Approximation of landfill drainage discharge by De Zeeuw-Hellinga model, and its verification on sanitary landfill of solid domestic waste

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ABSTRACT

The goal of this work is to present a suitable tool or model for the evaluation of the internal landfill water discharge, in relation to the basic design parameters of internal landfill drainage system and other processes. De Zeeuw-Hellinga's drainage theory fulfils those requirements. De Zeeuw-Hellinga's drainage intensity factor takes in basic design parameters of internal landfill drainage system and also hydro-physical properties of the collected waste. The drainage theory calculates with landfill internal water recharge to the drainage system within a certain time interval. In practice this method was successfully verified in a sanitary landfill of solid domestic waste in Osecna (a region near Liberec, Czech Republic). The comparison of the real data of the measured values of the internal landfill water discharges with calculated values, demonstrated eligibility of the use of De Zeeuw-Hellinga drainage theory as a good instrument for approximation of the internal landfill water discharges. This tool needs only a minimum of information and can be applied for the evaluation of basic design parameters of the internal landfill drainage system, for the design of the landfill reservoir capacity, and also for description of the landfill hydrology processes.

Keywords: landfills; drainage discharge; internal landfill water; De Zeeuw-Hellinga drainage theory; drainage system

Water management of landfills is one of the most important factors, interrelated with environmental protection. A correct design of the landfill's technical measures, especially the landfill internal drainage system, should be based on the theory of landfill hydrology, where the drainage discharges of internal landfill waters play a key role.

The main function of the internal landfill drainage system is, besides others, to eliminate overpressure of leachate of waste and to lower the total pressure, which affects the base line of landfills, and this method protects the soil environment.

The design of the internal landfill drainage system placed at the bottom of the sanitary landfills of solid domestic waste should be proceeded by a water management project. And should be based on mathematical and physical description of the hydraulic processes inside the landfill body (Stibinger 1994), the hydrological conditions locality, the amount and physical properties of incoming solid domestic waste and last but not least with regard to the way of landfilling.

The way of determining the hydraulic calculations of the drainage discharge from the internal landfill drainage system in the bottom of the sanitary landfill, were, in this case, based on the De Zeeuw-Hellinga drainage theory, where the non-steady saturated drainage flow conditions are assumed (Ritzema 1994). The results were verified and compared to the actual data from the sanitary landfill of solid domestic waste in Osecna location, situated in the Northern Bohemia.

MATERIAL AND METHODS

Study area

The sanitary landfill of solid domestic waste Osecna, situated near the location Osecna, region Liberec, Northern Bohemia, opened in December 1995. It was assumed that the landfill would be finished and operating at the end of 2004.

The landfill location is situated in the Luzicke Mountains with an altitude of 770–800 m above sea level, in the forested territory of the Ještěd Mountains base. The long-term annual average of precipitation amounts to 910 mm, long-term annual average of temperature amounts to about 7.3°C.

The effective area S (m^2), delimited for waste landfilling during the years 1997 and 1998, amounted to about 2.14 hectares (21 400 m^2). The landfill's internal drainage system, placed at the bottom of landfill body, comprised the drain spacing L (m)

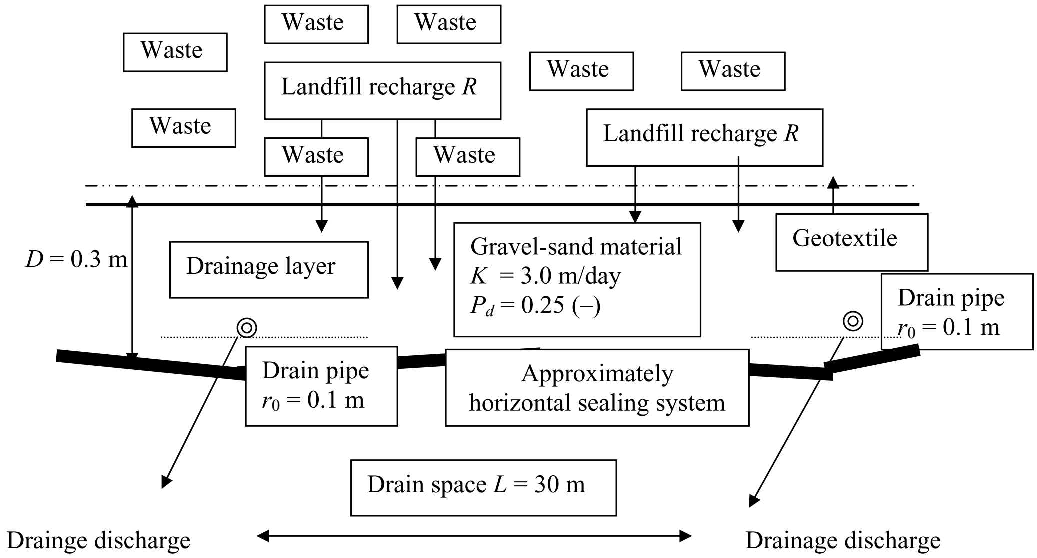

Figure 1. Simplified scheme of the internal landfill drainage system inclusive of the landfill drainage discharge and recharge processes at the Landfill Osecna, Northern Bohemia, Czech Republic, 1998

= 30, average of the thickness of the gravel drainage layer D (m) = 0.3 and diameter of the lateral drains r_0 (m) = 0.1. Plastic perforated drainage pipes were placed under the drainage layer on the approximately horizontal landfill base liner. Saturated hydraulic conductivity of the gravel-sand material of drainage layer K = 3.0 m/day, drainable pore space P_d = 0.25 (–), (Figure 1).

The base liner of the sanitary landfill Osecna is approximately horizontal. The slope of the base with plastic sealing foil is neglected. This fact is corresponds with the premises of the De Zeeuw-Hellinga's drainage theory, which is based on, besides others, on a presence of the approximately horizontal impervious layer. In the case of a strongly sloped landfill base liner system, other models and other methods will have to be applied (D'Antonio and Pirozzi 1991, McEnroe 1992, Upadhyaya and Chauhan 2001).

De Zeeuw-Hellinga theory

To simulate the landfill leachate rate, in this case actually the landfill drainage discharge q (m/day), during a period with a non-uniform distribution of landfill recharge R (m), the period was divided into time intervals of equal length (day, month, year).

De Zeeuw and Hellinga discovered (Ritzema 1994), that the change in the drainage rate is proportional to the excess drainage rate ($R - q$) (m/day) if the recharge R (m) in each time-interval is assumed to be constant. De Zeeuw-Hellinga drainage intensity factor a (per day) = $\pi^2 KH/(P_d \times L^2)$ represents the constant of proportionality and depends on the parameters of pipe drainage system and on the position of the impervious layer (Dieleman and Trafford 1976), where: a = De Zeeuw-Hellinga drainage intensity factor (per day); L = drain spacing (m); P_d = drainable pore space of drainage layer (–); K = hydraulic saturated conductivity of the gravel-sand material of drainage layer (m/day); H = average depth of aquifer (m).

In this case, drainage intensity factor also express the hydraulic efficiency of the landfill internal drainage system, which is situated at the bottom of landfill body. Then the basic equation can be formed as:

$$\frac{dq}{dt} = a\,(R - q) \qquad (1)$$

After integration between the limits $t = t$, $q = q_1$ and $t = t - 1$, $q = q_{t-1}$ can be written:

$$q_t = q_{t-1}\,e^{-adt} + R\,(1 - e^{-adt}) \qquad (2)$$

where: q = landfill drainage discharge (m/day); ∂q = change in the landfill drainage discharge (m/day); q_t, q_{t-1} = landfill drainage discharge in time-interval t, $t - 1$ (m/day); $\partial t = t - (t - 1)$ time interval (day); R = recharge of percolation water of landfill, constant in time interval (m).

Water balance equation for landfills

The recharge of the percolation water of landfill R (m) to the internal drainage system at the bottom of the landfill body, can be derived from the

$\sum_{i=1}^{n} r_i$ series of the cumulative values of recharges (m), which was constructed by help of the simplified water balance equation, formed as:

$$\sum_{i=1}^{n} r_i = \sum_{i=1}^{n} S_i + \sum_{i=1}^{n} I_i - \sum_{i=1}^{n} E_i - \sum_{i=1}^{n} O_i - V \sum_{i=1}^{n} W_i \qquad (3)$$

where:

I = interval in the tested period

N = total number of intervals in the tested period

$\sum_{i=1}^{n} r_i$ = series of the cumulative values of recharges in tested period (m)

$\sum_{i=1}^{n} S_i$ = series of the total precipitation amounts in tested period (m)

$\sum_{i=1}^{n} I_i$ = series of the total landfill irrigation amounts in the tested period (m)

$\sum_{i=1}^{n} E_i$ = series of the total landfill evaporation amounts in tested period (m)

$\sum_{i=1}^{n} O_i$ = series of the total quantity of the landfill surface run-off in tested period (m)

$V\sum_{i=1}^{n} W_i$ = series of the total wastewater retention capacity amounts in tested periods (m)

V = water storage capacity or drainable pore space of the domestic waste (% of volume).

Parameter W (m) represents the amount of waste in length units and can be approximated by expression $W = (N/G)/S$ where N is the amount of waste in tons, G represents the density of waste in ton per volume and S (m^2) is area delimited for waste landfilling. Because the series of the cumulative values of recharges $\sum_{i=1}^{n} r_i$ (m) represents in reality cumulative curve, the values of the recharges of the percolation water of landfill R (m) for individual corresponding time interval [$\partial t = t - (t - 1)$] can be derived by equation (4).

$$R = \frac{\partial(\sum_{i=1}^{n} r_i)}{\partial t} \quad \text{(m)} \qquad (4)$$

If the expression

$$\frac{\partial(\sum_{i=1}^{n} r_i)}{\partial t} \leq 0, \text{ then } R = 0.$$

From the known values of the recharges R (m) and by the application of the De Zeeuw-Hellinga drainage theory, the landfill leachate rate q_t (m per day) was estimated according to equation (2) in the each time interval ∂t.

Experimental set up

All the data, which are necessary for the calculation of the parameters of equation (3), (4) and for an approximation of the De Zeeuw-Hellinga drainage intensity factor (day^{-1}) and finally for the estimation of the landfill drainage discharge q_t (m/day) according to equation (2), were used from the monthly hydrological records of the location Osecna, region Liberec and from the landfill Osecna's working records (monthly data) and from the monitoring of the landfill Osecna. In accordance with De Zeeuw-Hellinga drainage theory is assumed, that all values in selected time-interval (month) are constant.

Results of hydraulic approximations

For a description of the hydraulic behavior of drainage discharge (landfill leachate) at the bottom of sanitary landfill Osecna by De Zeeuw-Hellinga drainage theory, was chosen in the year 1998, the third year of the landfill running. The actual hydrological and working data from landfill Osecna during the year 1998 are presented in Table 1 and viewed on Figure 2.

The water storage capacity V (% of volume) of the domestic waste and the waste density G (t/m^3) in the conditions of the landfill Osecna, were approximated by the field experimental measure-

Table 1. Measured characteristics from the landfill Osecna (solid domestic waste), location Osecna, Northern Bohemia, Czech Republic, 1998

Month	Precipitation (mm)	Domestic waste (t)	Drainage discharge (mm)
1	54.0	15 014	4.5
2	53.5	11 718	13.0
3	102.0	17 162	24.0
4	19.5	23 815	15.0
5	22.5	23 626	5.6
6	73.0	23 758	4.0
7	69.0	104 138	9.0
8	36.5	23 266	2.3
9	100.0	21 405	32.5
10	80.3	18 457	25.4
11	66.1	17 823	26.6
12	24.4	12 924	2.3
Total	700.8	313 100	164.2

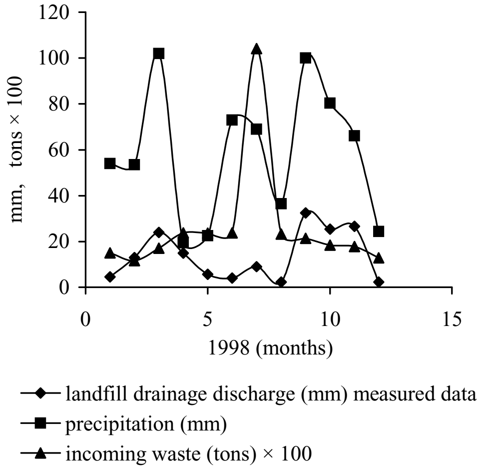

Figure 2. Measured data from the landfill Osecna (solid domestic waste) Northern Bohemia, Czech Republic, 1998

ment, laboratory testing (Kutílek and Nielsen 1994, Genuchten and Nielsen 1985) and from the landfill working records as V (% of volume) = 25.0 and G (t/m^3) = 0.85.

The specific hydrological conditions of the territory of the Ještěd Mountains base, the way of landfilling of the domestic waste and the handling of percolation waters from landfill (landfill irrigation) in the landfill Osecna, allowed to reduced the water balance equation (3) in tested period in the shape:

$$\sum_{i=1}^{n} r_i = \sum_{i=1}^{n} S_i - V \sum_{i=1}^{n} W_i \qquad (5)$$

By reduced water balance equation (5), were approximated the cumulative values of the landfill $\sum_{i=1}^{n} r_i$ recharges (mm) from landfill Osecna, which in reality form cumulative curve (Table 2). In Table 2 are also presented the cumulative values of precipitation, the total amounts of the incoming domestic waste and cumulative values of the wastewater retention capacity (Figure 3). All this data created the input parameters of the reduced water balance equation (5) for approximation of the cumulative values of the landfill recharges.

The results of the initial hydraulic calculations indicate the value of the average depth of aquifer H (m) = 0.14 (lateral drains are placed almost to an impervious sealing system), and indicate a value of the De Zeeuw-Hellinga drainage intensity factor a (day^{-1}) = 0.0184 = 0.552 (month^{-1}).

By the known constant values of landfill recharge curve R (mm) in the monthly time interval (Figure 3 and Table 3) and from the known value of the De Zeeuw-Hellinga drainage intensity factor a (day^{-1}) = 0.0184 = 0.552 (month^{-1}), were calculated, according to equation (2), the values of the landfill drainage discharge q_t (mm/month) for every month

Table 2. Measured and calculated cumulative values from the landfill Osecna (domestic waste) Northern Bohemia, Czech Republic, 1998

Cumulative values from 12. 1995 to	Precipitation (mm)*	Domestic waste (t)*	Wastewater retention (mm)**	Landfill recharge (mm)**
1997	1640.0	118 313.6	1626.0	13.9
1998 (month) 1	1694.0	119 815.0	1646.7	47.2
2	1747.5	120 986.8	1662.8	84.6
3	1849.5	122 703.1	1686.4	163.0
4	1869.0	125 084.6	1719.1	149.8
5	1891.5	127 447.2	1751.6	139.8
6	1964.5	129 823.0	1784.2	180.2
7	2033.5	140 236.8	1927.3	106.1
8	2070.0	142 563.5	1959.3	110.6
9	2170.0	144 704.0	1988.7	181.2
10	2250.3	146 549.8	2014.1	236.1
11	2316.4	148 332.1	2038.6	277.7
12	2340.8	149 624.5	2056.4	284.3

*measured values, **calculated values

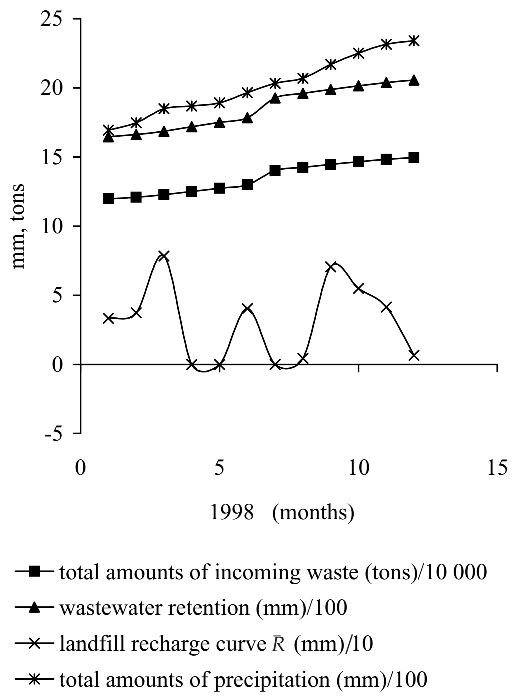

Figure 3. Total amounts of precipitation, incoming waste and total values of wastewater retention capacity with course of the landfill recharge *R*, Landfill Osecna, Northern Bohemia, Czech Republic, 1998

(time-interval t) of the year 1998. In accordance with De Zeeuw-Hellinga's drainage theory, it is supposed that the landfill leachate rate in the corresponding time interval (month) will be constant.

If, for example, q_6 = 26.5 (mm/month), it means, that the total landfill drainage discharge in the June (at 1 month) will be 26.5 mm. The calculated values of the landfill drainage discharge q_t are expressed in mm per corresponding month (time-interval t). The results of the estimations (together with actual monthly measured values of the landfill drainage discharge) are presented in Table 3 and graphically demonstrated in Figure 4.

The values of the recharges of the landfill percolation water R (mm) in the corresponding time intervals with constant length (months) were derived according to equation (4). The results, landfill recharge curve R (mm), are graphically symbolized in Figure 3 and presented in Table 2.

RESULTS AND DISCUSSION

From the comparison of the monthly values of the landfill drainage discharge q_t calculated according to equation (2) for the landfill Osecna conditions, and the actual measured monthly values of the landfill leachate from the same field (Figure 4 and Table 3). It is obvious, that the shape of the curve of equations (2) and the shape of the curve of the actual measured monthly values is identical. Even the certain differences between the curves are apparent.

It seems that the biggest difference of affect is when precipitation is at its maximum level. This means, that the De Zeeuv-Hellinga drainage model

Table 3. Landfill recharge monthly values and landfill drainage discharge – measured and calculated monthly values from the landfill Osecna, (solid domestic waste), Northern Bohemia, Czech Republic, 1998

Month	Precipitation (mm)	Landfill recharge R (mm)	Landfill drainage discharge measured values (mm)	Landfill drainage discharge q_t, calculated values (mm)
1	54.0	33.4	4.5	20.0
2	53.5	37.4	13.0	27.4
3	102.0	78.4	24.0	49.1
4	19.5	0.0	15.0	28.2
5	22.5	0.0	5.6	16.2
6	73.0	40.3	4.0	26.5
7	69.0	0.0	9.0	15.2
8	36.5	4.5	2.3	10.7
9	100.0	70.6	32.5	36.2
10	80.3	55.0	25.4	44.2
11	66.1	41.6	26.6	42.8
12	24.4	6.6	2.3	27.4
Total	700.8	367.8	164.2	343.9

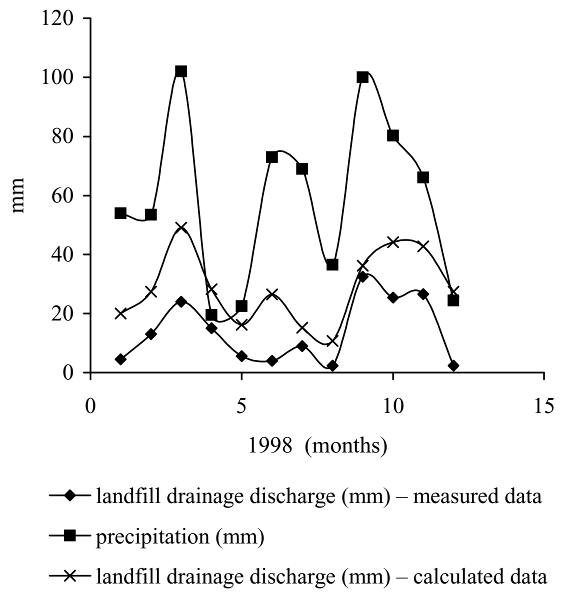

Figure 4. Comparison between the measured and calculated values of the landfill drainage discharge, Landfill Osecna, Northern Bohemia, Czech Republic, 1989

reacts better for precipitation than for an incoming amount of domestic waste, which creates the wastewater retention capacity of the landfill body and reduces the direct precipitation effects.

The use of the De Zeeuv-Hellinga way of estimation will probably be more effective at the beginning of landfilling, where the impact of precipitation is strong and the landfills are especially in this period, more unstable during the precipitations and heavy rains action. De Zeeuv-Hellinga's drainage theory also supposes, the relatively large distance between drain pipe level and impervious layer. This requirement was not completely carried out in the case of the landfill Osecna.

On the other hand, it has to be noted that the modeling of the time series of the landfill leachate during the landfilling is very difficult and complicated. The mathematic-physical description of the incoming waste compacting and increasing in connection with hydrological processes can be very exacting, especially for long period of landfilling.

And from this conclusion the De Zeeuv-Hellinga drainage model is a suitable tool for landfill drainage discharge approximation in a selected (critical) time period of the landfilling. It also appears that the De Zeeuv-Hellinga drainage model approximation yields the slightly higher values of the landfill drainage discharges then the actual data, so that is why the application of its results can guarantee the more effective probability of the internal landfill drainage system design.

The correct estimation of landfill drainage discharge during the landfilling has a key role in landfill hydrology and landfill drainage policy and is necessary for the impact evaluation of the existing internal landfill drainage systems or for the calculation of parameters of a new one.

Verification of the simple analytical De Zeeuv-Hellinga solution as applied to estimate the landfill leachate rate from the internal drainage landfill system at the bottom of landfill, formed in equation (1) and (2), showed a good conformity between calculations and measured data under the unsteady state saturated landfill drainage flow (leachate) in the bottom of landfill body.

The estimation of the internal landfill water drainage discharge is mostly defined by the term of landfill laechate and it means the internal landfill water flow-of (discharge) by drainage system, situated at the bottom of landfill. It is not concerned with any leakage or percolation of internal landfill waters via the sealing system placed at the bottom of landfill.

The problem of the evaluation of landfill water drainage discharge, or landfill laechate, has been described and solved by many authors, whose works are more or less comparable with author's experiment presented in this article.

From the former works it is necessary in this case to talk about (McEnroe 1989), (D'Antonio and Pirozzi 1991) or (Blakey 1992). The first two works solve the leachate collection in landfills on the slope of the landfill bottom by the hydraulic methods. This is the main difference in comparison with our contribution, because sanitary landfill Osecna disposes by the approximately horizontal impervious layer.

It should be noted that the works of McEnroe (1989, 1992) are especially important and create the basis for calculations of the transmissivity of the internal landfill drainage systems layers.

On the other hand, Blakey (1992) comes out from balance methods of landfill hydrology.

Some of the present products for the evaluation of the landfill leachate (discharge), especially in the form of calculators are very operative, very user friendly and are based just on the solution of the McEnroe's equations (Richardson et al. 2002).

The research results of the TENAX Corporation with Vice President of Engineering Dr. A. Zhao, were in respect to the corresponding US standards.

And last but not least the US EPA's HELP (Hydraulic Evaluation of Landfill Performance) model (Schroeder et al. 1994, Berger 2003) is a tool for analyzing water balance in landfill lining and capping systems. However, a proper simulation of geocomposite lateral drainage layers in the HELP Model is not well established. A misinterpretation of the model's output results could lead to an unsafe design of the drainage systems in landfills.

The comparison of the instruments mentioned above with the application of De Zeeuw-Hellinga's theory for landfill leachate (drainage discharge) evaluation described in this article is very difficult and complicated.

The tools for this type of HELP model need relatively a larger range of input information to give a complex figure of the landfill hydrology processes in connection with landfill lining and landfill capping.

The calculators, based on the application of the McEnroe's equations, are set up to determine the value of transmissivity of the internal landfill drainage layers and are indispensable for the landfill engineering practice.

The tools are the HELP model, various calculators, and the other similar products that mostly come out from the steady state of saturated landfill drainage flow, in contrast to the De Zeeuw-Hellinga's drainage (landfill leachate) application which works under the transient (unsteady state) saturated landfill drainage flow and requires only the minimum of the input information to approximate the values of the landfill leachte rate.

This first introduced that De Zeeuv-Hellinga's landfill drainage discharge approximation should be used as a simple tool for immediate estimation of the values of landfill drainage discharge for certain selected time intervals before being further corrected and specified.

It should serve as a tool what requires only minimum amount of information (the basic hydrology data, working data of the waste collecting and landfill bottom drainage system basic design parameters).

The verification of the field test results and measurements reflects that the possibilities of application and their benefits, mentioned above, can be fulfilled.

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ABSTRAKT

Odhad drenážních odtoků vnitřních skládkových vod pomocí De Zeeuw-Hellingova modelu s ověřením na řízené skládce tuhých domovních odpadů

Cílem práce bylo představit vhodný nástroj či model pro odhad drenážních odtoků vnitřních skládkových vod, který by zohledňoval mimo jiné také návrhové parametry vnitřního drenážního systému skládky. Drenážní De Zeeuw-Hellingova teorie tento požadavek splňuje. V intenzitním faktoru odvodnění podle De Zeeuw-Hellingovy teorie jsou zahrnuty návrhové parametry vnitřního drenážního systému skládky a také hydro-fyzikální vlastnosti ukládaného odpadu, drenážní teorie pak počítá s přítokem vnitřních skládkových vod do drenážního systému v určitém časovém intervalu. Tato metoda byla v praxi úspěšně ověřena na řízené skládce tuhých domovních odpadů Osečná (Liberecký kraj). Porovnání skutečných naměřených údajů drenážních odtoků vnitřních skládkových vod s vypočtenými hodnotami prokázalo oprávněnost použití drenážní De Zeeuw-Hellingovy teorie jako metody pro odhad drenážních odtoků vnitřních skládkových vod, jež vyžaduje pouze minimum informací a kterou je možné použít pro stanovení návrhových parametrů vnitřního drenážního systému skládky, návrhu kapacity bezodtoké drenážní jímky a také pro popis hydrologických procesů (ve skládkování) skládky.

Klíčová slova: skládky; drenážní odtok; vnitřní skládkové vody; De Zeeuw-Hellingova drenážní teorie; drenážní systém

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