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MODELLING WATER FLOW IN FREE DRAINAGE LYSIMETERS AND SOILS WITH DIFFERENT ANISOTROPY

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Original scientific paper
In this paper a numerical model was used to evaluate water flow in free drainage lysimeters with respect to soil anisotropy (hydraulic conductivity). Lysimeters were installed in undisturbed soil profile on two soil types with different anisotropy (low and high). The soil types were classified as Luvic Stagnic Phaeozem Siltic and Haplic Gleysol Calcaric Eutric Siltic. For numerical simulation the HYDRUS-2D software was used, which solves water flow with the Richard's equation and uses the Galerkin's finite element method for space discretization. Simulations have shown evident differences in water flow in the case of different anisotropy. Free drainage lysimeters can be useful devices to collect water in soil profile and to describe water flow in heterogeneous soil, but anisotropy has a large influence on efficiency.

Keywords: *anisotropy, HYDRUS-2D, lysimeter, numerical modeling, water flow*

Modeliranje toka vode na procjednim lizimetrima i tlima s različitom anizotropijom

Izvorni znanstveni članak
U ovom radu numerički model primijenjen je za procjenu toka vode u procjednim lizimetrima s obzirom na anizotropiju tla (hidrauličku vodljivost). Lizimetri su postavljeni u tlo u neporemećenom stanju na tlima s različitom anizotropijom (niskom i visokom). Tipovi tla su klasificirani kao močvarno, glejno hipoglejno i močvarno glejno amfiglejno – vertično. Numeričke simulacije su provedene pomoću HYDRUS-2D softvera koji rješava tok vode pomoću Richardsove jednadžbe i koristi Galerkinov tip konačnih elemenata za diskretizaciju prostora. Simulacije su pokazale značajnu razliku toka vode obzirom na anizotropiju. Procjedni lizimetri mogu biti korisni uređaji za sakupljanje vode i opisivanje toka vode u heterogenim tlima, no međutim, anizotropija ima veliki utjecaj na njihovu efikasnost.

Ključne riječi: *anizotropija, HYDRUS-2D, lizimetar, numeričko modeliranje, tok vode*

1 Introduction

Understanding of leaching processes has improved significantly during the past decades for which the credit goes mainly to numerical models. The models are able to simulate water flow in different soil types under different condition. However, the performance of model depends on accurate input data collected in the field or by the laboratory methods. Lysimeter can simulate actual field condition and for that reason is used for scientific studies of the fate and movement of water through different soil types [1].

Lysimeter can be classified according to different criteria such as type of soil block used (monolithic or reconstructed), drainage (drainage by vacuum or under natural gradient), or weighing or non-weighing lysimeters [2, 3]. In soil science it is often ideal to use a monolithic soil core in undisturbed condition [4, 5]. In free drainage lysimeters water is allowed to drain freely through the soil profile under gravity and the main advantage is that they are easy to install and it is much cheaper than the monolith lysimeters [6]. The problem of free drainage lysimeters is that the lower boundary condition is exposed to atmospheric pressure and a saturated zone must occur at the bottom of the lysimeter before the leachate can be collected. This kind of condition can occur more often in soils with high clay content which has greater water storage capacity, which we have in experimental area in Eastern Croatia [7]. The hydraulic conductivity of soil, K_s, is one of the most important soil properties which control the ground water flow. This property depends on physical properties of the soil i.e. soil texture, particle arrangement, and structure as well as the properties of the fluid i.e. fluid density, acceleration due to gravity and dynamic viscosity and can vary in space, time, and flow direction. In anisotropic soils, the vertical saturated hydraulic conductivity, K_v, of a given volume of soil differs from the horizontal saturated conductivity, K_h, of the same volume of soil [8]. Typically, anisotropy of hydraulic conductivity produced by consolidation of natural clays is in the range of 1,1–3. The discrepancy arises from particle clustering and irregularities in particle packing. Although somewhat higher levels of anisotropy may exist as a consequence of lamination within individual beds, values >10 that are known to exist on the formation scale are produced by strong contrasts between the hydraulic conductivities of interlayered beds [9]. The numerical simulations of transient water flow in field condition in two types of soil with heavier texture and very large differences in anisotropy were performed. In this study mathematical model for water flow was numerically solved with HYDRUS-2D [10] which has been previously tested on heavy soil types and zero tension lysimeters [11]. Main goal of this research was to evaluate (i) water flow in two soil types with different anisotropy, and to evaluate (ii) lysimeter efficiency in different soil condition.

1.1 Experimental site

The research area is located in the Biđ field in Eastern Croatia. The area is geographically situated between 18°15' to 19°00' east longitude and 44°45' to 45°20' north. Climatic data are collected from the Gradište meteorological station (45°09' N and 18°42' E). The study was performed on two types of soil. Soil types were classified according to WRB classification as Luvic Stagnic Phaeozem Siltic (Horizons: Ap-Bt-Bg-C, Soil-1) and Haplic Gleysol Calcaric Eutric Siltic (Horizons: Ap-

Bg-Cr-Cg, Soil-2) (Fig. 1). Detailed physical properties of each soil type are shown in Tab. 1.

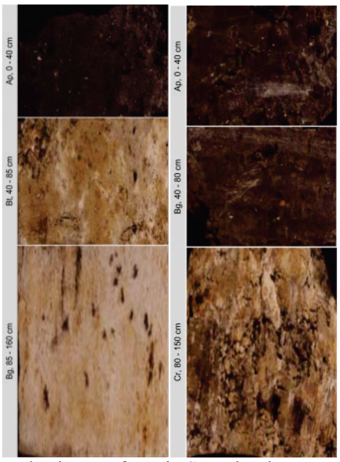

Figure 1 Different horizons of Luvic Stagnic Phaeozem Siltic (left) and Haplic Gleysol Calcaric Eutric Siltic (right)

The 100 cm^3 undisturbed soil samples were used to measure the bulk density and soil hydraulic properties (water retention and hydraulic conductivity). Vertical conductivity, K_v, was measured using the falling head method [12]. The saturated water content, θ_s, was measured using the saturation pan. The points of the soil water retention curve were measured using pressure plate apparatus [13]. Applied pressure heads were 33, 100, 625 and 1500 kPa. Soil texture was determined with pipette method [14], which determines the percentage of each fraction (% sand, % silt and % clay particles). Horizontal saturated hydraulic conductivity, K_h, was determined on field with Auger-Hole method [15]. Groundwater levels were measured on daily basis on installed lymnigrapfs.

While the saturated water content, θ_s, was measured, the remaining parameters of the soil water retention curve (2) (θ_r, α, and n) were optimized using the RETC software [16] (Tab. 2) by fitting measured data. Unsaturated hydraulic conductivities (3) were predicted using the θ_s, θ_r, and n values, the measured values of saturated hydraulic conductivities, K_v and K_h, and the pore connectivity parameter which equaled an average value for many soils (l = 0,5) [17].

Table 1 Soil texture and physical properties of two different soil types

	Depth (cm)	Sand / %	Silt / %	Clay / %	θ_s (cm^3/cm^3)	*BD* (g/cm)	K_s (cm/s)	TH33	TH625	TH1500
Soil 1	0 ÷ 40	13	65	22	0,38	1,59	0,00012	0,349	0,226	0,203
	40 ÷ 75	4	63	33	0,37	1,57	0,00017	0,34	0,223	0,2
	75 ÷ 105	14	54	32						
	105 ÷ 150	5	69	26						
Soil 2	0 ÷ 30	5	54	41	0,42	1,37	0,00013	0,393	0,28	0,226
	30 ÷ 70	3	54	43	0,41	1,55	0,00016	0,373	0,273	0,211
	70 ÷ 100	3	54	43						

Table 2 Data that was optimized with RETC software

	Depth (cm)	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	K_h (cm/day)	K_v (cm/day)	Alpha	*n*
Soil 1	0 ÷ 40	0,38	0	0,000318	0,000173	0,00261	1,17607
	40 ÷ 75	0,37	0			0,00263	1,17177
Soil 2	0 ÷ 30	0,42	0	0,00175	0,000127	0,00136	1,19612
	30 ÷ 70	0,41	0			0,00212	1,17585

2 Mathematical model
2.1 Flow equation

In general form, the Richard's equation is given by:

$$\frac{\partial \theta}{\partial t} = \nabla (K\nabla h + K\nabla z) - S_w, \quad (1)$$

where θ is the volumetric water content, t is time, ∇ a vector differential operator, K the hydraulic conductivity, h is pressure head, z is gravitational head, and S a sink term accounting for root water uptake. K and S can be functions of position, θ or h, and time.

Soil hydraulic functions were described using the van Genuchten-Mualem model [18], which is defined as follows:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m} \quad \text{for } h < 0 \quad (2)$$

$$\theta(h) = \theta_s \text{ for } h \geq 0$$

$$K(h) = K_s S_e^l (1 - (1 - S_e^{\frac{1}{m}})^m)^2 \quad (3)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

$$m = 1 - \frac{1}{n};\ \ n > 1 \quad (5)$$

where $\theta(h)$ and $K(h)$ are volumetric water contents and unsaturated hydraulic conductivities at the soil water pressure heads of h, respectively; θ_r and θ_s denote residual and saturated water contents, respectively; S_e is the effective saturation, K_s is the saturated hydraulic conductivity, α is the inverse of air-entry value or (bubbling pressure, n is the pore size distribution index, and l is the pore connectivity parameter.

2.2 Initial and boundary conditions

The atmospheric boundary conditions (Fig. 2) were set at the top. The grown crop was corn (Zea mays L.) and the evapotranspiration was calculated from Feddes' parameters selected from the database [19]. Evapotranspiration was calculated according to the Penman-Monteith equation:

$$ET_{\mathrm{o}} = \frac{0{,}408 \cdot \Delta \cdot (R_{\mathrm{n}} - G) + \gamma \cdot \frac{900}{T+23} \cdot u_2 \cdot (e_{\mathrm{s}} - e_{\mathrm{a}})}{\Delta + \gamma \cdot (1 + 0{,}34 \cdot u_2)}, \tag{6}$$

where ET_{o} is potential evapotranspiration, R_{n} is net radiation at the crop surface, G is soil heat flux density, T is air temperature at 2 m height, u_2 is wind speed at 2 m height, e_{s} is saturation vapour pressure, e_{a} is actual vapour pressure, $e_{\mathrm{s}} - e_{\mathrm{a}}$ is saturation vapour pressure deficit, Δ is slope vapour pressure curve, and γ is psychrometric constant. Measured pressure heads at the bottom (lymnigrapfs data) were defined at the bottom. No water flux was defined for both lateral boundaries, and the bottom and sides of the lysimeter plate. The seepage face was applied at the top of the lysimeter plate. Initial conditions were defined as hydrostatic pressure head distribution with initial pressure heads measured at the bottom.

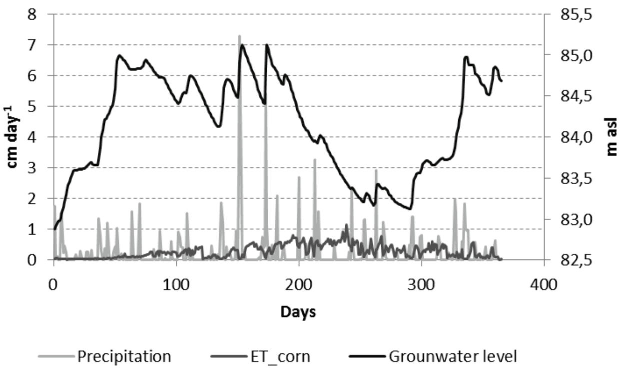

Figure 2 Daily evapotranspiration, precipitation and groundwater level for simulation period

3 Numerical model

Water flow was simulated using the HYDRUS-2D model which numerically solves Richard's equation for saturated-unsaturated flow in two dimensions using the Galerkin type finite element scheme. The HYDRUS-2D model can solve non-uniform and anisotropic flow domains, delineated by irregular boundaries. The flow domain is represented by a finite element grid, where material properties such as hydraulic characteristics must be provided for each computational node and a degree of anisotropy must be assigned to each element in the flow domain. The model can handle atmospheric boundary conditions given by meteorological values at time intervals. From the given table of main crops and the data about root depth and its density in the modelling domain, the model calculates the actual evapotranspiration taking into account the prevailing root zone soil moisture conditions. The size of the model domain for both sites was 300 cm in width and 200 cm in depth. The finite element grid consisted of a total of 5278 nodes and 10 310 elements (Fig. 3). Two layers were assumed for each soil type. The grid was spaced 4 cm at the top, 7 cm at the bottom of domain and 2 cm around the lysimeter plate. Time simulation period was 365 days. In this paper, simulations are presented for the days when it was ≥ 2 cm of precipitation. Time discretization was set as follows: initial time 0,0001 day, minimum time step 1e–005, and maximum time step 5 days. The model was run for 365 days starting on January 1st, 2010.

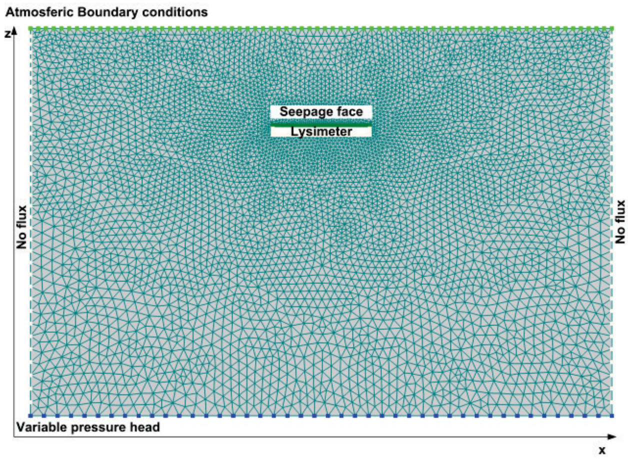

Figure 3 Domain properties

4 Results and discussion

Measurements of hydraulic conductivity showed a great difference in anisotropy values in two types of soil (Fig. 4). Average anisotropy in soil-1 was 1,84 ($K_{\mathrm{v}} : K_{\mathrm{h}}$) which had lesser clay content (30 %), and average anisotropy in soil-2 was 13,84 which is a very high value and it is normal for some types of clay soil with heavier texture (for the 0 ÷ 2 depth).

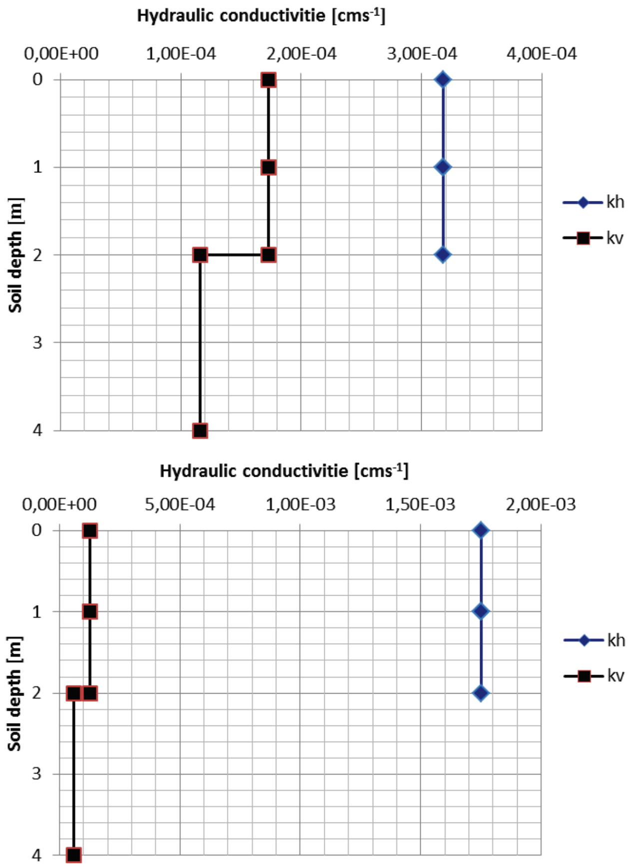

Figure 4 Difference in anisotropy at soil-1 and soil-2 up to 2/4 m depth

Fig. 4 shows the difference in K_{v} and K_{h} in two analysed soil types up to 2 m depth (K_{h}) and 4 m (K_{v}). Hydraulic conductivity anisotropy produced by consolidation of natural clays is in the range of 1,1 ÷ 3 and does not reach the high levels predicted by simple models of clay particle reorientation. The discrepancy arises from particle clustering and irregularities in particle packing. Although somewhat higher levels of anisotropy may exist as a consequence of lamination, values > 10 that are known to exist on the formation scale are produced by strong contrasts between the hydraulic conductivities of interlayered beds.

Fig. 5 shows water content in two different soils from which can be seen the greater water content in Haplic Gleysol. Free drainage lysimeters collect water only when the pressure head above the plate reaches values ≥0 cm [20]. In all other cases the water can circumvent the lysimeter. Only in soils with low hydraulic conductivities close to saturation water will be collected regularly. The total outflow from lysimeter installed in Luvic Stagnic Phaeozem was 29,90 cm and for Halic Gleysol 32,28 cm. This also indicates the greater collection efficiency in heavier type of soil (with more than 40 % of clay).

The output data from numerical model shows the pressure head for the days when the rain intensity was more than 2 cm of rain, e.g. when the precipitation had high intensity – in that period one can expect higher influence of soil type and lysimeter plate on the water flow.

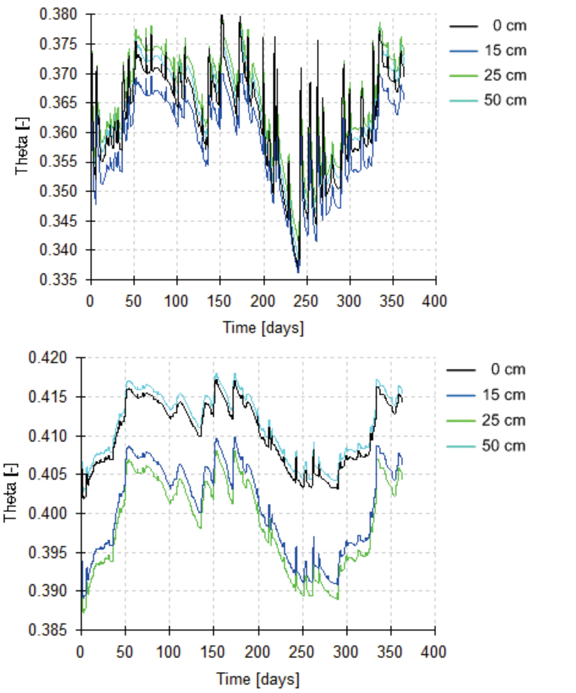

Figure 5 Water content in Luvic Stagnic Phaeozem (upper) and Haplic Gleysol (lower) at different depth

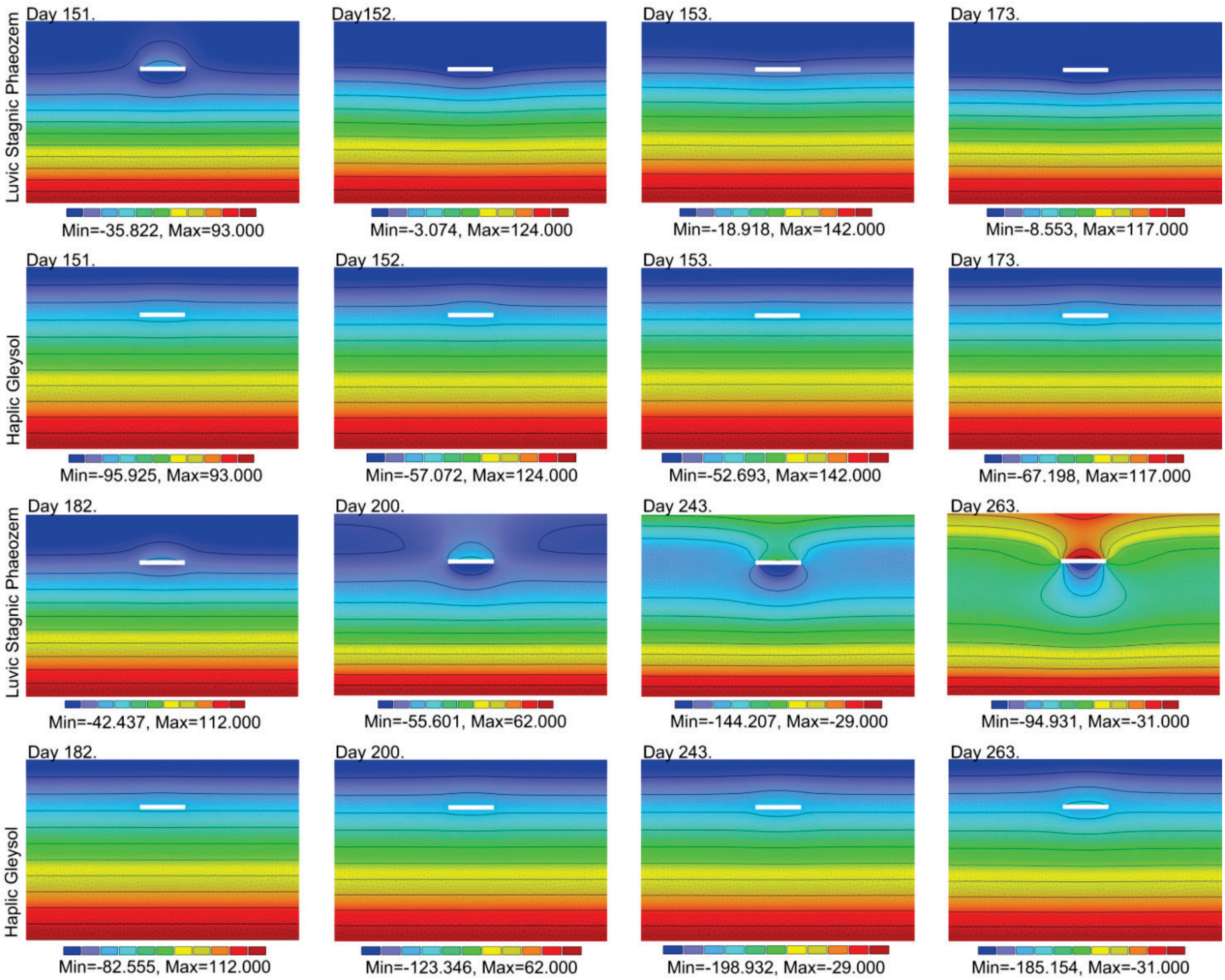

Figure 6 Simulated pressure head in Luvic Stagnic Phaeozem and Haplic Gleysol in two dimensional transect

Fig. 6 shows simulated domain in two soil types and influence of each on water flow above and below the lysimeter plate. Some irregularities that can be distinguished in the simulation results are the consequence of the interaction of two horizons or interactions between percolating water and ground water. From the picture it can be seen that the lysimeter plate had minor influence in Haplic Gleysol because of its greater water storage capacity and larger anisotropy in which the horizontal conductivity is >10 times greater than vertical. This can be best seen on the days 243 and 263 when the intensity was high and the soil was not previously saturated due to a dryer period of the year. Because of differences in water potential, the lysimeter plate influence on the water flow behaviour above the plate in Luvic Stagnic Phaeozem soil.

It can be seen that the top horizons have more water storage capacity because they lie above the horizons with heavier texture and also in that area is the main root system that can hold water (the model does not take into account the soil structure).

5 Conclusion

Free drainage lysimeters can be useful devices to collect water in soil profile and to describe water flow in heterogeneous soil, but their efficiency depends on the texture of the soil and also on the anisotropy. Modelling with HYDRUS-2D has shown large differences in water content and pressure head in different soil types having different anisotropies. Luvic Stagnic Phaeozem soil with lower anisotropy (1,84) has shown greater influence on water flow during high intensity precipitation. Lysimeter plate influenced the pressure head above and below the plate especially in a dryer period with high intensity rainfall. Haplic Gleysol showed greater water storage capacity and minor influence on pressure head during the simulation period. Very high anisotropy (13,84) is the main reason for the uniform pressure head distribution during the entire year.

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