

Article

Shrink–Swell Dynamics and Complete Profile Reversal in a Smectitic Vertisol from Western Romania: Evidence from a Long-Term Experiment (1967–2020)

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Abstract

Vertisols represent some of the most dynamic pedological systems due to the high content of smectitic clays and the intense shrinkage–swelling processes associated with seasonal variations in humidity. The present work analyzes the dynamics of pedoturbations and the rheological behavior of a smectitic Vertisol located in the Cheglevici experimental field (Aranca Plain, western Romania), continuously monitored for a period of over 50 years (1967–2020). In a stationary experiment, inert markers were buried at depths ranging from 25 to 150 cm to track the vertical displacement of the soil mass. Periodically collected samples were analyzed from a granulometric, mineralogical, chemical, and rheological point of view (plasticity limits, activity index, volumetric shrinkage, free swelling, deformation modulus, cohesion, conventional pressure). The results indicate a high smectite content (69–76%) and rheological indices specific to highly active soils ($PI > 35\%$, $A > 1.0$, $VS > 100\%$, $FS > 140\%$). The progressive redistribution of the markers provides strong evidence of substantial profile-scale soil redistribution associated with long-term pedoturbation processes, supporting the hypothesis of a near-complete profile turnover over multidecadal timescales. A significant increase in apparent density and a tendency for granulometric homogenization across the profile, associated with structural reorganization, are also highlighted. The study provides long-term experimental evidence on the vertical dynamics of the soil mass in Smectitic Vertisols and reveals major implications for agricultural management, infrastructure stability, and water flow modeling in expansive soils.

Keywords: Vertisol; smectite; shrink–swell; pedoturbation; rheological behavior; gilgai; swelling pressures; long-term monitoring; Aranca Plain



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1. Introduction

Vertisols are one of the most distinct and dynamic soil groups globally, characterized by a high content of expandable clays and intense shrinkage–swelling processes associated with seasonal variations in humidity [1–3]. According to the WRBSR (World Reference Base for Soil Resources) and Soil Taxonomy classification, these soils are defined by the presence of a vertic horizon, with over 30–45% clay, mineralogically dominated by smectites, and by the development of wide cracks (>1 cm) that often penetrate up to 1 m deep during dry periods [4,5]. The alternation of drying–wetting cycles determines the appearance of friction mirrors (slickensides), the sphenoidal structure and the specific gilgai-type microrelief [6–8].

Globally, Vertisols occupy approximately 335 million hectares, being widespread in tropical, subtropical and temperate regions, including East Africa, India, Australia, South America and South Eastern Europe [2,9]. In Romania, these soil types are present especially in the Western Plain and the Romanian Plain, where they are associated with fine parental materials, rich in smectite clay minerals [10,11]. Within the Romanian Soil Taxonomy System (SRTS), Vertisols are distinguished by vertic properties developed at depths that can exceed 100 cm and by high clay contents (>45%) [12].

The particular behavior of Vertisols is mainly controlled by the mineralogy of the clay fraction. Smectites, especially montmorillonite, have an expandable crystal lattice, capable of incorporating water molecules into the interlamellar space, causing significant volumetric increases upon wetting and pronounced contractions upon drying [13–15]. These structural dynamics directly influence the physical, hydrophysical and mechanical properties of the soil, including permeability, porosity, cation exchange capacity and shear strength [16–18]. Plasticity and mineralogical activity indices are frequently used to characterize the degree of expansiveness of these soils [19].

Repetitive contraction–swelling processes generate intense pedoturbations, materialized by vertical and lateral displacement of the soil mass, leading to the mixing of horizons and the continuous renewal of the pedological profile [7,20]. The formation of micro-ridges and microdepressions on the soil surface is the morphological expression of these internal movements, being associated with the differential redistribution of clay, salts and organic matter [8,21]. However, the quantitative mechanisms of profile overturning and the duration of complete pedoturbation cycles are insufficiently documented experimentally, most studies being based on morphological observations or theoretical models [22].

From an engineering and agricultural perspective, Vertisols have major implications. The pressures developed by the hydration of clay minerals and some salts can reach considerable values, affecting building foundations, drainage systems and agricultural infrastructure [23]. Also, the low permeability in the wet state and the formation of deep cracks during dry periods determine a complex water regime, characterized by preferential flow through cracks and temporary stagnation above compacted horizons [24]. In the context of climate change and the intensification of water alternations, understanding the long-term behavior of these soils becomes essential [25].

Despite their global importance, long-term (>30–40 years) experimental studies on the internal dynamics of the profile mass in Vertisols are rare. Direct data quantifying the amplitude and rate of vertical displacement of pedological material over multidecadal timescales are lacking. This scientific gap limits the understanding of pedoturbation processes and their implications for the evolution of physical and rheological properties.

In this context, the objective of the present study was to analyze the dynamics of pedoturbations and the rheological behavior of a smectitic Vertisol from Câmpia Aranca (Câmpia de Vest, Romania), based on a stationary experiment initiated in 1967 and monitored for over five decades. The study had the following objectives: (I) to quantify the

vertical displacement of the soil mass by using inert synthetic markers (polyester markers) positioned in 1967 at different depths on the soil profile; (II) to evaluate the dynamic evolution of the granulometric, mineralogical and chemical properties of the soil; (III) to characterize the rheological behavior by determining the indices of plasticity, activity and mechanical parameters of the soil; (IV) and to estimate the duration of a complete cycle of soil profile overturning. The working hypothesis was that the cyclic drying–wetting alternation, associated with the high smectite content and the presence of soluble salts in the lower part of the profile, generated sufficient internal pressures to cause a complete overturning of the soil mass within an interval of approximately 40–50 years. Through its unique longitudinal character, the study provides direct experimental evidence on the mechanisms of profile renewal in Vertisols and contributes to the substantiation of conceptual models regarding the dynamics of expansive soils.

2. Materials and Methods

2.1. Location and Pedogeographical Framework of the Study Area

The study area was located in the Aranca Plain, Northwestern sector of the Western Plain of Romania, near the locality of Cheglevici, Timiș County, Romania, Figure 1. The region is characterized by a low, poorly fragmented plain relief, with altitudes ranging between 80 and 90 m, developed on fine, predominantly clayey alluvial-lacustrine deposits.

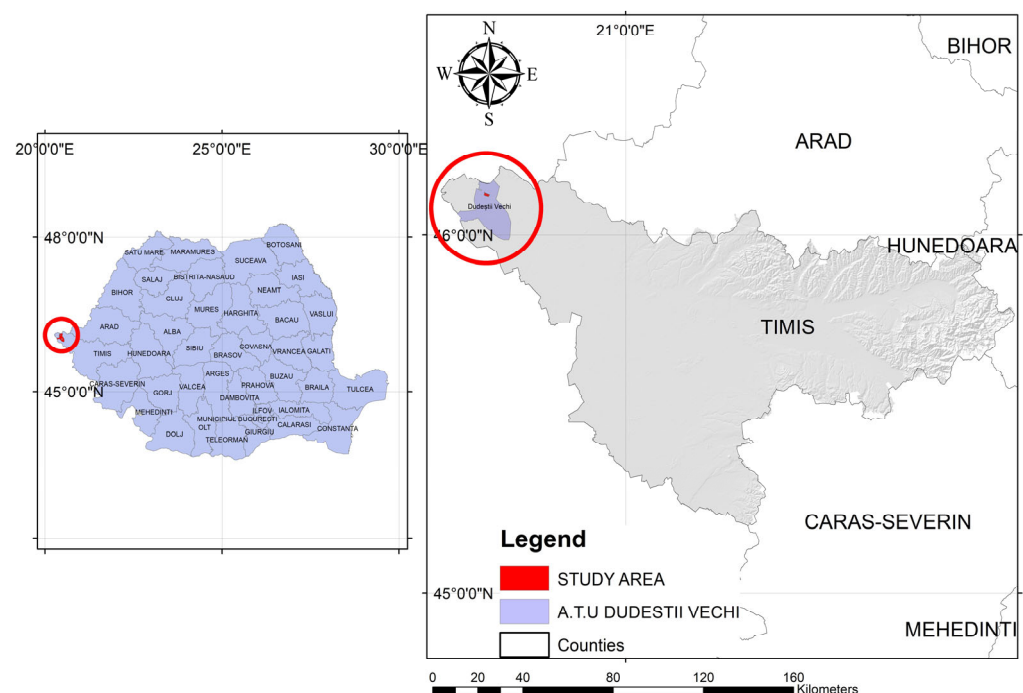


Figure 1. Study location.

The climate is temperate-continental, with sub-Mediterranean influences, with an average annual temperature of approximately 11 °C and an average multiannual rainfall of 520–600 mm. The seasonal alternation of dry periods with episodes of intense wetting favors the development of shrink–swell processes characteristic of Vertisols, according to some studies [2,3]. The parent material was represented by fine sediments, rich in smectitic clays, with intercalations of soluble salts in the lower part of the soil profile.

The climatic regime of the Aranca Plain is characterized by the alternation of wet and dry periods, which determines important seasonal variations in soil water content. These

alternations are the main factor responsible for the development of repeated contraction–swelling cycles specific to Vertisols rich in expandable minerals.

The presence of soluble salts in the lower part of the profile was identified during the pedological description and is consistent with the geological characteristics of the parent material. Since quantitative analyses of the composition of soluble salts were outside the scope of the present study, their influence is discussed only from a qualitative pedological perspective. [1]. The main soil types in Timis County, among which the studied soil falls, are presented as area and weight in Table 1, and as spatial distribution in Figure 2, according to [26].

Table 1. Soil type in Timis County, Romania.

Soil Type	Area (Ha)	Percentage (%)
Alluvial soil	151,701.8	15.00
Water	1157.84	0.10
Chernozem	291,655	28.90
District cambisol	66,387.18	6.60
Aerodisols	7104.09	0.70
Eutric cambisol	45,173.42	4.50
Gleysol	81,894.35	8.10
Luvosol	175,368	17.40
Preluvosol	75,671.76	7.50
Rendzinic	6177.21	0.60
Solonet	26,549.35	2.60
Stagnosol	10,610.22	1.10
Vertisol	70,473.64	7.00
Grand Total	1,009,924	100.00

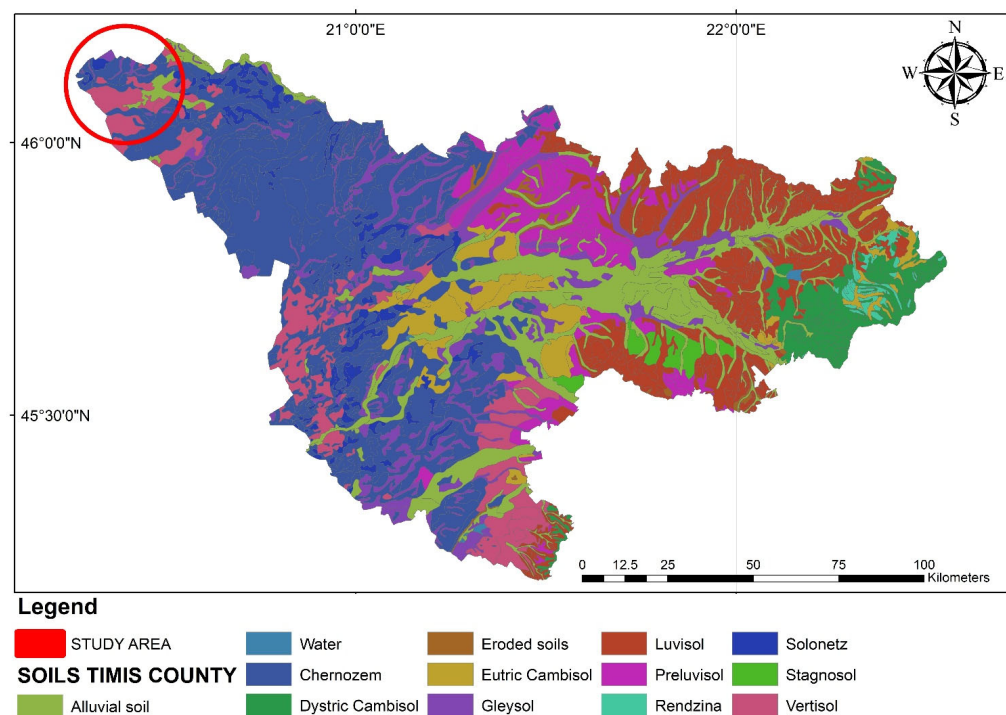


Figure 2. Geographic distribution of soil types in Timis County, Romania; Figure generated based on [27].

During the monitoring period, the experimental land was maintained in conditions similar to neighboring agricultural lands, without interventions that would modify the natural soil evolution regime.

2.2. Characterization of the Studied Soil

The studied soil is classified according to the Romanian Soil Taxonomy System (SRTS) as Vertisol and corresponds to a Pellic Vertisol according to the World Soil Resources Reference Base (WRB). The soil profile is characterized by the sequence Az–Bssz–Cz, where Az (0–30 cm), Bssz (30–110 cm), and Cz (110–150 cm). The Az horizon is characterized by a dark color and a granular structure associated with the accumulation of organic matter. The underlying Bssz horizon presents well-developed slippery faces, wedge-shaped aggregates, and pronounced shrinkage–swelling characteristics typical of Vertisols, while the suffix “z” indicates the presence of soluble salts in the lower part of the profile. The Cz horizon corresponds to the parent material, consisting predominantly of fine-textured clayey sediments, which contain localized salt accumulations inherited from the depositional environment, as shown in Table 2.

Table 2. Clay mineral composition of the studied Vertisol horizons.

Soil Horizon	Depth (cm)	Smectite (%)	Illite (%)	Kaolinite (%)
Amp;	0–30	69	27	4
Bzy	30–110	72	25	3
Cz	110–150	76	21	3

2.3. Stationary Monitoring Experiment (1967–2020)

The experiment was designed as a long-term longitudinal study, aiming to monitor the evolution of a representative Vertisol profile under natural conditions. The investigations were carried out successively on the same experimental system in 1967, 1985, 2005 and 2020, using the same general monitoring strategy. By its nature, the experiment was not designed as a factorial experiment with independent replicates, but as an observational study intended to follow pedoturbation processes over a very long term. The historical documentation of the experiment no longer allows the exact reconstruction of the number of all points investigated in each monitoring stage.

In 1967, a stationary experiment was set up on a soil parallelepiped with dimensions: length 15 m, width 3 m, investigated depth 1.50 m. To monitor the vertical displacement of the soil mass, inert synthetic markers (0.5 cm balls) of different colors were introduced at the following depths: 25 cm (red balls), 50 cm (dark blue balls), 75 cm (green balls), 100 cm (yellow balls), 125 cm (purple balls), 150 cm (light blue balls), according to Figure 3. The synthetic markers were positioned in a uniform layer over the entire surface of the parallelepiped, at each specified level, according to Figure 3.

The stationary experiment was established in 1967 on a specially prepared experimental plot, with dimensions of 15 m × 3 m and a depth of 1.50 m. The installation of the markers represented the initiation stage of the experiment and involved a controlled intervention on the soil profile. The markers used in the experiment were made of inert polyester, a material chosen due to its chemical stability and resistance to degradation under the conditions of the pedological environment. The markers played an exclusive role as passive tracers of the redistribution of the soil mass and were not used to measure the individual displacement of soil particles.

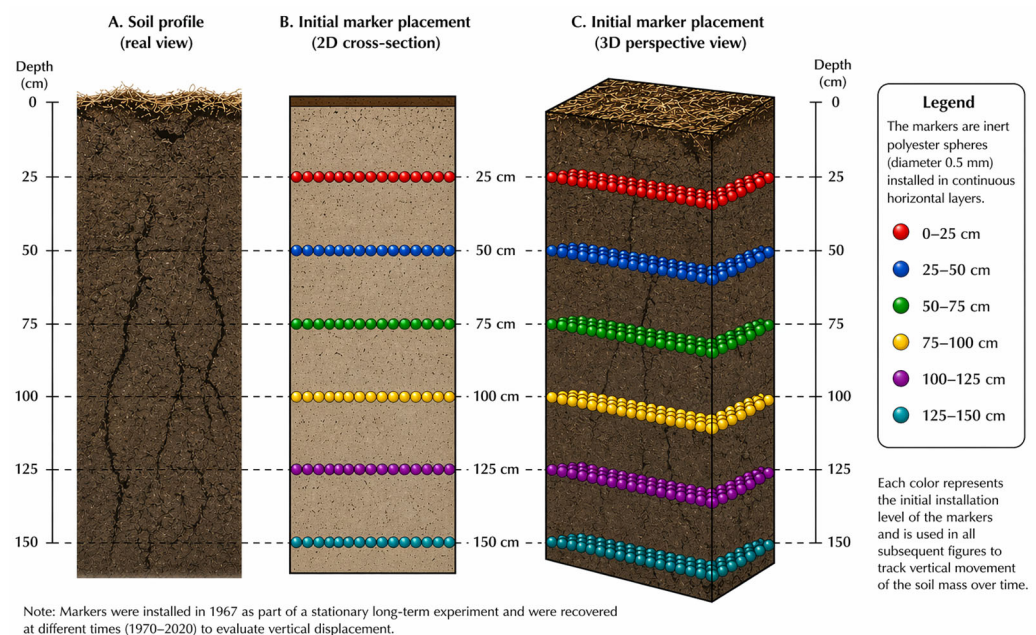


Figure 3. Initial positioning of markers on the soil profile.

During the installation phase, the soil profile was excavated under controlled conditions, while preserving the original sequence of genetic horizons. Inert spherical polyester markers (approximately 5 mm in diameter) were placed horizontally at six predetermined depths (25, 50, 75, 100, 125 and 150 cm). The installation of the markers was carried out during the progressive reconstruction of the soil profile, rather than by insertion from the soil surface. After the positioning of each level of markers, the pedological material was reconstituted respecting the natural sequence of horizons, without artificial mechanical compaction. Subsequent stabilization of the profile was achieved exclusively by natural processes carried out during the more than five decades of monitoring.

After each marker layer was positioned, the corresponding soil material was carefully replaced, following the original order of horizons. The soil was returned without artificial mechanical compaction, allowing for natural settlement under climatic conditions in the following years. This procedure minimized disturbance of the original soil architecture while ensuring a stable baseline for long-term monitoring.

The distance between the markers within each layer was maintained approximately uniform throughout the experimental area to obtain representative information on the vertical redistribution of the soil mass during successive contraction–swelling cycles.

After installing the markers and restoring the soil profile, the experimental area was maintained under natural field conditions. The subsequent evolution of the profile took place under the influence of natural environmental factors, including the climatic regime, spontaneous vegetation and biological processes specific to the local ecosystem. During the monitoring period, no interventions were carried out that would artificially modify the structure or natural functioning of the soil profile.

The monitoring of the marker positions was carried out in 1967, 1985, 2005 and 2020 through investigation points located inside the experimental area. The marker locations were carried out through pedological surveys and manual checks using a soil probe, followed by controlled sampling of soil monoliths to identify the marker positions on the profile.

For each investigation point, a volume of soil with an area of approximately 50×50 cm was extracted, over the entire thickness of the analyzed interval, corresponding to the investigated horizon [28]. The extracted material was manually examined to iden-

tify the markers and establish their position in the soil profile. After the determinations were completed, the investigated area was reconstructed to limit the disturbance of the subsequent evolution of the experiment.

Although the installation procedure inevitably represented an initial disturbance of the soil profile, all subsequent observations were carried out under undisturbed field conditions, over a period of more than five decades. Therefore, it is considered that the monitored changes reflect natural long-term pedoturbation processes, rather than short-term effects associated with the conduct of the experiment.

2.4. Experimental Design Considerations

The experiment presented in this study represents a very long-term stationary experiment, initiated in 1967. Both the installation of markers and the successive monitoring campaigns involved local interventions on the soil profile, inherent to such a type of research. However, the monitoring was carried out over a period of over five decades, during which the natural processes of pedoturbation, contraction–swelling and structural reorganization represented the dominant factors of the profile evolution. Consequently, the results obtained must be interpreted in the context of a long-term observational experiment, highlighting the general trends of the redistribution of the soil mass and not the changes produced exclusively by the experimental interventions.

2.5. Marker Installation and Monitoring

Polyester markers were used as passive tracers to highlight the redistribution of soil mass during the experiment. Their monitoring was carried out within successive investigation campaigns, and the interpretation of the results was based on the final position observed in the soil profile and not on the individual tracking of each marker. The redistribution of the markers was used to assess the general pedoturbation trends developed in the studied Vertisol.

2.6. Soil Sampling and Analysis

Soil sampling for physical, mineralogical, and rheological determinations was carried out exclusively at the monitoring points established within the experiment. The amount of material extracted was limited to the needs of laboratory analyses. After the determinations were completed, the investigated areas were reconstructed to limit local disturbance of the soil profile.

Samples were collected at regular depth intervals (0–25, 25–50, 50–75, 75–100, 100–125, 125–150 cm) and analyzed according to standards and classical pedological methodologies, according to Table 3.

Table 3. Physical, chemical, mineralogical and rheological parameters analyzed in the study.

Category	Parameters	Method/Standard
Physical	Particle size distribution (sand, silt, clay)	Sedimentation method (STAS 1913/5–85)
	Bulk density (BD)	Core method
Mineralogical Rheological	Void ratio (e)	Calculated from bulk density
	Clay mineral composition (smectite, illite, kaolinite)	X-ray diffraction (XRD), DTA
	Plastic limit (w_p)	STAS 1913/4–86
	Liquid limit (w_L)	STAS 1913/4–86
	Plasticity index (PI)	$PI = w_L - w_p$
	Activity index (A)	Skempton relationship
	Volumetric Shrinkage (VS)	STAS 1913/12–88
	Free swelling (FS)	STAS 1913/12–88

Table 3. Cont.

Category	Parameters	Method/Standard
Mechanical	Shrink–swell index (SSI)	Calculated
	Cohesion (c)	Direct shear apparatus
	Internal friction angle (φ)	Direct shear/Triaxial
	Deformation modulus (E)	Triaxial compression test
Chemical	Conventional pressure (Pconv)	Laboratory determination
	pH (H ₂ O)	Potentiometric method
	Soluble salts	Conductivity method
	Exchangeable Na ⁺	Standard soil extraction

2.6.1. Granulometric Analysis

Particle size distribution was determined using the hydrometer (sedimentation) method, according to the Romanian standard STAS 1913/5–85 [29]. The Romanian standard STAS 1913/5–85 [29] follows the same methodological principles as internationally recognized procedures such as ISO 11277:2020 [30] and ASTM D7928–21 [31], allowing reliable comparison of results. Particle diameter was calculated using Stokes' law, Equation (1) [32].

$$d_p = \sqrt{\frac{18\eta h}{(\rho_s - \rho_w)gt}}, \quad (1)$$

where d_p —the particle diameter (mm); η —the dynamic viscosity of water (Pa·s); h —the effective depth (m); ρ_s —the particle density (kg/m³); ρ_w —the water density (kg/m³); g —the gravitational acceleration (9.81 m/s²); t —the sedimentation time (s).

2.6.2. Mineralogical Analysis

The clay fraction (<2 μ m) was analyzed by X-ray diffraction (XRD), differential thermal analysis (DTA), and infrared spectroscopy. The content of smectite, illite, and kaolinite was determined semi-quantitatively.

2.6.3. Determination of Plasticity Limits

The Atterberg limits were determined in accordance with the Romanian standard STAS 1913/4–86 [33], comparable to ISO 17892-12 [34] and ASTM D4318 [35].

Determination of plasticity index (PI). The plasticity index (PI) was calculated as the difference between the liquid limit (w_L) and the plastic limit (w_P), according to Equation (2) [36].

$$PI = w_L - w_P, \quad (2)$$

where PI—plasticity index (%); w_L —liquid limit (%); w_P —plastic limit (%);

Mineralogical activity index (Skempton). The activity index (A), according to Skempton (1953) [37], was calculated as the ratio between the plasticity index and the clay fraction (<2 μ m), according to Equation (3).

$$A = \frac{PI}{\% \text{clay}}, \quad (3)$$

where A—activity index; PI—plasticity index; % clay—percentage of particles smaller than 2 μ m.

2.6.4. Determination of Rheological Indices

To characterize the processes that occurred in the soil, the following indices were calculated: volumetric shrinkage (VS), free swelling (FS), and shrink–swell index (SSI). Volumetric shrinkage (VS) was calculated according to Equation (4), based on [16,38,39].

$$VS = \frac{V_i - V_f}{V_i} \times 100, \quad (4)$$

where VS—the volumetric shrinkage (%); V_i —the initial volume; V_f —the final volume.

Free swelling (FS) was determined according to Equation (5), based on Chen (1988) [16], and ASTM D4546-14 [40].

$$FS = \frac{V_f - V_i}{V_i} \times 100, \quad (5)$$

where FS—the free swell (%); V_f —the final volume; V_i —the initial volume.

The shrink–swell index was defined as the ratio between free swelling and volumetric shrinkage, as in Equation (6), based on [16,39].

$$SSI = \frac{FS}{VS}, \quad (6)$$

where SSI—the shrink–swell index; FS—the free swelling (%); VS—the volumetric shrinkage (%).

2.6.5. Mechanical Determinations

The shear strength was determined using the direct shear apparatus and the triaxial apparatus. The shear strength of the soil was described using the Mohr–Coulomb failure criterion, as in Equation (7), according to [41,42].

$$\tau = c + \sigma \tan \varphi, \quad (7)$$

where τ —the shear strength; c —the cohesion; σ —the normal stress; φ —the internal friction angle.

The deformation modulus (E) was determined experimentally.

2.7. Determination of Vertical Pressure

The total vertical stress was calculated using Equation (8), according to [39,43].

$$\sigma_z = \gamma \cdot z, \quad (8)$$

where σ_z —the vertical stress (kPa); γ —the unit weight of the soil (kN m^{-3}); z —the depth (m).

2.8. GIS Analysis

The distribution of soil types in Timiș County was analyzed using GIS technologies and Landsat satellite data to contextualize the regional extension of Vertisols [4,5]. The thematic maps were created in the national coordinate system and allowed the determination of the share of Vertisols within the analyzed administrative unit.

2.9. Statistical Analysis

The experimental data were analyzed to evaluate the interdependence between the parameters considered in the description and characterization of the soil at the considered levels. The correlations between the physical and rheological parameters were evaluated using the Pearson coefficient, with the significance level $p < 0.05$. The PAST software

v.4.17 [44] and the JASP software v.0.16.2 [45] were used for data analysis and generation of graphical representations.

Descriptive statistics (mean, standard deviation, and coefficient of variation) were calculated for variables for which sufficient experimental observations were available. Since the experiment represents a longitudinal study on the same experimental system and not an experiment with independent replicates, classical statistical comparison tests between variants were not considered appropriate for all data sets analyzed.

Pearson correlation analysis was used exclusively for exploratory purposes, to highlight the relationships between physical, rheological, and mechanical properties, determined at different levels of the soil profile in the final stage of monitoring. Given that the observations come from the same profile and do not represent independent replicates, the results should be interpreted as descriptive relationships and not as generalizable statistical evidence.

3. Results

3.1. Granulometric Distribution and Long-Term Evolution of the Clay Fraction

The presented results should be interpreted mainly from a descriptive perspective, following the general trends of evolution of the soil profile during the monitoring period. Statistical analyses were used exclusively in situations where the structure of the data set allowed their application in a justified manner.

The evolution of the analyzed parameters during the four monitoring stages should not be interpreted as a linear process. The shrinkage–swelling processes specific to Vertisols are controlled by climatic and pedological factors that vary over time, which leads to successive changes in the distribution of the physical properties of the profile.

Granulometric analysis [29] revealed progressive changes in the distribution of the clay fraction during the four monitoring stages (1967, 1985, 2005 and 2020). The initial profile, characterized by an obvious textural differentiation between the superficial and deep horizons, showed a tendency towards uniformity of the clay content over time.

In 1967, the clay content varied between 25.4% and 62.9%, highlighting a pronounced stratification of the profile. In 1985, the first changes in the vertical distribution were observed, followed by a more pronounced redistribution in 2005. At the last monitoring stage (2020), the variation in the clay content was considerably reduced, the differences between the horizons becoming much smaller compared to the initial situation.

The reduction in the coefficient of variation in the clay content from 26.07% in 1967 to 6.57% in 2020 indicates an obvious trend of textural homogenization of the profile, compatible with the pedoturbation processes developed over the long term in Smectite-rich Vertisols.

Comparative data for the period 1967–2020 indicated systematic changes in the vertical distribution of clay, as shown in Table 4.

Table 4. Evolution of clay content (%) along the soil profile (1967–2020).

Depth (cm)	Years During the Study Period			
	1967	1985	2005	2020
0–25	60.4	63.1	57.9	54.4
25–50	62.9	64.3	53.4	51.1
50–75	55.0	57.1	51.9	49.3
75–100	53.3	31.4	46.3	44.6
100–125	53.2	33.8	50.4	48.8
125–150	25.4	26.8	45.0	48.2

Analysis of textural evolution. The initial situation (1967) showed a differentiated textural profile, high clay content in the first 125 cm (53–63%), and a sudden decrease at 125–150 cm (25.4%). The average clay content recorded in 1967 presented the average value $\text{clay} = 51.70\% \pm 5.50$, with the coefficient of variation $\text{CV} = 26.07$. A relatively heterogeneous soil profile was observed, as seen in Figure 4. The situation recorded in 2020 showed a narrow range of variation in clay content ($44.60\text{--}54.40 \pm 1.33\%$), with the average clay content of $49.40 \pm 1.33\%$, and the coefficient of variation $\text{CV} = 6.57$. A significant increase was recorded at a depth of 125–150 cm (48.20%), from 25.40% in 1962. A reduction in the difference between horizons was recorded, as shown in Figure 4. There was a reduction in the coefficient of variation (CV) values from 26.07% (1967) to 6.57% (2020), which indicated pronounced textural homogenization on the soil profile. The distribution of clay on the soil profile, in the range of 125–150 cm (+22.8%), demonstrated upward vertical transport. The slight decrease in clay in the upper horizons suggests internal redistribution of clay on the soil profile. This behavior was consistent with intense pedoturbation processes generated by “shrink–swell” cycles.

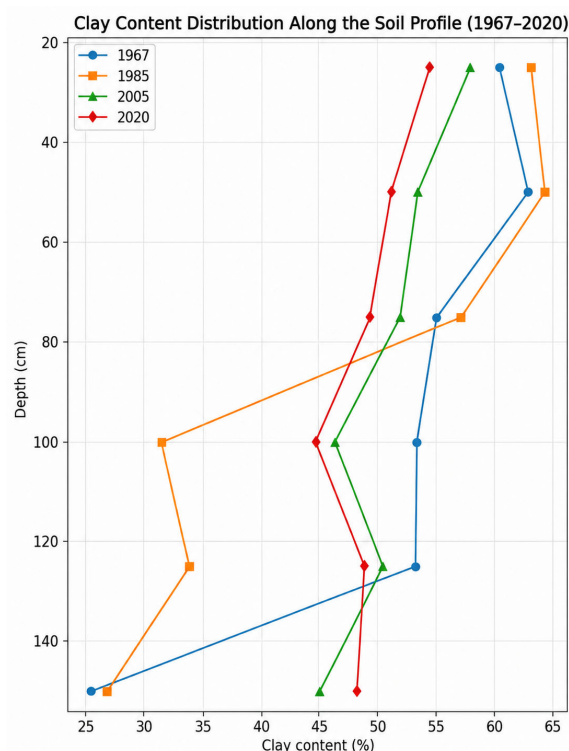


Figure 4. Variation in clay content over time along the depth of the soil profile.

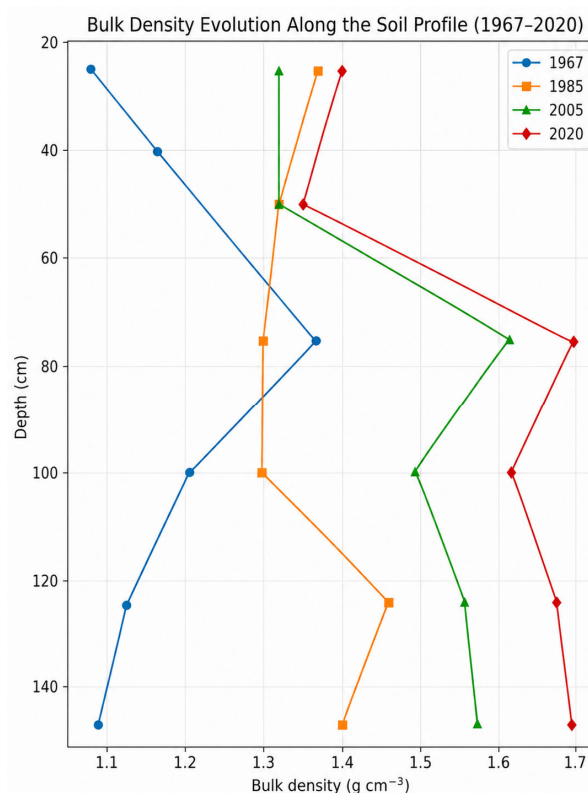
The redistribution of markers observed in the profile should be interpreted as a result of the differential movement of soil aggregates and volumes and not as the synchronous movement of all markers installed at the same depth. The shrinkage–swelling processes characteristic of Vertisols produce repeated local displacements, so that the final position of the markers reflects the cumulative effect of the numerous deformation cycles developed during the monitoring period.

3.2. Evolution of Bulk Density and Structural Reorganization

The variation in apparent density values reflected the change in the internal structure and the reduction in structural porosity, as shown in Table 5. Starting from the average value $\text{BD} = 1.19 \pm 0.04 \text{ g cm}^{-3}$, with the coefficient of variation $\text{CV} = 9.08$ in 1967, the apparent density recorded an increasing variation over the study period, up to $\text{BD} = 1.58 \pm 0.06 \text{ g cm}^{-3}$, with $\text{CV} = 10.06$ in 2020, as shown in Figure 5.

Table 5. Evolution of apparent density over soil depth and study period (g cm^{-3}).

Depth (cm)	BD Values over the Study Period				ΔBD
	1967	1985	2005 (g cm^{-3})	2020	
0–25	1.08	1.37	1.32	1.40	0.32
25–50	1.22	1.32	1.32	1.35	0.13
50–75	1.38	1.30	1.62	1.70	0.32
75–100	1.21	1.30	1.50	1.62	0.41
100–125	1.14	1.46	1.56	1.68	0.54
125–150	1.11	1.39	1.58	1.70	0.59

**Figure 5.** Bulk density evolution along the soil profile (1967–2020).

The variability observed between successive monitoring stages reflects the dynamic nature of the internal reorganization processes of the soil mass and does not imply the existence of a uniform evolution between observation times.

The absolute increase in bulk density over the period 1967–2020 (ΔBD) recorded values ranging from $\Delta\text{BD} = 0.13 \text{ g cm}^{-3}$ (depth 25–50 cm) to $\Delta\text{BD} = 0.59 \text{ g cm}^{-3}$ (depth 125–150 cm), as seen in Table 5.

The bulk density values showed a progressive increase in most of the investigated depth intervals during the monitoring period. This evolution suggests structural changes produced in the soil mass during repeated shrinkage–swelling cycles.

However, in the present study, no direct determinations were made regarding the evolution of structural porosity, particle orientation, or the degree of clogging of cracks. Therefore, these processes are discussed exclusively as possible mechanisms, described in the literature for Vertisols rich in smectite.

The increase in bulk density observed in the lower horizons must be interpreted together with the pedoturbation processes highlighted by the redistribution of markers. These phenomena are not antagonistic but reflect two complementary components of

the internal reorganization of the soil profile generated by the alternation of wetting and drying cycles.

The highest values of apparent density ($1.68\text{--}1.70\text{ g cm}^{-3}$) were recorded in the lower horizons of the profile, especially at depths of 50–75 cm, 100–125 cm and 125–150 cm.

3.3. Shrink–Swell Behavior of the Vertisol

The rheological parameters presented in this section characterize the state of the soil profile determined at the last monitoring stage (2020). Since the determinations of rheological properties were not systematically performed in all stages of the experiment started in 1967, the results presented do not follow the temporal evolution of these parameters but describe the mechanical and rheological behavior of Vertisol after over five decades of natural evolution.

Rheological determinations performed according to [33,34] highlighted the very active character of the studied Vertisol, as shown in Table 6.

Table 6. Key rheological and mechanical parameters along the soil profile.

Deph (cm)	PI (%)	A	VS (%)	FS (%)	E (kPa)	Pconv (kPa)
0–25	41.50	1.30	107.25	116.13	15,800	425
25–50	40.10	1.06	115.03	142.51	15,200	420
50–75	40.10	1.08	106.38	146.43	26,800	625
75–100	33.40	0.80	82.92	158.93	22,000	685
100–125	38.40	0.96	88.83	123.48	23,500	710
125–150	36.00	0.88	92.39	112.40	23,800	585

Note: Deph—depth on soil profile; PI—plasticity index; A—activity index; VS—volumetric shrinkage; FS—free swelling; E—modulus of deformation; Pconv—conventional pressure.

The plasticity index (PI) ranged between $33.40 \pm 1.24\%$ and $41.50 \pm 1.24\%$, with the mean $PI = 38.25 \pm 1.24\%$ ($CV = 7.93$), Figure 6. PI values $> 35\%$ placed the soil in the category of very plastic soils.

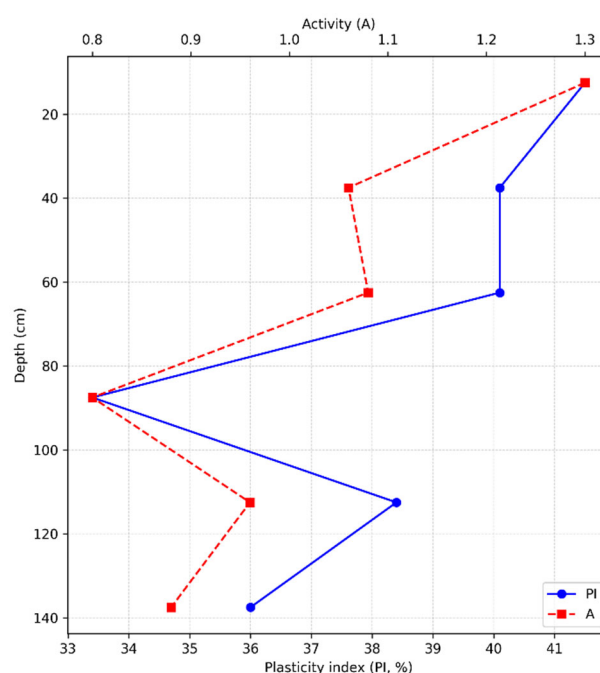


Figure 6. Variation in plasticity index (PI) and activity (A) along the soil profile. PI is represented by a continuous line with circular markers, while A is shown by a dashed line with square markers.

The activity index (A) recorded values between 0.90 ± 0.07 and 1.30 ± 0.07 , with the mean value $A = 1.01 \pm 0.07$ and the coefficient of variation $CV = 17.37$. The activity index (A) showed values above 1 ($AI > 1.00$) in the first 75 cm, with the maximum value in the depth of 0–25 cm ($A = 1.30 \pm 0.07$). The recorded values confirmed the dominance of smectites in the clay fraction of the soil, as seen in Figure 6.

Volumetric shrinkage (VS) presented values ranging from $VS = 82.92 \pm 5.12\%$ to $VS = 115.03 \pm 5.12\%$, with a mean value of $VS = 98.80 \pm 5.12\%$, and with low variability ($CV = 12.68$). Free swelling (FS) presented values in the range (112.40, 158.93), with a mean value of $FS = 133.31 \pm 7.62\%$ and low variability ($CV = 14.00$). The values of the VS and FS indices indicated an extremely high potential for expansion of the soil textural fractions, as shown in Figure 7.

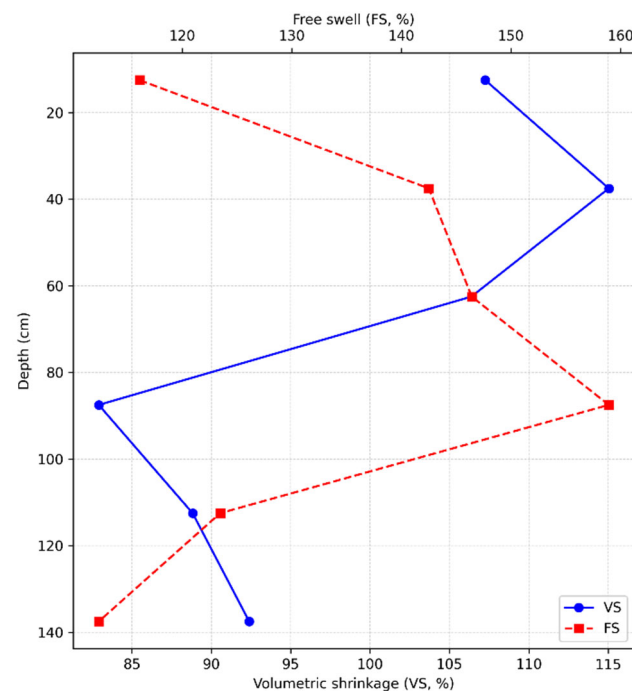


Figure 7. Variation in volumetric shrinkage (VS) and free swell (FS) with depth. VS is represented by a continuous line with circular markers, while FS is shown by a dashed line with square markers.

Within the mechanical parameters, the modulus of deformation (E) recorded increasing values from 15,800 kPa to 26,000 kPa, as seen in Table 6. The conventional pressure (Pconv) varied in the range (420.00, 710.00), with the average value $P_{conv} = 575.00 \pm 51.45$ kPa. The conventional pressure recorded the maximum value of 710.00 ± 51.46 kPa at a depth of 100–125 cm. These values suggested the development of internal pressures capable of generating vertical displacements, as shown in Figure 8.

3.4. Correlations Between Physical and Rheological Parameters

The Pearson correlation analysis presented in this section was performed using the data set obtained at the last monitoring stage (2020). Its purpose was to identify the relationships between the physical, rheological, and mechanical properties of the soil profile in the final state of the experiment and not to assess the change in these relationships throughout the entire monitoring period.

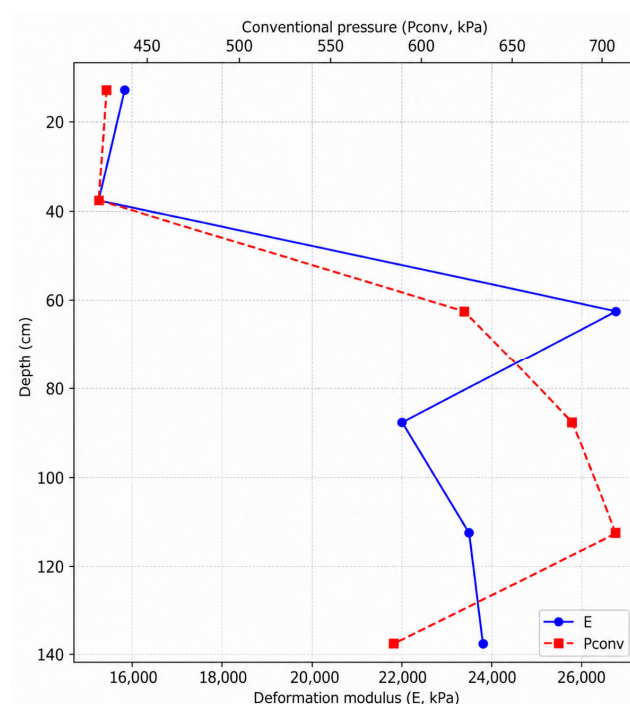


Figure 8. Variation in deformation modulus (E) and conventional pressure (Pconv) along the soil profile. E is represented by a continuous line with circular markers (blue), while Pconv is shown by a dashed line with square markers (red).

The values of the Pearson correlation coefficient indicated different levels of inter-dependence between the indices considered for the characterization of Vertisol and the phenomena evaluated on the soil profile, at the level of 2020, as shown in Figure 9.

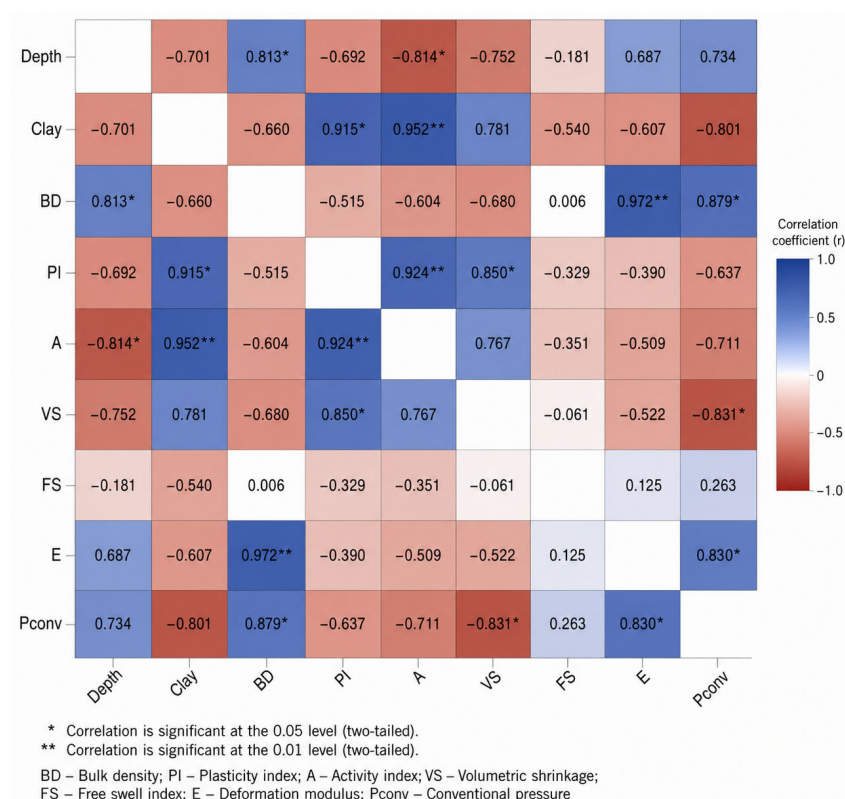


Figure 9. Pearson correlation matrix between clay content and rheological parameters of the studied Vertisol.

A very strong, positive correlation was recorded between clay content and plasticity index (PI), $r = 0.915^*$, and between clay content and activity index (A), $r = 0.952^{**}$, which confirmed the determining role of the fine fraction (clay) on the rheological behavior of the soil profile. Also, a very strong positive correlation was recorded between bulk density (BD) and modulus of deformation (E), $r = 0.972^{**}$. The positive correlation between clay and volume shrinkage (VS), $r = 0.781$, suggested that the intensity of shrink–swell processes increased with the increase in the clay fraction. Bulk density (BD) showed a strong positive correlation with depth on the soil profile (Depth), $r = 0.813^*$, and with conventional pressure (Pconv), $r = 0.879^*$. Volumetric shrinkage also showed a strong positive correlation with the plasticity index (PI), $r = 0.85^*$, and with the activity index (A), $r = 0.767$. The very strong, positive correlation ($r = 0.924^{**}$) between PI and A indices reflected the mineralogical control over plasticity. In contrast, the VS and FS indices showed a very weak correlation ($r = -0.061$), indicating that, in this data set, shrinkage and swelling did not vary proportionally across all depth intervals. It should be noted that correlations were calculated based on six depth intervals; therefore, results should be interpreted as indicative trends rather than definitive statistical relationships.

3.5. Vertical Displacement of Markers (1967–2020)

The redistribution of polyester markings throughout the profile thickness during the study period (1967–2020) was evaluated and recorded, according to the data in Table 7 and Figure 10. For a unified interpretation of the results, the recovered markers were classified according to their final position in the soil profile relative to the initial installation depth. The purpose of this classification was to highlight the degree of vertical redistribution produced by repeated contraction–swelling cycles and not to reconstruct the individual trajectory of each marker.

Table 7. Marker movement summary.

Initial Depth (cm)	Situation 2020	Interpretation
125–150	Available in 25–59 cm	Upward travel ~100 cm
100–125	Present at the surface	Complete release
75–100	Redistribution 50–75 cm	Mixed movement

The experiment was initiated in 1967, and the original methodology did not include individual quantification of each recovered marker. Consequently, the interpretation is based on the observed spatial distribution of the markers in the soil profile and not on the tracking of each individual marker.

The presence of markings in the range of 25–50 cm (initially positioned at 125–150 cm) confirmed the existence of a mechanism of soil mass overturning on a multidecadal time scale. This dynamic involved an internal vertical flow system controlled by the pressures generated by the alternation of shrink–swell, with direct implications for the structural stability and the evolution of the physical properties of the profile.

The proposed conceptual model, Figure 11, summarizes the mechanisms responsible for the redistribution of soil mass in smectite-rich Vertisols. Contraction–swelling processes determine the development of slickensides, on which the soil mass moves both vertically and laterally. Consequently, the final position of the markers observed in the profile represents the result of a sequence of three-dimensional displacements produced during numerous wetting and drying cycles. The vertical redistribution highlighted in the present study should be interpreted as the final expression of these complex processes and not as an exclusively vertical displacement.

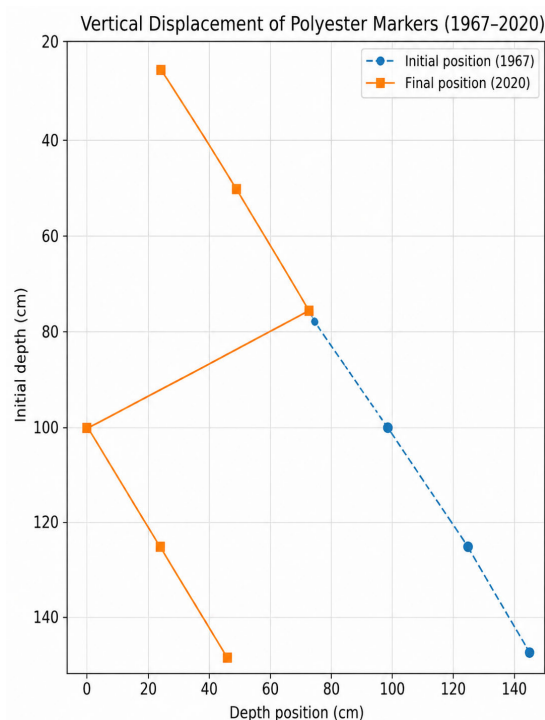


Figure 10. Vertical displacement of polyester markers.

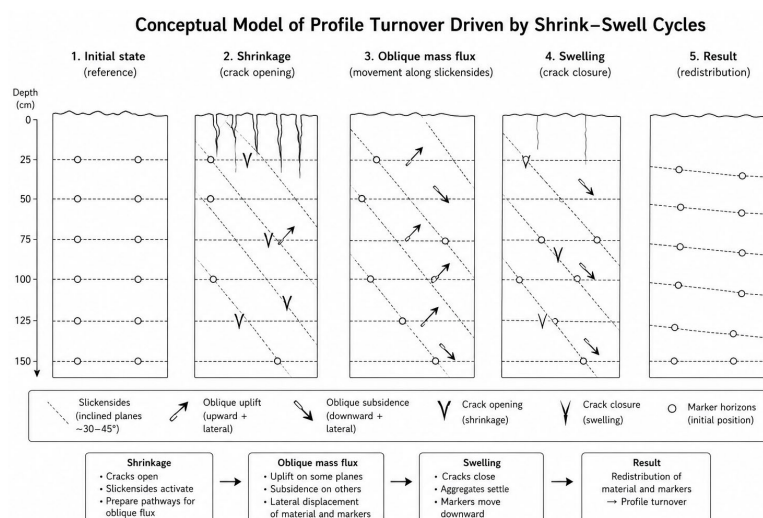


Figure 11. Conceptual model of soil mass redistribution in a smectitic Vertisol.

Based on the recorded values, a maximum displacement of approximately 100 cm/50 years was estimated, resulting in an average displacement rate of approximately 2 cm/year, with variations over shorter intervals (e.g., approximately 1 cm/year in 1995), Figure 12. Colored spheres indicate the initial installation depth of polyester markers (0–25, 25–50, 50–75, 75–100, 100–125, and 125–150 cm). Blue and yellow arrows illustrate upward displacement driven by shrink–swell dynamics and soil profile turnover, respectively. Red curved arrows indicate pedoturbation and complete redistribution of soil material, whereas the red horizontal arrow represents the dominant direction of mass transfer. Circular arrows denote cyclic wetting–drying processes responsible for Vertisol self-mulching and profile renewal. White dashed arrows show the progressive upward migration of polyester markers during the 53-year monitoring period (1967–2020).

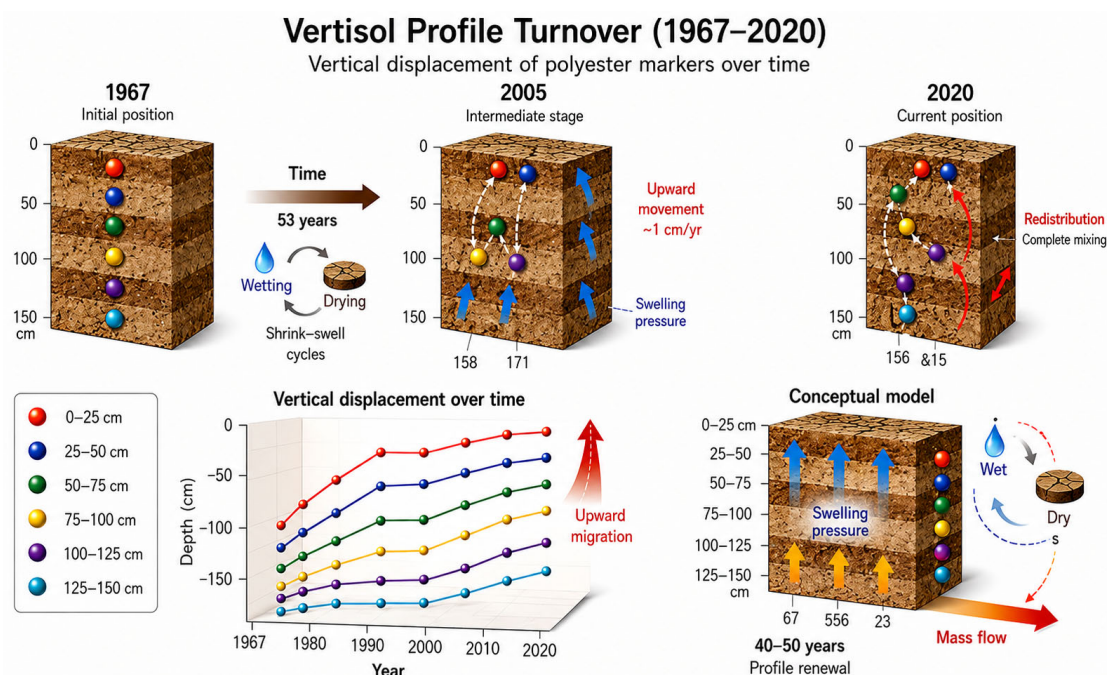


Figure 12. Vertical displacement of polyester markers over time—sequential stages.

3.6. Microcomas vs. Microdepressions

Due to the dominant presence of smectic clays and the hydration processes of some salts at the base of the soil profile, under the conditions of alternating drying–wetting, pressures were generated to gradually push the soil masses towards the surface, with the development of polishing surfaces so that the soil at the base of the profile reaches the surface. It can be estimated that in about 50 years the entire mass of a Vertisol is completely overturned and renewed. The hypothesis is supported by the morphological, physical and chemical analyses made on microdepressions and microcomas in the study area, between which there were differences of approx. 20–30 cm in height. As a result of the processes recorded in the volume of the soil profile during the study period, microdepressions (ML) and microcomes (MH) formations were formed on the soil surface, which were analyzed in terms of clay content (clay, %), soil reaction (pH, H₂O), and salt content, as shown in Table 8. Data in Table 8 presents the average results obtained from 5 drillings in microdepressions and 5 drillings in microcomes.

Table 8. Values of some indices at the level of microformations at the soil surface compared to the soil profile.

Depth (cm)	Color 10YR (Wet)		Clay (%)		pH (H ₂ O)		Soluble Salts (mmho/cm)		Na ⁺ Soluble (me/100 g)		Ca ²⁺ Soluble (me/100 g)	
	ML	MH	ML	MH	ML	MH	ML	MH	ML	MH	ML	MH
0–10	2/1	3/2	50.10	65.60	7.39	7.71	0.20	0.36	0.80	0.80	0.30	0.40
40–50	3/1	3/2	58.50	67.30	7.87	7.91	0.34	0.39	0.70	0.90	0.30	0.40
60–70	3/2	4/1	69.80	66.40	7.98	7.92	0.36	0.55	0.60	0.60	0.30	0.20
75–90	3/2	4/1	64.60	64.60	7.89	7.95	0.38	0.55	0.60	0.60	0.10	0.30
95–105	4/1	3/2	61.80	48.70	8.01	8.00	0.55	0.58	0.90	1.10	0.20	0.50
105–120	4/2	3/2	58.90	40.60	7.97	8.05	0.69	1.13	1.10	2.60	0.10	0.30

Notes: ML—microlows; MH—microhighs.

Based on the analyses presented in Table 8, it was assessed that the surface layer represented by the microcome formations was richer in clay (67.3 and 65.7%), more alkaline (pH 7.71 and 7.91), richer in soluble salts (0.36–0.55 mmho/cm) and with a higher content

of soluble Na^+ and Ca^{2+} , compared to the surface layer represented by the microdepression formations. The striking similarity between the properties of the layers from 60 to 70 cm and 75–90 cm in the microdepression area with the surface layers (0–10 cm and 40–50 cm) in the microcoma area led to the conclusion that the current surface layers on the microcoma are the former layers from the depth of 60–90 cm of the microdepressions, pushed to the surface by the pressures that appeared in the vertisol soil mass. The statement was also supported by the identical color (10 YR 3/2), the similar clay content, and the identical content of soluble salts. The integrated results indicated an active and continuous process of pedoturbation, characterized by textural homogenization, an increase in apparent density, and development of significant internal pressures. Multidecadal monitoring of the markings experimentally demonstrated a complete cycle of profile overturning in an estimated time interval of 40–50 years. This evidence supports the hypothesis of a dynamic pedological system, predominantly controlled by the alternation of drying–wetting and the dominant smectitic mineralogy.

4. Discussion

4.1. Pedoturbation as a Profile Renewal Mechanism

The results obtained demonstrated that the analyzed Vertisol functioned as a dynamic pedological system, characterized by a continuous process of vertical pedoturbation. The granulometric homogenization observed between 1967 and 2020, reflected by the reduction in the coefficient of variation in the clay fraction from approximately 26% to 6.7%, indicated a progressive redistribution of fine material throughout the profile thickness.

Under the conditions of the natural alternation between wet and dry periods, characteristic of the studied region, repeated contraction–swelling processes represent the mechanism most likely responsible for the redistribution of soil mass observed in the experiment.

It should be noted that sampling is an unavoidable intervention in long-term experiments. However, the punctual nature of these interventions and the long intervals between monitoring campaigns reduce the likelihood that they will significantly influence the general trends of the pedoturbation processes highlighted in the present study.

The interpretation of the results must be carried out taking into account the specifics of long-term historical experiments, in which the interventions necessary to install and monitor the experimental system cannot be completely eliminated. However, the monitoring period of over 53 years allows the assessment that the natural processes characteristic of Vertisols had a dominant influence on the changes observed in the soil profile.

It should be emphasized that pedoturbation processes do not evolve continuously and uniformly. The alternation of periods with different intensity of the contraction–swelling processes can determine local variations in the analyzed parameters, without these necessarily indicating methodological inconsistencies. Consequently, the results must be interpreted as an expression of a complex pedological system, characterized by a long-term nonlinear evolution. This type of vertical uniformization has been previously reported in Vertisols from semiarid and subtropical regions, where repeated shrink–swell cycles caused horizon mixing and blurring of pedogenetic differentiation [46–48]. However, most of these studies were based on morphological observations or conceptual models, without direct long-term (multidecadal) experimental quantification. In the present case, the displacement of inert positioning markers to depths of up to 150 cm provided direct evidence of complete overturning of the profile mass within an estimated interval of 40–50 years. This result supports the hypothesis that pedoturbation in Vertisols is not just a local redistribution process, but a mechanism capable of generating integral profile renewal [49,50]. Recent studies have increasingly emphasized the role of climate variability in intensifying pedoturbation

processes in Vertisols. Changes in precipitation regimes, particularly the alternation of prolonged droughts and intense rainfall events, have been shown to amplify shrink–swell dynamics and enhance vertical soil mixing. Iverson et al. (2020) [51] demonstrated that increased frequency of wetting–drying cycles leads to accelerated structural turnover in expansive clay soils, while Li et al. (2022) [52] reported that climate-driven variability significantly influences the redistribution of clay and soluble salts along the soil profile. Similar findings have been reported by Zhang et al. (2021) [53] and Singh et al. (2023) [54], who highlighted the sensitivity of shrink–swell processes to hydroclimatic variability in clay-rich soils. These findings support the interpretation that pedoturbation is not only an intrinsic property of Vertisols but also a process highly sensitive to external climatic forcing. Although the installation of the experiment involved an initial disturbance of the soil profile, the very long duration of monitoring (1967–2020) allows us to consider the results as an expression of natural pedoturbation processes developed over time. The repeated contraction–swelling processes characteristic of Vertisols lead to the continuous reorganization of the internal structure, progressively diminishing the influence of the initial disturbance.

It is known that vegetation and biological activity influence the pedogenesis processes and the hydrological behavior of Vertisols. In the present experiment, these components evolved under natural conditions during more than five decades of monitoring, contributing to the progressive restoration of the biological balance of the profile after the initial stage of installation of the experiment.

Since the markers were used exclusively as passive tracers, their final position must be interpreted in relation to the movement of the soil mass and not as a result of independent displacements. Mechanisms such as buoyancy or individual transport by water cannot explain the redistribution observed throughout the profile, which is compatible with the complex pedoturbation processes described for Vertisols rich in expandable minerals.

4.2. Mineralogical Control over Rheological Behavior

The high values of the plasticity index ($PI > 35\%$), the activity index ($A > 1$ in the upper horizons), and the shrink–swell parameters (VS and FS) confirmed the determining role of smectites in the internal dynamics of the soil profile. The strong positive correlations between the clay content and PI ($r = 0.915$), and between the clay content and A ($r = 0.952$), highlighted the direct relationship between the fine fraction and the intensity of the expansive behavior. These results are consistent with classical studies that showed that smectites, through their interlamellar hydration capacity, generated significant volumetric variations under conditions of water alternation that were translated into the development of internal pressures capable of moving the soil mass vertically [16,55]. The increase in apparent density in the deep intervals suggested that repeated contraction–swelling processes not only caused vertical mixing, but also progressive structural reorganization, by orienting particles and reducing macroporosity. This reorganization may enhance the transmission of vertical stresses and contribute to the mechanism of uplift of material from depth. The increase in apparent density in the deep soil horizons suggested that repeated contraction–swelling processes not only caused vertical mixing, but also progressive structural reorganization by orienting particles and reducing macroporosity. This reorganization process may enhance the transmission of vertical internal stresses and contribute to the mechanism of uplift of material from depth [56,57].

4.3. The Physical Mechanism of Profile Reversal

The integration of granulometric, rheological and mechanical results allowed the formulation of a conceptual model of soil profile dynamics, with different stages: 1—during

wetting phases, the hydration of smectites and soluble salts in the lower horizons generates swelling pressures; 2—the developed pressures exceed the local structural resistance and produce differential vertical displacements; 3—during the drying phases, shrinkage generates deep cracks that allow water to infiltrate during the next cycle; 4—the repetition of cycles (wetting—drying phases) leads to a slow, but cumulative, vertical flow of soil mass. The estimate of an average rate of approximately 2 cm/year, resulting from the redistribution of markers, indicated a slow but systematic process, compatible with the slow but continuous dynamics of Vertisols, also reported by other studies [58,59].

4.4. Implications for Management and Engineering Stability

The experimental confirmation of a complete cycle of profile reversal in this type of soil (Vertisol) has important implications in different fields. In agriculture, continuous mixing can affect the distribution of nutrients, the stability of the soil structure, and the development of the root system [60,61]. In civil engineering, internal pressures generated by shrink–swell processes can compromise foundations and infrastructure [62,63]. In hydrological modeling, the existence of deep cracks and preferential flow requires specific approaches for expansive soils [64,65]. Recent studies have highlighted that climate variability has amplified the shrinkage–swelling processes and implicitly the rate of pedoturbation [66,67]. In addition, recent advances in soil physics and geotechnical research have highlighted the importance of integrating shrink–swell behavior into predictive models of soil–structure interaction and hydrological processes. Studies by Tang et al. (2021) [68] and Peth et al. (2023) [69] have shown that the coupling between soil deformation, crack development, and preferential flow plays a critical role in determining both mechanical stability and water transport in expansive soils. Furthermore, numerical modeling approaches increasingly incorporate cyclic stress–strain responses associated with smectitic mineralogy, providing improved predictions of long-term soil behavior under changing environmental conditions. Similar conclusions were reported by Zhao et al. (2022) [70] and Kumar et al. (2024) [71], emphasizing the need for coupled hydro-mechanical models in expansive soils. These developments reinforce the need to consider Vertisols as dynamic systems in both agricultural and engineering applications.

4.5. Original Contribution and Limitations

The major contribution of the study lies in its longitudinal character, rarely encountered in the literature. Monitoring over a period of over 50 years provides direct experimental evidence on the vertical dynamics of the profile in Vertisols. However, the correlation analysis was based on a limited number of depth intervals ($n = 6$), which forced the interpretation of statistical results as indicative trends. Extension of the investigations through continuous monitoring and the use of modern techniques (e.g., tomographic imaging or strain sensors) could provide a more detailed characterization of the internal mechanisms [72,73]. One of the limitations of the study is that complete rheological determinations were only available for the final monitoring stage. Consequently, the analysis of temporal evolution was mainly based on textural changes, bulk density and marker redistribution, while rheological parameters were used to characterize the final state of the soil profile. Future research should include periodic monitoring of mechanical and rheological properties to highlight their long-term dynamics. It should be noted that the installation of markers required an initial intervention on the soil profile. Although this intervention can be considered an inherent limitation of very long-term experiments, the monitoring period of over 53 years allows the assessment that the observed changes predominantly reflect the natural processes of Vertisol evolution.

Another limitation inherent to the experiment is represented by the temporary disturbance of the biological component at the time of marker installation. Since the monitoring was carried out over a period of over 53 years, we consider that the natural processes of vegetation restoration, microbiological activity and soil structure have significantly reduced the influence of this initial disturbance. However, the lack of systematic biological determinations is a limitation that must be taken into account when interpreting the results.

An additional limitation of the study is represented by the need to periodically take soil samples for laboratory analyses. Although these interventions were spatially limited and carried out at long intervals, the existence of local effects on the profile structure in the investigated areas cannot be excluded. However, it is considered that their influence on the general behavior of the experimental system is reduced compared to the effects of natural processes carried out over the five decades of monitoring.

The correlation analysis was carried out exclusively on the basis of the parameters determined in the final stage of monitoring (2020). Consequently, the statistical relationships presented describe the internal structure of the final data set and do not allow for the assessment of the modification of these relationships during the evolution of the experiment. The extension of the periodic monitoring of all analyzed parameters will allow, in future research, the development of longitudinal statistical models.

5. Conclusions

The present study provides direct experimental evidence of long-term pedoturbation dynamics in a smectitic Vertisol from western Romania, monitored continuously between 1967 and 2020. Based on the integration of granulometric, rheological, and mechanical data, the following conclusions can be drawn:

1. The soil profile underwent progressive textural homogenization over 53 years, as reflected by the significant reduction in vertical variability of clay content.
2. Bulk density increased systematically, particularly in deeper horizons, indicating structural reorganization and gradual reduction in macroporosity associated with repeated shrink–swell cycles.
3. High plasticity indices ($PI > 35\%$), activity indices close to or exceeding unity, and elevated shrink–swell parameters confirm the dominant control of smectitic mineralogy on the mechanical behavior of the profile.
4. Strong positive correlations between clay content and rheological indicators demonstrate the direct influence of fine fraction dynamics on volumetric contraction and expansion processes.
5. The redistribution of inert polyester markers buried at depths up to 150 cm demonstrates a complete turnover of the soil profile within an estimated 40–50-year cycle, with an average upward displacement rate of approximately 2 cm year^{-1} .
6. The results support a conceptual model in which cyclic wetting–drying, coupled with smectite hydration and internal stress development, drives a slow but continuous vertical mass flux within the Vertisol.
7. These findings have important implications for agricultural management, infrastructure stability and hydrological modeling in expansive clay soils, particularly under scenarios of increasing climatic variability.

By providing rare long-term experimental data, this study contributes to a better understanding of internal soil mass dynamics and reinforces the view of Vertisols as highly active pedological systems characterized by multidecadal renewal cycles.

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Abbreviations

The following abbreviations are used in this manuscript:

BD	Bulk density
e	Void ratio
w _P	Plastic limit
w _L	Liquid limit
PI	Plasticity index
A	Activity index
VS	Volumetric Shrinkage
FS	Free swelling
SSI	Shrink–swell index
c	Cohesion
φ	Internal friction angle
E	Deformation modulus
P _{conv}	Conventional pressure
XRD	X-ray diffraction
DTA	differential thermal analysis

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