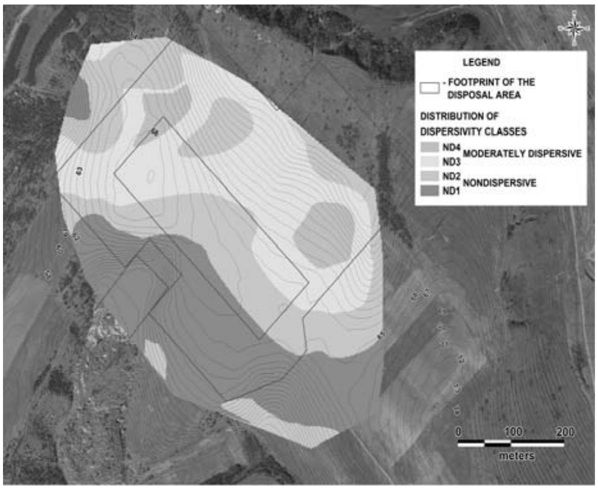

Fig. 11 *Distribution of dispersivity classes*

For a better understanding of the results and of the factors and parameters influencing the dispersion process, two more charts, previously drafted, were included in the analysis: the clay fraction distribution chart (fig. 1) and the organic matter distribution chart (fig. 2). The charts were drafted based on the 55 samples collected in November 2008, for the RUSLE method, and which were submitted to grain size and organic matter content tests.

The organic matter distribution chart (fig. 2) cannot be correlated in any way with the dispersivity distribution chart. By way of conclusion, organic matter does not play a significant part in either stopping or enhancing soil dispersion.

In exchange, the clay fraction distribution chart (fig. 1) displays mostly the same trend as the dispersivity chart. Thus, the areas with a higher clay percentage are more susceptible to dispersion. This is the case of the Northern and Eastern sites, where dispersivity classes are ND4 and ND3, and the clay percentage exceeds 23%.

Another comparison attempted was the one between the RUSLE theoretical method and the PINHOLE test. The results obtained from the two methods differ, which was to be expected since the RUSLE method incorporates more parameters into the formula. Moreover, RUSLE quantifies erosion caused by rain water at the surface of the ground, whereas the PINHOLE is used to calculate soil dispersivity by channeling a water flow through a sample, at an imposed gradient.

In conclusion, the soils present at the surface of the DFDSMA site are moderately dispersive and nondispersive, depending on the degree of use for agriculture, in the past and present. Therefore, no specific works are needed to reduce the rate of dispersion at ground surface.

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