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The relationship between the unsaturated permeability coefficients (UPC) determined and oxidation-reduction potential (ORP) in the subsurface wastewater infiltration system (SWIS)

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ABSTRACT

The estimation of unsaturated permeability coefficients (UPC) is of great importance on the properties of the matrix. Aim to study the relationship between the UPC and oxidation – reduction potential (ORP) in different matrix depths in the subsurface wastewater infiltration system (SWIS) and provide scientific basis for regulating SWIS and increasing pollutant removal, a test experiment of simulating the SWIS which included an inflow period (12 h) and a drying period (12 h) in one cycle was designed with a hydraulic load of 0.10 $m^3\cdot(m^2\cdot d)^{-1}$. Results investigated that ORP could increase with UPC increasing in 70 and 115 cm and decrease with the UPC increasing in 100 and 130 cm matrix depths. Phenomena indicated that capillary action could affect UPC and ORP obviously. Moreover, the existence of oxygen and low volumetric water contents could impose UPC and ORP. UPC in the 100 cm matrix depth below proved that anaerobic area could be found in aerobic environment under alternation conditions. UPC in different matrix depths of a satisfactory SWIS could change from 2.49×10^{-7} to 1.16×10^{-3} $cm\cdot s^{-1}$. Treated water met reused requirements and no clogging was found.

Keywords: Wet-dry alternation condition; UPC; ORP; SWIS

1. Introduction

Subsurface wastewater infiltration systems (SWISs) are eco-treatment systems with both anaerobic and aerobic processes. The main process of wastewater treatment is that the wastewater is pretreated by sedimentation and then drained into a water dispersion pipe and finally evenly infiltrated into the aerobic filter layer and diffused under the action of capillary force and gravity of the soil [1]. The pollutants are removed by biological, physical and chemical reactions and treated water is collected by a collecting pipe. SWISs are considered to be satisfactory biological reactors with low construction, operation expenses, satisfactory pollutant removal performances and less cost in maintenance need [2,3]. Furthermore, treated wastewater by means of SWISs meets water reclamation and reuse requirements.

The SWIS is an unsaturated sustainable wastewater treatment system, consisting of solid particles, water and air [4]. In terms of unsaturated soils, the permeability function is vital hydraulic properties required for analyzing whether the system runs normally [5]. During the long-term seepage process, the growth the microorganisms and the precipitation of pollutants cause clogging in both capillary action area and filtration action area of the system [6]. Relative displacements among different matrix occur and the skeleton of the matrix deform. As a consequence, pore water pressure and pore air pressure in the SWIS changed. Furthermore, matrix suction and permeation rates are affected and the functions of the

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SWIS are further influenced as well, including decreasing the removal of COD, NH_4^+-N and TP. As a consequence, it is necessary to observe on-line UPC in the SWIS. UPC is the function of the degree of saturation, volumetric water content and matrix suction [7]. It can be measured directly in the laboratory or in the field [5]. However, the direct measurement is considered to be a time consuming task [8]. Moreover, results obtained might not be convinced because of great errors. Up to date, there are amount of models measuring the soil water curve to obtain UPC indirectly, including Brooks and Corey [9], van Genuchten (VG), pore-solid fractural model [10]. Where, VG model is considered to be one of the most common measurements to characterize UPC. If instantaneous UPC was obtained, redox microenvironment of the SWIS can be known at any time [11]. In that case, the potential of removing TN and TP of the SWIS can be predicted [12]. In addition, UPC may affect oxidation–reduction potential (ORP) by changing redox microenvironment.

ORP which can be used instead of dissolved oxygen (DO) plays a critical role in characterizing internal environment in the system, anaerobic or aerobic [13–15]. In recent decades, many researchers have studied so much on the removal of TN and TP in the SWIS under different operation conditions. It is vital to analyze the relationship between on-line UPC and ORP so that performances of operated SWIS can be monitored at any time and pollutants removal can be satisfactory. In that case, if one of UPC and ORP can be obtained, the other can be predicted, which is benefit for analyzing redox microenvironment. However, little researches were studied to learn how the UPC affects the capillary action area and gravity action area in the SWIS. The microstructural changes caused by the fluid-solid coupling and irregular changes of the ORP values are unclear.

In order to research the regulations of UPC changes in the SWIS, study the effects of UPC on the ORP under capillary action and gravity action and further afford a satisfactory SWIS for engineering application, a simulated SWIS which was able to observe on-line ORP was designed to reveal regulations mentioned earlier.

2. Material and methods

2.1. System description

The schematic diagram of the SWIS was shown in Fig. 1. The system was mainly made up of the plexiglass column and a multi-data acquisition system (MDAS). To fill the matrix conveniently, the plexiglass column was divided into the upper (50 cm), middle (60 cm) and bottom part (70 cm) by flanges. The plexiglass column was wrapped up by black cloth in order to simulate the similar conditions of underground soil. A distributing pipe (90 cm in height, 1 cm in diameter) was put in the middle of the column over a niimi slot. The dispersing pipe was 10 cm in length and 1 cm in diameter. On the side surface of the column, four sampling holes in five matrix depths (50, 70, 100, 115, and 130 cm) from the top of the column were arranged. Sampling holes in each matrix depth were designed for the installations of a depolarization ORP detection probe, a soil water potential

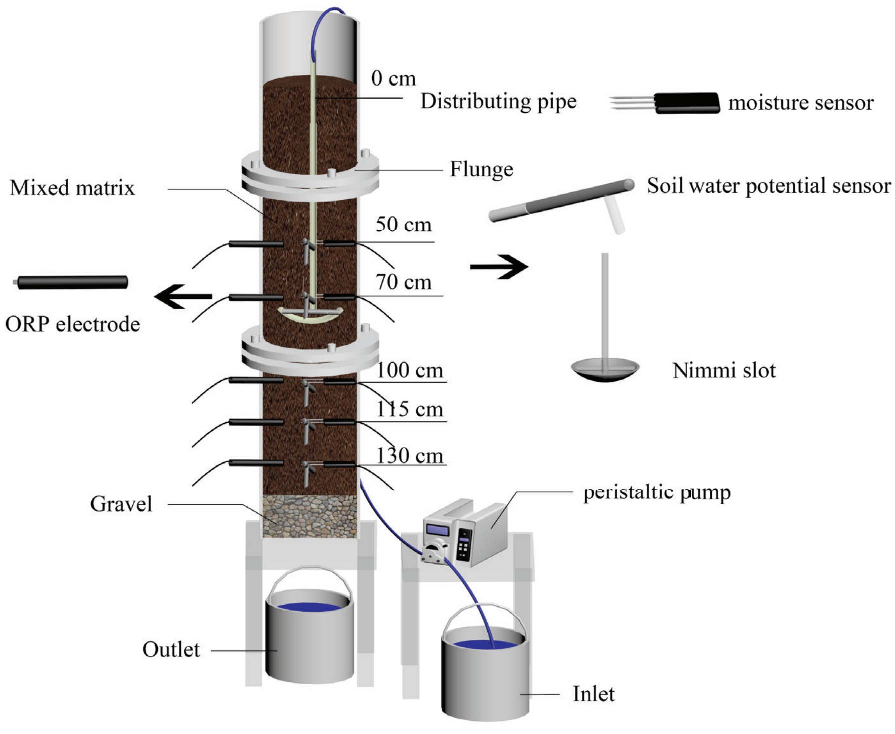


Fig. 1. Schematic diagram of the SWIS. A peristaltic pump (Prefluid BT100 - YZ15) controls the hydraulic load ($0.10\ m^3\cdot(m^2\cdot d)^{-1}$). A transmitter (MDAS) which was connected with all the probes was invented by Nanjing Soil Research Institute. The computer was utilized to accept data.

sensor, a moisture sensor and collections of the soil samples. Data was transmitted to the sensors in the form of electrical signal and collected by the MDAS. On-line ORP, matrix suctions and volumetric moisture contents can be effectively monitored by ORP probes, soil water potential sensors and moisture sensors at the same time.

2.2. Matrix

The column was filled by mixed matrix, which was tiled in volume (65% brown soil, 25% coal slag and 10% sand) for the SWIS. The brown soil was obtained from Shenyang Agricultural University. It should be selected through a fine sieve with 2 mm pores after drying naturally. The coal slag was obtained from the boiler room near the university. 2–5 mm coal slag was selected after sieving. Sand was purchased directly, which was 1–3 mm in diameter. In order to avoid clogging, pebbles were selected and tiled about 20 cm thick at the bottom of the SWIS. For the purpose of avoiding filling the matrix heterogeneously and collecting data incorrectly, water should infiltrate evenly when the column was filled by 2 cm thick. As a consequence, the matrix compacted naturally. This operation mentioned earlier was carried out repeatedly until the matrix was filled up to 160 cm. If there was large volume of space in the SWIS, the sensors which were utilized to collect data would be affected. Therefore, once the matrix was filled up to the depths where sampling points were designed, depolarization ORP electrodes soil water potential sensors and moisture sensors needed to be inserted in advance after corrections.

2.3. Analysis

2.3.1. Water quality

The raw wastewater was made up by the experimental reagents. The specific doses were obtained in Table 1. COD, BOD_5, NH_4^+-N, TN and TP of the wastewater were analyzed according to the standard methods [16]. Water equality indicator was shown in Table 2.

2.3.2. Matrix

It is significant to analyze physical and chemical properties of the matrix. The particle distribution was determined by a monitoring company. In addition, the porosity was computed referring to Grossman and Reinsch's method [17]. The bulk density was measured by the single-ring infiltrometer method [18]. The specific properties were shown in Tables 3 and 4.

Table 1
Experimental reagents

Glucose (g·3 L^{-1})	1.75
pH	6–9
Ammonium chloride (g·3 L^{-1})	0.78
Potassium nitrate (g·3 L^{-1})	0.23
Sodium nitrite (g·3 L^{-1})	0.047
Potassium dihydrogen phosphate (g·3 L^{-1})	0.23

2.4. Theory

The estimation applied for investigating the UPC in the SWIS was based on Darcy's law and unsaturated soil water equation of motion. Eqs. (1)–(3) show the model from van Genuchten [8].

$$\theta_w = \theta_r + \frac{\left(\theta_s - \theta_r\right)}{\left[1+\left(\alpha h\right)^n\right]^{1-\frac{1}{n}}}, \quad h < 0 \tag{1}$$

$$K\left(\theta\right) = K_s\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{0.5}\left(\int_0^{\theta}\frac{\Delta\theta}{|h|} \Big/ \int_0^{\theta_s}\frac{d\theta}{|h|}\right)^2 \tag{2}$$

$$K\left(h\right) = K_s \cdot \frac{\left\{1-\left(\alpha|h|\right)^{n-1}\left[1+\left(\alpha|h|\right)^n\right]^{-m}\right\}^2}{\left[1+\left(\alpha|h|\right)^n\right]^{\frac{2}{m}}} \tag{3}$$

where α fitting parameter related to the inverse of air-entry value of the soil (1 kPa^{-1}), according to the Hydrus 1D, $\alpha = 0.075$; n is the fitting parameter related to the slope of the

Table 2
Inflow–outflow quality indicators for the SWIS

Water quality (mg·L^{-1})	Inflow	Outflow
COD	132.3–160.2	15.4–20.3
BOD_5	105.5–125.8	3.5–8.7
NH_4^+-N	27.2–30.9	1.6–3.1
TN	38.5–42.2	12.1–16.3
TP	3.5–4.0	0.11–0.19

Table 3
SWIS matrix properties

Organic matter (%)	2.0
pH	6–9
Porosity (%)	55.4
>0.05 mm particle size distributing (%)	51.96
0.005–0.002 mm particle size distributing (%)	45.30
<0.002 mm particle size distributing (%)	2.24

Table 4
Coal slag properties

pH	7.3
Size (mm)	≤3
Porosity (cm·s^{-1})	2.4×10^{-4}
SiO_2 (%)	52.98
Al_2O_3 (%)	20.02
CaO (%)	3.18
MgO (%)	1.27

SWCC, $n = 1.89$; m is the fitting parameter related to the residual water content of the soil, $m = 1-\frac{1}{n}$; ϑ is the dummy variable of integration representing suction, θ_s is the saturated volumetric water content, θ_w is the volumetric water content. θ_r is the residue water content. $K_s = 10.61$ cm d^{-1}.

2.5. Data analysis

In terms of the SWIS, ORP values, matrix suctions and volumetric water contents were collected by the MDAS. The data were recorded every 30 min. All the data were sorted after the whole experiment accomplished. Origin 2017 was employed to describe the regulations between ORP and UPC. SPSS 19.0 was used to determine whether there was a significant difference between the UPC and ORP values.

2.6. Experiment

A SWIS was set up and ORP in five matrix depths (50, 70, 100, 115, and 130 cm) was collected by MDAS with a hydraulic load of 0.10 m^3·(m^2·d)$^{-1}$. Each cycle of the intermittent operation contained an inflow period (12 h) and a dry period (12 h). The flow rate of wastewater was controlled by a peristaltic pump. Before the data was collected, the SWIS has run for one month so that the system was under a stable situation. The on-line matrix suction, ORP and volumetric water content monitored in one matrix depth at the same time constituted a set of original data. After the matrix suction was collected, UPC could be calculated using Eq. (3). Therefore, the relationship between UPC and ORP was observed obviously. The experiment operated for 60 d, all data was obtained after the experiment was accomplished and triplicate readings for UPC and ORP values were recorded for analyzing.

3. Results and discussion

3.1. Unsaturated permeability

Relative volumetric water contents in the 50 matrix depth were about 85%, which indicated that capillary action occurred here [5]. As can be seen in Fig. 2, UPC did not increase obviously in the 50 cm matrix depth at the initial stage at the inflow period. The main reason was that the capillary action in this area was weak. As this unsaturated area was close to the surface of the SWIS, efficient oxygen made matrix suction high. Matrix could be compacted gradually when wastewater infiltrated. Oxygen occupied the pore-water position and accelerated the speed of wastewater permeation [19]. Therefore, UPC in the 50 cm matrix depth was relatively high. UPC had a sharp increase when the SWIS operated for 12 h. UPC values was up to 5.6×10^{-6} cm·s^{-1}. The slow growth rate was that matrix in 25 cm matrix depth was close to the surface of the SWIS. It was hard for wastewater to climb and slight capillary effect could be found for a long time. Therefore, the sewage rose slowly. UPC in this area dropped when it was time for the dry periods. It indicated that the SWIS had a good ability to recovery the previous state [20].

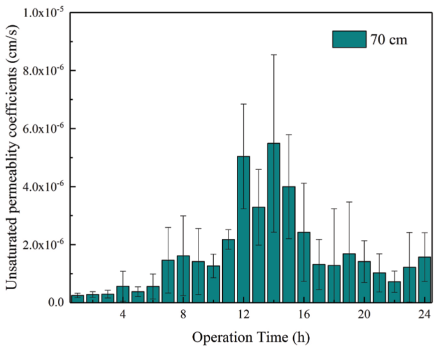
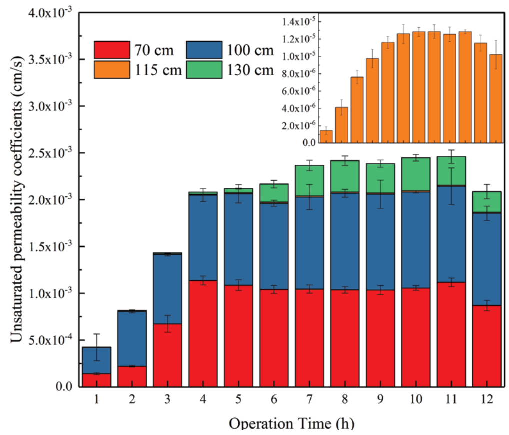


Fig. 2. UPC values in the 50 cm matrix depth in the SWIS. The X-axis represented the operation time for one cycle (24 h) and the Y-axis represented the UPC.

Figs. 3(a) and (b) show UPC variations in 70, 100, 115 and 130 cm at the inflow period (1–12 h) and the dry period (13–24), respectively. Reproducibility of the experiments was demonstrated according to the error bars. Moreover, it illustrated that the SWIS was steady.

UPC in the 70 and 100 cm matrix depths could up to minus four orders of magnitude and values were similar



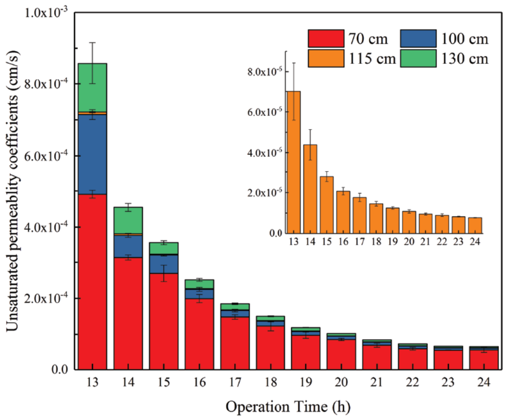


Fig. 3. UPC variations in 70, 100, 115, and 130 cm matrix depths: (a) at the inflow period; (b) at the dry period. The X-axis in Fig. 3(a) indicates the operation time during the inflow period and the Y-axis indicated UPC. The X-axis in Fig. 3(b) indicates the operation time during the dry period and the Y-axis indicated UPC.

at the same time. However, UPC in these two areas were affected by the capillary action and infiltration action, respectively. Compared with the UPC in the 50 cm, wastewater could reach 70 cm matrix depth naturally and the capillary action was stronger. Matrix in the 100 cm was close to the inlet position. This area was close to the saturation condition. Matrix suction was small and the UPC values were big because of the high water contents [21]. Therefore, matrix suction decreased with UPC increasing when water contents increased at the inflow periods [22].

UPC in the 115 cm matrix depth shown in the Fig. 3(a) were small. The maximum UPC was only up to 1.288×10^{-5} cm·s^{-1}. UPC should get smaller than those in the 115 cm with the matrix depths increasing. However, results found that UPC in the 130 cm rose. The maximum UPC was 4.19×10^{-4} cm·s^{-1}. The main reason was that treated wastewater accumulated in this area, which increased volumetric water contents.

According to the studies learned before, water contents were one of the major factors affecting UPC [5]. Zhou pointed out that when the water contents increased, more pores in the matrix were occupied by the water [23]. As a result, the breathability decreased and the water permeability increased.

Overall, UPC in each matrix depth increased at first four hours of an inflow period and kept steady with slight fluctuations. It indicated that the SWIS had satisfactory permeation and it could stabilize after running for 4 h.

As it can be seen from Fig. 3(b), UPC in four matrix depths had obvious regulations. Gravity action dominated in the SWIS. Standard deviation (SD) was shown in the form of error bars. According to error bars, data showed that UPC fluctuated obviously because the SWIS transformed the operation conditions. UPC in different matrix depths fell at the end of inflow periods. The SWIS tried to recover the situations which were resemble to those at the beginning. Volumetric water contents fell as well.

UPC in the 70 cm was the highest among other matrix depths at the same time despite that all UPC values decreased. The minimum UPC was about 4.71×10^{-5} cm·s^{-1}. It concluded that capillary action could maintain the volumetric water contents for a while and then wastewater infiltrated by gravity. Under the action of gravity, moisture exuded the pores. Different from data shown in Fig. 2(a), UPC in the 100 and 130 cm matrix depths were similar. The reason was that the matrix in these two areas could be exposed to the air. The velocities of wastewater were slow because of the high volumetric water contents. What's more, the water contents for bottom and the middle depths were still high at the next periods.

Overall, UPC at the dry periods was a little bit lower than those at the inflow periods.

Compared with the UPC in the 50 cm matrix depths, the frequency of UPC fluctuations was higher in the 70 cm matrix depths. UPC increased sharply at inflow periods, which spanned three orders of magnitude during one cycle (4.71×10^{5} to 1.16×10^{-3} cm·s^{-1}). After undergoing a drying period, water contents decreased. Because the matrix was unsaturated, air could replace a part of wastewater in the larger pores at first. As a consequence, the water flowed through the smaller pores with an increased tortuosity of the flow path. In addition, water occupied the pore easily with matrix suctions increasing [24]. As a result, the UPC decreased rapidly as the space available for the water flow declined.

3.2. Effects of ORP on unsaturated permeability

The experiment found that UPC had a certain impact on ORP. Fig. 4(a) shows, the ORP did not fluctuate intensely in the 50 cm matrix depth, only increasing from 336 to 446 mV. According to the study found before, ORP values above 300 mV, 200 mV to 100 mV, 100 mV to −200 mV and −200 mV below, were under the aerobic environment, hypoxic environment, facultative anaerobic environment and completely anaerobic environment, respectively [25]. As can be seen in Fig. 4(a), it was aerobic environment in the 50 cm matrix depth. The main reason was that the matrix in this depth was close to surface of the SWIS and had sufficient contact with the oxygen. ORP fluctuated when the system transformed the conditions from the inflow periods to the drying periods, which was mainly due to water contents changing [26]. As a consequence, UPC changed.

As can be seen from Fig. 4(a), UPC fluctuated greatly and ORP values were also obvious here, increasing about 100 mV. Results showed that if the UPC increased, the water contents became bigger.

Compared with Fig. 4(a), the relationship between ORP and UPC from Fig. 4(b) was more obvious. At the same time, the periodicities of UPC changes and ORP changes were more obvious. In general, ORP decreased with wastewater increasing [19]. The water contents increased. However, as time went at the inflow period, ORP values increased and the UPC values increased as well in the 70 cm matrix depth. The main reason was that wastewater climbing to this area by capillary action carried oxygen. The existence of oxygen promoted ORP efficiently. Due to the dispersion from the capillary action in the 70 cm matrix depth at the inflow period, UPC and ORP had similar regulations. The ORP fluctuated greatly under alternating dry-wet conditions and the SWIS could be converted from an aerobic state to an anaerobic state, demonstrating the strong nitrification and denitrification [27] potential in 70 cm matrix depth. The water flow moved downward because of the gravity at dry periods. Therefore, the water contents increased and the UPC values dropped significantly.

In Fig. 4(c), ORP decreased at the inflow periods and increased at the dry periods However, UPC increased at the inflow periods and decreased at the dry periods. The maximum ORP was 301 mV; the minimum ORP was −262 mV. The internal environment varied from facultative anaerobic environment to completely anaerobic environment. Results showed that nitrification and denitrification could occur in this area. UPC values varied rapidly because this area was close to the dispersing pipe. High volumetric water contents played a key role in discharging oxygen immediately [19]. The matrix had good permeability. As a result, UPC and ORP values changed frequently.

ORP values showed that environment changed between facultative anaerobic environment and anaerobic environment in the 115 cm matrix depth (Fig. 4(d)). Similar to the trends in Fig. 4(b), UPC values and ORP values had a clear relationship. Both ORP and UPC increased at the inflow periods and decreased at the dry periods. The phenomena were caused by the infiltration action. UPC and the ORP decreased when the operation transformed from the inflow periods into dry periods. The fluctuations were so big, which demonstrated the

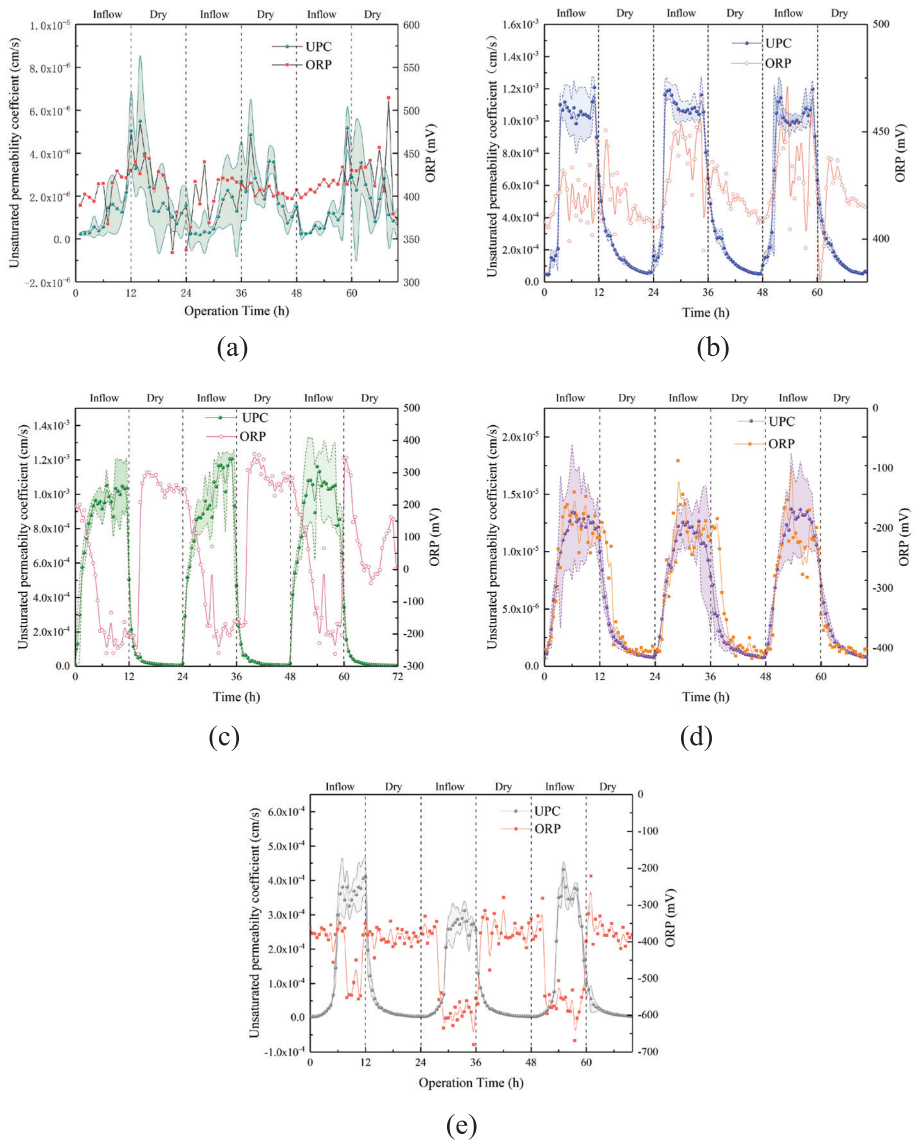


Fig. 4. The regulations of UPC and ORP with the operation time: (a) the 50 cm matrix depth; (b) 70 cm matrix depth; (c) 100 cm matrix depth; (d) 115 cm matrix depth; and (e) 130 cm matrix depth. The X-axis indicated the operation time. The left Y-axis indicated UPC and the right Y-axis indicated ORP.

SWIS had good conditions of treating wastewater. However, since it is located below the niimi slot, the water in the inflow area will move downward due to gravity at the early inflow periods. The SWIS had no long-term dry conditions. The fluctuations of ORP values and UPC values were obvious.

The UPC values showed that the system in the 130 cm matrix depth was still under anaerobic environment (Fig. 4(e)). ORP decreased from −300 to −655 mV at the inflow periods. However, UPC increased from 3.88×10^{-6} to 4.19×10^{-4} cm·s^{-1} at flow periods. There was a sharp increase of both ORP and UPC in the SWIS. Because the existence of the hysteresis [28], UPC values only changed after half an hour. What's more, UPC maintained a low value for almost 16 h at one cycle.

In summary, both ORP and UPC increased at the inflow periods and decreased at the dry periods in 70 and 115 cm. However, ORP decreased with UPC increasing at the inflow periods and ORP increased with UPC decreasing at the dry periods in 100 and 130 cm matrix depth. During the long-term operation, there would be relative displacements among the matrix. UPC values could change the ORP values. Thus, the microbial degradation of pollutants could be affected. What's more, the progress of the redox reaction could be affected as well [29]. Therefore, in order to make the system perform well, it was necessary to regulate the matrix depth. Porosity could change the UPC values [20]. Both cohesive and sandy matrixes were not good for subsurface infiltration systems [30]. Matrix in this SWIS could be selected for decentralized wastewater treatment. It can be seen that ORP did not decrease with depths in the SWIS, but related to the presence of dissolved oxygen and variations of volumetric water contents. What's more, ORP was susceptible to the unsaturated permeability coefficients.

4. Conclusion

In this paper, a novel SWIS which monitored instantaneous ORP and UPC in different matrix depths was designed. A relationship between the online UPC and ORP in the SWIS at the hydraulic load of 0.10 $m^3·(m^2·d)^{-1}$ was investigated. It was found that UPC increased with the volumetric water contents increasing at the inflow periods and then decreased at the dry periods. ORP values increased with the UPC values increasing in the 70 and 115 cm matrix depths due to the existence of ample oxygen. However, ORP decreased with UPC increasing in the 100 and 130 cm matrix depths. UPC had slight ability to change the ORP in the 40 cm matrix depth and slight capillary action was found. Anaerobic environment could transform into aerobic environment under alternation conditions in the 100 cm matrix depth below. SWIS could be stable when wastewater was fed into the SWIS for 4 h. Treated water met reused requirements and no clogging was found, which indicated that UPC of matrix can be changed from 2.49×10^{-7} to 1.16×10^{-3} $cm·s^{-1}$ in a satisfactory SWIS. UPC and ORP in different matrix depths when clogging is found should be discussed and it is benefit to give a quantitative analysis between UPC and ORP in the following study.

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