Effect of evaporation on land salinization after storm surge overtopping embankment

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Abstract. Based on SUTRA, a numerical simulation software of groundwater with variable saturation and density, the influence of evaporation after storm surge on soil pore water flow and salt transport process was studied. The results showed that the seawater overtopping caused land soil salinization, and evaporation would weaken the vertical infiltration of salt water, keep salt in the shallow soil, and increase the salt content in the shallow soil, which made it difficult to eliminate soil salinization.

1. Introduction

Storm surge is the abnormal rise and fall of seawater caused by severe atmospheric disturbances (such as strong winds and sudden changes in air pressure) [1], and is a frequent coastal disaster event in recent years [2-4]. At present, the construction standard of seawall engineering in China is low, and the event of overtopping easily occurs under the combined action of storm surge and sea waves [5, 6], which leads to the land area behind the seawall being submerged by seawater. Due to the seawall blocking, the seawater cannot enter the sea through surface runoff, and then vertically seeps into the coastal underground aquifer, resulting in salinization of coastal soil [7-9]. Coastal soil salinization and its recovery is a long and slow process. It is of great significance for improving coastal groundwater resources management and improving coastal ecological environment to explore the influence of seawater infiltration on soil salinization in the land behind the dike after the dike overtopping event.

At present, researches at home and abroad believe that the process of groundwater salinization and recovery after storm surge flooding is closely related to coastal topography and soil characteristics, among which coastal topography is considered as the main factor affecting groundwater salinization [10-16]. Chui and Terry [11] used trapezoidal depression to represent the central topography of typical atolls, and found that coastal depression topography can prolong the detention time of submerged seawater, resulting in more seawater infiltration. The larger the volume of seawater that can be accommodated, the more salt is infiltrated. As a result, the degree of land salinization is more serious, and the inland fresh water scouring (i.e., natural restoration) takes longer [13]. Soil characteristics are also an important factor affecting the process of groundwater salinization and restoration [17-20]. Yang et al. [17] think that in low permeability soil, salt water moves very slowly, and seawater is difficult to continue infiltration after being filled with unsaturated zone, and can stay in the upper aquifer for up to 20 years; However, saline water in high permeability soil can seep in a short time, reach aquifer and be washed and diluted. Mahmoodzadeh et al. [18] found that the area of salt-fresh water mixed zone increased and the pollution of underground aquifer intensified by setting heterogeneous soil permeability coefficient. In addition, aquifers with low horizontal permeability and high vertical permeability are more easily polluted by seawater infiltration.

Previous studies on the simulation of storm surge inundation events mostly simplified it as a fixed flow boundary or a constant head boundary applied to the upper surface for a certain time [11, 15, 22].
However, the height of submerged water level should be closely related to topography and dynamically change with time. In addition, previous studies on groundwater salinization caused by storm surge did not consider the influence of evaporation, which is an important factor affecting soil salinization. Soil evaporation will take away surface water and keep salt in shallow soil, which will lead to the increase of salinity in shallow soil and aggravate land salinization [23-26]. In view of the lack of research at present, this paper will establish a model of soil water and salt transport after storm surge overtopping the embankment by using SUTRA[27] numerical simulation software, focusing on analyzing the influence of evaporation on soil pore water flow and salt transport process.

2. Research method

2.1 conceptual model

Fig. 1(a) is a schematic diagram of the physical process of storm surge overtopping the dike. Under the action of storm surge, seawater passes over the seawall and is trapped in the land by the seawall and cannot be discharged by surface runoff. The model assumes that this part of seawater can only be discharged by evaporation and infiltration. In this study, the saline infiltration process of coastal soil submerged by seawater was simulated, and the change of pore water salinity with or without evaporation was compared. Schematic diagram of simplified physical model is shown in fig. 1b. boundary AB of model domain is no-flow boundary, which represents aquitard, boundary AD and BC are set as constant head boundary, which respectively represent sea side boundary and inland boundary, and boundary CD at top of model domain is set as time-varying hydraulic boundary (head and discharge boundary).

The evaporation calculation formula [28-30] used in the model is as follows:

\[
E_v = \frac{v_E}{d_{mm}} \cdot \frac{a}{\alpha} \cdot \frac{w_U}{U} \cdot \frac{s_T}{a} \cdot \frac{v_P}{a_P} \cdot \frac{s_s}{S} \cdot \frac{\phi}{\phi'}
\]

In which: \(E_v\) is evaporation rate, \(\text{mm} \cdot \text{d}^{-1}\); \(\rho_a\) is air density, 1.205 \(\text{kg} \cdot \text{m}^{-3}\); \(U\) is wind speed, 3 \(\text{m} \cdot \text{s}^{-1}\); \(q_a\) is air humidity, 0.0072 \(\text{g} \cdot \text{kg}^{-1}\); \(T_s\) is temperature, 15°C; \(P_r\) is saturated water vapor pressure, kPa; \(P_a\) is surface atmospheric pressure, 101kPa; \(S_s\) is soil surface saturation; \(\phi\) is soil porosity, 0.45. The meteorological parameters of evaporation model are fixed, and the field observation results are adopted [31]. The potential evaporation rate of the model is set to 10 \(\text{mm} \cdot \text{d}^{-1}\), and the actual evaporation rate varies with soil saturation, as shown in Figure 2a.
2.2 Numerical model

In this paper, based on SUTRA[27] numerical simulation software, considering the vertical two-dimensional section of a coastal unconfined aquifer, the process of unsaturated pore water flow and salt transport with variable density is simulated, and the governing equation of water and salt transport is as follows:

$$\frac{\partial (\rho \phi S_w)}{\partial t} = - \nabla \cdot (\rho q) + \rho_s Q$$  \hspace{1cm} (3)

$$q = -K(\psi) \nabla \cdot \left( \frac{p}{\rho g} \right) + z$$  \hspace{1cm} (4)

$$\frac{\partial (\rho \phi S_u C)}{\partial t} = - \nabla \cdot (\rho q C) + \nabla \cdot (\rho \phi S_u^C D \nabla C) + \rho_s Q C_s$$  \hspace{1cm} (5)

In which: $S_w$ is saturation; $t$ is time, s; $q$ is pore water velocity, m·s$^{-1}$; $Q$ is the source and sink item, m$^3$·s$^{-1}$; $\rho_s$ is the density of fluid source and sink term, kg·m$^{-3}$; $K(\psi)$ is the relative permeability coefficient, m$^2$·s$^{-1}$; $P$ is pore water pressure, Pa; $g$ is the acceleration of gravity, m$^2$·s$^{-1}$; $z$ is water level height, m; $\Psi$ is soil capillary head, m; $C$ is the salinity of pore water, g·g$^{-1}$; $D$ is hydrodynamic dispersion tensor, m$^2$·s$^{-1}$; $C$ is the salinity of fluid source and sink, g·g$^{-1}$; $\rho$ is fluid density, kg·m$^{-3}$, calculated according to formula $\rho = \rho_0 + \xi C$, where $\rho_0$ is fresh water density, 1000 kg·m$^{-3}$, and $\xi$ is proportional constant, 714.3 kg·m$^{-3}$.

According to the empirical formula proposed by van Genuchten[32], the hydraulic parameters of unsaturated soil are determined by formulas (6)~(7):

$$S_w = S_{wr} + (1 - S_{wr}) \left[ \frac{1}{1 + (\alpha \Psi)^n} \right]^{\frac{n+1}{n}}$$  \hspace{1cm} (6)

$$K(\psi) = K_s \left( \frac{S_w - S_{wr}}{1 - S_{wr}} \right)^{1/2} \left[ 1 - \left( \frac{S_w - S_{wr}}{1 - S_{wr}} \right)^{n-1} \right]^{2}$$  \hspace{1cm} (7)
In the formula, $\alpha$ and $\beta$ are shape parameters, which are 2 and 1.41 respectively, and $K_s$ is saturated permeability coefficient, which is $1.23 \times 10^{-6} \text{m} \cdot \text{s}^{-1}$, which are typical values of silty loam. $S_{wr}$ is residual saturation, 0.1, and its soil moisture characteristic curve is shown in Figure 2b.

2.3 Boundary conditions and simulation

The CD boundary condition at the top of the model domain depends on three stages of simulation: (1) before the embankment overflow; (2) Submerged infiltration; (3) Evaporation.

(1) Before overtopping: the pressure heads at the boundary of AD and BC are set to 22 m and 23 m respectively, and the boundary of CD at the top is set to no-flow boundary. The purpose of this stage is to obtain a stable initial condition, that is, a stable groundwater flow field and salinity distribution in the aquifer;

(2) Submerged infiltration: at this stage, the CD boundary is set as a time-varying water head boundary, the initial surface water level is 25.5 m, and the single-width seawater volume after crossing the dike is $62.5 \text{m}^3 \cdot \text{m}^{-1}$. The new head boundary is obtained by calculating the amount of seawater remaining after infiltration until the submerged seawater is completely infiltrated. At this stage, at each time step, the pore water pressure $P$ of the node on the upper surface (CD boundary) of the model domain is used to judge whether the node evaporates. At the same time, the water surface evaporation in the process of surface water infiltration is also considered, the water surface evaporation rate is set to $10 \text{mm} \cdot \text{d}^{-1}$, and the salinity of the overlying water boundary is obtained by calculating the remaining salt mass after infiltration and evaporation divided by the remaining seawater mass;

(3) Exposure stage: at this stage, all surface water infiltration has been completed, and all nodes on the upper surface (CD boundary) of the model domain are flow boundaries affected by evaporation, and their flow is determined by the saturation of this node (Figure 2a). At the same time, the salinity of the flow boundary is 0, which means that the evaporated effluent is fresh water.

The model domain is divided into 81,750 grids (82,610 nodes). The horizontal grid size is 0.33 m, and the vertical grid size is 0.005 m and the vertical grid size is 0.1 m. The lateral dispersion $\alpha_T$ is 0.05 m, and the longitudinal dispersion $\alpha_L$ is 0.5 m. The model runs for one year, and the time step is set to 150 s.

3. Results and analysis

3.1 Soil water and salt transport after storm surge overtopping embankment

![Fig.3 Temporal variations of surface water elevations and salinity](#)

As shown in fig. 3, when evaporation is not considered, all the surface water penetrates into the soil, and the water level shows a monotonous downward trend with time, which takes about 3.9 days
to drop from 25.5 m to 25 m. When evaporation is considered, one part of surface water evaporates and the other part penetrates into the soil. The infiltration time of surface water is shortened to 3.5 days, which is 0.4 days faster than that without evaporation. In addition, surface evaporation consumes a part of surface water, and the infiltration rate of surface water decreases due to the decrease of overlying water-soil interface, which further affects the salt amount of infiltration on the upper side of slope. With the evaporation, the salinity of surface water increases. In the later stage of infiltration process, more salt will enter the lower side of the slope with low elevation and deepen the local salinization degree.

Fig. 4 shows the salinity distribution results of aquifer pore water after storm surge inundation with and without evaporation. Before the levee overtopping event, the groundwater level (purple line in Figure 4) was controlled by water heads on both sides, and the horizontal direction gradually increased from 0 m to 250 m (Figure 4a). Without evaporation, the surface water level (grey line in fig. 4c) decreased from 25.5 m to 25.32 m on the first day after the levee overtopping, and there was no water exchange on the soil surface above the water line. The pore water of shallow soil is rapidly polluted by salt, forming a salt water plume (Figure 4c). The expansion of salt water plume is indicated by the front of 5% seawater salinity (isoline with salinity of 1.75 ppt) (white line in Figure 4). The salinity of pore water on the lower side of the slope is obviously higher than that on the upper side, and the maximum salinity can reach 20 ppt. Evaporation is not considered in this model, and the maximum salinity of surface water and groundwater in this model is 35 ppt.

On the 5th day after the levee overtopping, the surface water has completely infiltrated, and the shallow soil pore water moves downward driven by gravity and density gradient. The salinity front of 5% seawater moves down by 1.3 m on average, and the salt water plume on the sea side expands faster, with the depth of the front moving down reaching 2.0 m and the salinity of pore water up to 31 ppt.
(Figure 4e). At this time, the groundwater level remains unchanged from the position before overtopping the embankment. On the 180th day, part of salt water reached the groundwater level, which caused the middle part of the water level to rise obviously, which was higher than the given inland water head (23 m), and the groundwater flowed to both sides driven by hydraulic gradient. At this time, the salt water plume front moves down 2.0 m on average, and the salinity of shallow soil pore water is diluted. Compared with the 180th day, on the 360th day, the salt plumes expanded slowly, the front moved down 2.1 m on average, and the salinity of soil pore water in unsaturated zone decreased to 27 ppt.

Under the action of evaporation, the surface water level dropped to 25.31 m on the first day, which was slightly lower than that without evaporation (25.32 m). At this time, the salinity of surface water increased slightly (36 ppt), and the salinity of the remaining surface water could reach 116 ppt until it completely penetrated. After evaporation, the pore water on the soil surface dissipated into the atmosphere, and the salinity of pore water increased rapidly. Salinity zone exceeding seawater salinity (35 ppt) appears in the unsaturated zone on the sea side, and the salinity of pore water can reach 56 ppt on the fifth day (Figure 4f). At this time, compared with that without evaporation, the average position of salinity front of 5% seawater is basically unchanged (down 1.3 m). After that, the salinity of surface pore water continued to increase, and the high salt area further expanded, and the difference of salinity distribution was more obvious than that without evaporation. While increasing the salinity of soil pore water, evaporation also slows down the downward movement of salt water plume, and its salt water plume front is shallower than that without evaporation. On the 180th day, the salt water plume front moved down 1.8 m on average, and the moving depth was 90.0% of that without evaporation. The amount of seawater infiltration decreases due to the influence of water surface evaporation and soil evaporation, and the lifting range of groundwater level line also decreases (Figure 4h). On the 360th day after the levee overtopping, the maximum salinity of pore water in the soil can reach 95 ppt, and compared with that without evaporation, the maximum salinity of pore water increases by 252% (Figure 4j), with obvious salt accumulation.

3.2 Quantification of salinity in shallow soil

In this section, the salinity of pore water in the soil layer within 1 m of the soil surface layer is quantitatively analyzed. In the initial state (day 0), the salinity of pore water is 0, and the salinity of surface soil pore water increases rapidly after crossing the embankment. In the case of no evaporation, the vertical average salinity within 1 m of the surface layer does not exceed the salinity of seawater 35 ppt (Figure 5a). On the first day after overtopping the embankment, the average salinity of pore water gradually decreased from coastal side to inland side. The vertical average salinity on the fifth day was significantly higher than that on the first day. On the 5th day, the 180th day and the 360th day, the vertical average salinity did not change obviously, which was close to a stable state. The results showed that the water and salt transport in the surface 1 m soil was extremely slow after the 5th day.

Under evaporation, the vertical average salinity at each time point after crossing the embankment is higher than that without evaporation (Figure 5). On the first day, the vertical average salinity under evaporation was only slightly higher than that without evaporation. With the increase of time, the difference between evaporation drooping to average salinity and no evaporation becomes more and more obvious. On the 180th day, the vertical average salinity within 56 m along the sea side has exceeded the seawater salinity (35 ppt), and on the 360th day, the range of exceeding the seawater salinity has expanded to 74 m, at this time, the vertical average salinity is up to 50 ppt, which is about twice that without evaporation. With the evaporation, the soil surface saturation gradually decreases, so does the evaporation rate. The vertical average salinity increment gradually decreases with the decrease of evaporation rate. Compared with the 180th day, the maximum vertical average salinity on the 360th day only increases by 5 ppt, while the maximum vertical average salinity increment from the 5th day to the 180th day is 13 ppt (Figure 5b).
4. Discussion

The results of this study reveal the influence of evaporation on soil salinization process after embankment overflow. Evaporation will increase the salt content of shallow soil, aggravate the salinization degree of shallow soil, and make it difficult to eliminate soil salinization. Similarly, Shen et al. [33] simulated salt transport in salt marshes under tidal action, and found that evaporation caused salt to accumulate in shallow soil, and even exceeded salt solubility and precipitated. Previous studies on salinization caused by storm surge inundation did not fully consider salt accumulation in shallow soil caused by evaporation. For example, Chui and Terry [15] only removed the amount of water lost by evapotranspiration in advance when setting the boundary of precipitation flow, and thought that seawater was vertically infiltrated into coastal underground aquifer driven by gravity and density gradient, washed and diluted by inland fresh water continuously under the action of hydraulic gradient, and could be restored to the state before overflowing embankment after 7-10 years. Evaporation causes fresh water to escape from the surface, leaving salt in the shallow layer of soil, which leads to more serious salinization of soil after overtopping the embankment. The ecosystem balance in coastal areas may be damaged by severe soil salinization, such as vegetation sensitive to salinity cannot grow normally. However, saline soil can be fully utilized after proper improvement, and understanding the mechanism of soil water and salt transport after embankment overflow is helpful to formulate a reasonable land improvement strategy.

After soil salinization, in order to improve soil ecological environment, leaching measures can be taken to improve soil desalination. However, a research and investigation on tracking the storm surge overtopping event shows that [36], within 3 years after the storm surge event, a total of 3000–7000 mm of rainfall was accumulated in some areas for leaching desalination, but the soil salinization in this area has not been improved. This shows that the natural leaching desalination process is very slow in actual conditions. In order to improve the efficiency of leaching desalination, drainage infrastructure such as laying underground pipes can be considered to discharge salt from shallow soil [37].

5. Conclusion

In this paper, the soil salinization process after storm surge overtopping embankment under evaporation is studied by numerical simulation. The main conclusions are as follows:

(1) After seawater overtopping the embankment, the land soil salinization was caused. After the surface water completely infiltrated, the pore water salinity reached the highest level (31 ppt), and the salt water plume moved downward driven by gravity and density gradient. On the 180th day, the average position of 5% seawater salinity front moved down by 2.0 m, while the pore water salinity was slowly diluted, and the highest salinity decreased to 27 ppt; on the 360th day.

(2) Evaporation will aggravate the soil salinization after seawater overtopping the embankment, and make the soil surface form a high salt area, and the salinization degree of the low elevation area is significant. At the same time, evaporation will slow down the downward expansion rate of salt.
plumes, making salt accumulate in the shallow soil layer, making it difficult to eliminate soil salinization;

In this paper, the numerical simulation only studies the influence of evaporation on soil salinization after overbreak under simple terrain and homogeneous soil conditions. In fact, coastal terrain and soil characteristics are more complex, and the process of water and salt transport in different terrain and heterogeneous soil needs to be clarified. In addition, rainfall leaching and drainage facilities are not considered in this paper, while storm surge events are mostly accompanied by rainfall, and drainage facilities such as laying, ditches and concealed pipes are often laid in saline areas. Therefore, the process of soil salinization and restoration under the influence of rainfall and drainage facilities needs further study.

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