Study on the influence of groundwater recharge on pile foundation of high-speed railway bridge

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Abstract. Under the action of deep groundwater recharge, the ground settlement can be moderated, which indicates that deep groundwater recharge can not only effectively control the ground settlement, but also cause the expansion of deep soil, thus leading to the uplift of the ground. Based on this, this paper uses the fluid-solid coupling method to control groundwater recharge flow to analyze the long-term settlement characteristics of typical elevated pile foundation on the North China Plain under the action of recharge. Numerical analysis shows that the elevated pile foundation has a change of uplift and subsidence under the coupling action of upper load and deep recharge, and the uplift becomes more obvious with the increase of the depth of recharge point. However, the increase of horizontal displacement will also lead to the opposite result, and the final settlement is determined by both of them. In addition, it is also affected by the flow of recharge load. The greater the flow of recharge load, the greater the uplift of elevated pile foundation. The results can provide reference for the settlement prediction of pile foundation.

Keywords: groundwater recharge elevated pile, long-term settlement, numerical method.

1. Introduction

With the increase in our population and the rapid increase in industrialization, the demand for fresh water is also increasing [1]. Over-exploitation of groundwater makes the aquifer system in negative equilibrium for a long period of time [2], and on the surface, a series of geologic hazards, such as ground subsidence, are presented [3,4]. Ground subsidence can cause a series of adverse consequences, such as foundation subsidence or instability leading to a reduction in the seismic strength of the building [5], when encountering minor earthquakes may produce wall cracks, house collapse; local ground subsidence will cause cracks, damage to farmland; ground subsidence in coastal areas can also cause seawater backflow, resulting in groundwater pollution, soil salinization.

Groundwater, as a natural resource that is difficult to recover, has a significant impact on the natural environment. As an important resource, groundwater should be protected, but many cities have developed groundwater unreasonably during the construction process. In Jinan, for example, a city rich in springs, karst groundwater is the most characteristic ecological resources of the spring city of Jinan [6], with the continuous increase in the hardening of the urban surface area, the seepage path of the spring is constantly blocked and irrational development and utilization of springs, the spring recharge is becoming more and more difficult.

In order to guarantee the sustainability of groundwater resources and prevent the damage of groundwater resources by pitfall construction, recharge technology can be applied to restore groundwater seepage [7]. Recharge is a technology in engineering, i.e., the use of drilling wells for water supply engineering or the use of well pits and other ways, through artificial methods to allow water to be injected into the underground aquifer by infiltration or pressure irrigation. Based on different recharge requirements, groundwater recharge in actual construction is divided into two main types based on construction safety control and water resource protection. The main role of recharge is to protect groundwater resources and raise the groundwater level, to prevent the deterioration of water quality, ground subsidence or seawater intrusion due to the significant decline in groundwater level, which is an important way to protect springs. Groundwater recharge technology was first proposed by foreign scholars, the domestic groundwater recharge technology started relatively late, the initial use of groundwater recharge technology to alleviate ground subsidence and seawater intrusion and other problems caused by over-exploitation of groundwater [8].

Under the action of deep groundwater recharge, the ground settlement is mitigated [9], which indicates that deep groundwater recharge, while effectively controlling the ground settlement, may also cause the expansion of the deep soil, which leads to the uplift of the ground, and therefore also affects the force deformation of the deep foundation [10]. Most of the previous studies focused on the effect of groundwater mining on the settlement of building foundations, and very few explored the deformation of building foundations under the effect of groundwater recharge. Both groundwater mining and recharge will have a certain impact on the building foundation, especially the deep foundation structure, which has a deeper pile foundation holding layer and is more significantly affected by the deep soil uplift and subsidence changes. Groundwater mining will cause larger pile foundation settlement, while deep groundwater recharge will control the settlement of bridge pile foundation and ground to a certain extent [11], and with the increase of recharge and the decrease of mining, the elevated pile foundation and the ground are gradually uplifted. And the deep soil layer is most affected by recharge, and it is constantly uplifted under the action of recharge load, while the elevated pile foundation and shallow soil layer first settle and then uplift under the coupling action of upper load and recharge load. The recharge point is also related to the settlement of pile foundation, the smaller the horizontal spacing, the deeper the depth of recharge, the larger the recharge flow, the larger the influence on the long-term deformation of the elevated pile foundation, which can be used as a reference for the prediction and control of the settlement of the pile foundation.

2. Numerical analysis of the effects of long-term groundwater recharge on pile foundations

The rapid development of cities in the North China Plain relies on groundwater resources, and the overexploitation of groundwater has made the North China Plain the region with the fastest rate of subsidence and the largest area of influence in China. Relevant studies have shown that the influence range of the deep groundwater funnel area and the serious area of ground subsidence basically coincide, so there is a direct relationship between the occurrence of ground subsidence in the North China Plain and the development and utilization of deep groundwater [12].

The interaction between elevated pile foundation, soil and groundwater is extremely complex, and it is difficult to use general theoretical models to get the analytical solution of the relationship between the three, and it is even more difficult to analyze the effect of groundwater recharge on the deformation of the elevated pile foundation and settlement, and the finite element numerical simulation method can effectively analyze the coupled problems of flow and solidity such as basement pit precipitation, and reasonably simulate the infiltration of the water flow in the water-soil coupling problem, so it is chosen here. Therefore, the finite element numerical simulation method is chosen to study the effect of long-term groundwater recharge on soil and pile foundation deformation on a section of elevated roadway from Xiongan New Area in North China Plain to Beijing Daxing International Airport Express Line.

2.1. Numerical model

In order to facilitate the study and simplify the model, a single well is chosen for recharge, and a section where an elevated pile foundation is located is selected for numerical analysis to establish a numerical model as shown in Fig. 1, and Abaqus finite element calculation software is used to perform finite element simulation. In order to facilitate the study of key issues, the following assumptions are made for the numerical model: A two-dimensional plane model is used, the recharge point is located in the center of the model, and the pile foundation and bearing platform are located on the left side of the recharge well. Elastic stress-strain relationship is used in the constitutive equations of the soil and the elevated pile foundation. The elastic modulus of the pile foundation and permeability coefficient of the soil need to be discounted in accordance with the planar problem. The schematic diagram of the numerical model is shown in Fig. All cell types are planar quadrilateral cells. The dimensions of the modeled soil body are selected according to the influence range and recharge depth of a single well in Beijing.

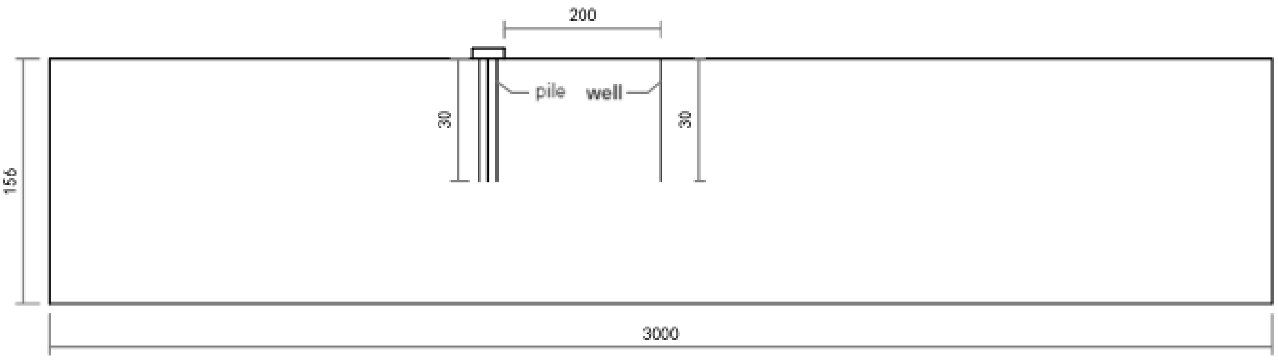

Fig. 1 Model diagram

The size of the two-dimensional model is selected as 3000m×156m, and a solid pore pressure unit is used for simulation. The recharge well is located in the center of the model, with an initial depth of 30m, located in the pressurized aquifer, and recharge is simulated by point flow load. 200m to the left of the recharge well is an elevated pile foundation, with a width of 2.5m, a height of 0.4m, and a depth of 30m in the pile bearing layer, which is simulated by a one-dimensional rod unit.

Before recharge, in order to achieve the equilibrium of the ground stress and the equilibrium conditions of the pore pressure, the initial conditions of the model are set, under the initial conditions, the water table is located at the surface, the soil is in a water-saturated state, the hydrostatic pressure reaches equilibrium, so the pore pressure boundary of the model is set as follows: the top is the water table, and the pore pressure is zero; the left and right boundaries are both recharge boundaries, and the pore pressure is unchanged, and it is always the hydrostatic pressure, and the hydrostatic head has a shallow depth of 156m, and the pore pressure is 1.5288Mpa. The bottom depth is 156 m, and the pore pressure is 1.5288 Mpa. The displacement boundary conditions of the model are: the left and right boundaries are constrained by lateral displacement, i.e., the lateral displacement is zero, and the bottom boundary is constrained by displacement, i.e., the lateral and vertical constraints are both zero.

2.2. Calculation parameters and analytical methods

The calculation parameters of the elevated pile foundation and bearing platform are as follows: modulus of elasticity $\mathrm{E} = 3\mathrm{Gpa}$, Poisson's ratio $\mu = 0.2$, density $\rho = 2000\mathrm{kg/m^3}$, long term load is taken as $\mathrm{p_1} = 150\mathrm{kPa}$, live load during the operation period is taken as pa=15kPa, and the ground uniform load is 15kPa, which is combined with the survey report on the section of elevated highway of Xiong'an New Area of the North China Plain to the Express Line of Beijing Daxing International Airport (mileage of approx. $\mathrm{K90} + 900$～$\mathrm{K113} + 630$), it can be seen that below the surface of this section is the recent sedimentary soil of Holocene alluvial cause in the Quaternary period, and the following is the general deposition of powdery clay, silt and sand, and then down to the late Pleistocene alluvial cause in the Quaternary period of clay, silt clay, silt and silt layer, so the soil body is roughly divided into 8 layers, and get the calculated parameters of the soil layers as follows, of which The third layer of soil is the pressurized aquifer soil, which is the main recharge soil layer, in the table: H is the depth of the layer; γ is the heaviness; μ is Poisson's ratio; E is the modulus of elasticity; k_v is the longitudinal permeability coefficient; k_h is the transverse permeability coefficient. Combined with the above parameters in abaqus software to establish the model as shown in Figure 2.

Table 1. Soil layer calculation table

Floor number	Soil layer name	H/m	$\gamma(kN\cdot m^{-1})$	μ	E/MPa	$k_v/(\mu m\cdot s^{-1})$	$k_h/(\mu m\cdot s^{-1})$
1	silty clay	3.5	18.5	0.28	19.5	1.8×10^{-3}	3.2×10^{-3}
2	sand	13	16	0.25	32	3.6×10^{-3}	6.2×10^{-3}
3	clay	22	18	0.4	120	1.05×10^{-4}	2.65×10^{-4}
4	sandy soil	29	17.5	0.23	110	1.0×10^{-1}	2.0×10^{-1}
5	silty clay	62	18.5	0.28	21	1.85×10^{-3}	3.3×10^{-3}
6	sand	108	16.8	0.25	36	3.6×10^{-3}	6.6×10^{-3}
7	powdered sand	136	19.5	0.3	70	1.5×10^{-1}	3.5×10^{-1}
8	clay	156	17.5	0.4	120	1.05×10^{-4}	1.65×10^{-4}

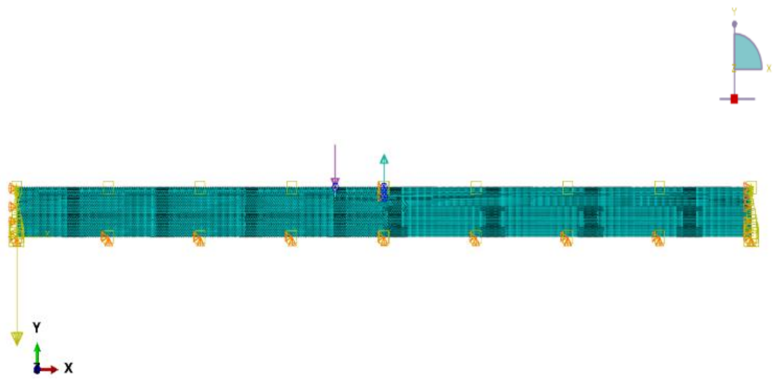

Fig. 2 Model diagram of the numerical value

2.3. Analysis of numerical results

The above numerical model was selected, the recharge time was set to 1 year, the recharge flow rate $Q=5\times10^{-6}m^3/s$, the depth of the recharge well was set to 60m, and the results obtained after using abaqus finite element analysis are shown in Figs. 3 and 4.

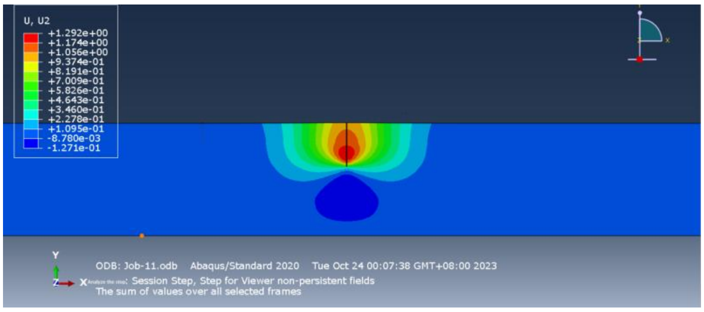

Fig. 3 Vertical displacement diagram of the model

From the above figure, it can be seen that the final soil augmentation is approximately symmetrically distributed, with a larger amount of soil augmentation above the recharge wells, whereas the soil below the recharge wells settles instead, and there is an insignificant rise in the elevated pile foundations.

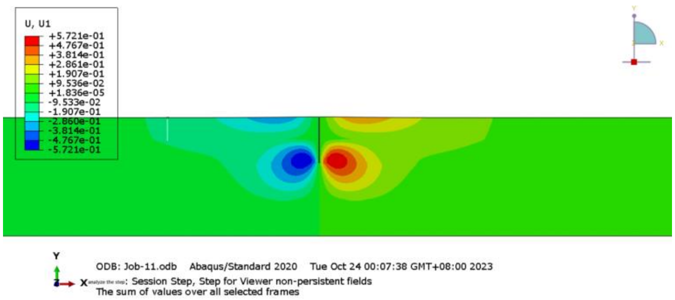

Fig. 4 Horizontal displacement diagram of the model

The displacement of the soil in the horizontal direction is also symmetrically distributed, are displaced in the direction away from the center, in which the soil displacement around the recharge well is the largest, it can be seen that the pile foundation also has a smaller displacement in the direction away from the center.

3. Impact analysis of recharge parameters

In order to further explore the effect of groundwater recharge on pile foundation, the above model is used as a basic example to numerically analyze the parameters related to the settlement affecting the pile foundation.

3.1. Effect of depth of irrigation point

Assuming that the model is the above model, but changing the depth of a single well to 30m, 40m, 50m and 60m respectively to ensure that the recharge point is always in the pressurized aquifer for recharge, the recharge time is 1 year, and the recharge flow rate is $\mathrm{Q} = 5 \times 10^{-6} \mathrm{m}^3/\mathrm{s}$, the results are obtained as shown in Fig. 5.

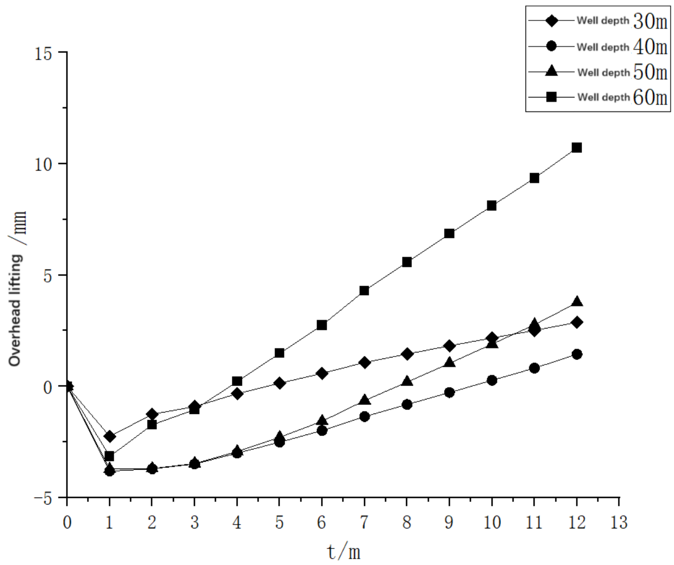

Fig. 5 Settlement of elevated pile foundation at different well depths

As can be seen from the figure, it is guaranteed that under the condition of the same pressurized aquifer, no matter at which depth the recharge point is, the elevated pile foundation is firstly settling and then bulging, the effect of recharge load is not obvious at the beginning, and the elevated pile foundation and the soil underneath are all settling due to their own gravity, but with the growth of recharge time, the effect is gradually obvious, and the elevated pile foundation is bulging along with it. And it can be noted that the elevated pile foundation bulging amount increases with the increase of the depth of the recharge point, i.e., the greater the depth of the recharge point, the greater the influence of recharge load on the deformation of the elevated, which is caused by this phenomenon is that, when recharge is carried out in the deeper soil layer, due to the effect of infiltration or cross-flow, it has a different degree of influence on the overlying soil layer, and the deeper the depth of the point of irrigation, the wider the influence on the soil layer, i.e., the soil layer above the point of irrigation will have more influence on the soil layer. That is to say, the soil layer above the irrigation point will have a certain amount of expansion under the influence of recharge load, and the deformation of the elevated pile foundation is mainly affected by the deep soil layer, that is to say, the soil layer below the bearing layer of the elevated pile foundation plays a key role in its settlement or uplift, so the deeper the depth of the recharge point, the wider the scope of the deep soil layer is affected, and the more the amount of uplift of the deep soil layer will be, so as to make the elevated pile foundation produce larger uplift.

However, this phenomenon is not absolute, as can be seen from the figure, when the depth of the recharge point is in transition from 40m to 50m, the elevated pile foundation's uplift volume shows inverse growth, i.e., the final uplift volume of the pile foundation when the depth of the recharge point is 40m is greater than that when the depth of the recharge point is 50m, which is obviously inconsistent with the speculated results, but combining with the previous lateral displacement diagram, it can be found that the soil body will move slightly in horizontal direction as shown in Fig. 6 when the depth of recharge point is increased, and it is speculated that the horizontal displacement of the soil body will also become larger. Horizontal direction will also have a slight movement as shown in Fig. 6, and with the increase of the depth of the recharge point, the wider the range of soil layer affected by recharge, it is presumed that the horizontal displacement of the soil body will become larger, which will lead to a greater inclination of the elevated pile foundation along with the surrounding soil body, and the vertical uplift will also decrease with the increase of the depth of the recharge point. Therefore, the abaqus software again derives the lateral displacement diagrams of the pile foundation at the depths of 30m, 40m, 50m and 60m in the recharge point as shown in Figs. 7, 8, 9 and 10, and derives the relationship between the displacement of the top and bottom of the pile foundation with the change of time as shown in Figs. 11 and 12.

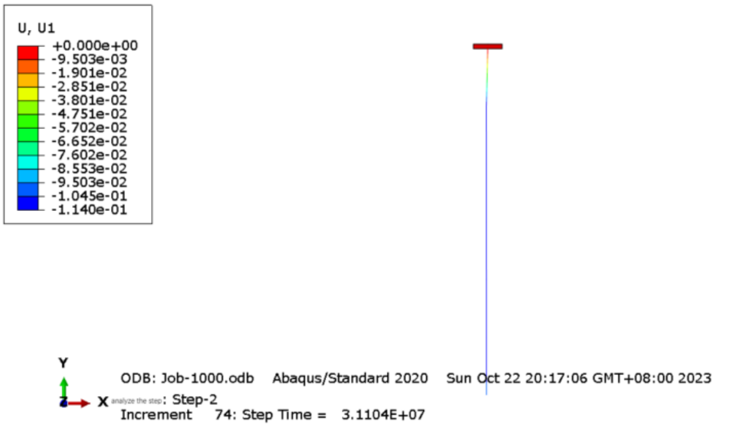

Fig. 6 Horizontal displacement diagram of pile foundation

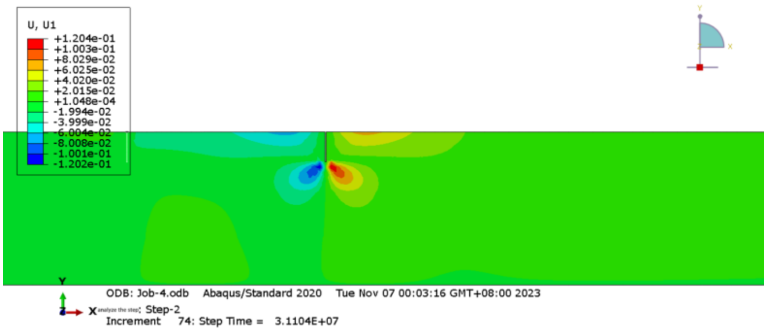

Fig. 7 Vertical displacement map for a single well at a depth of 30m

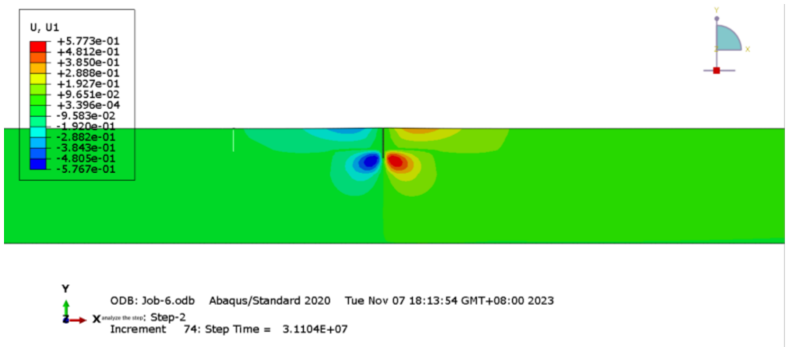

Fig. 8 Vertical displacement map for a single well displacement of 40m

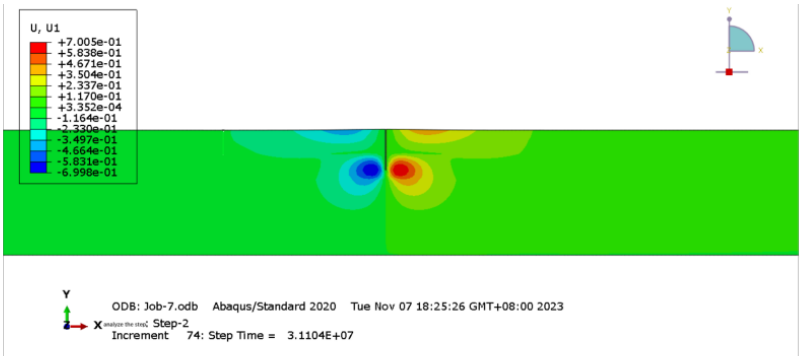

Fig. 9 Vertical displacement map for a single well displacement of 50m

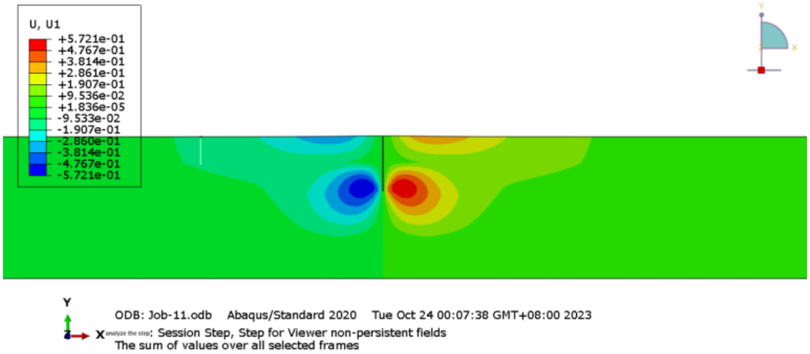

Fig. 10 Vertical displacement map for a single well at a depth of 60m

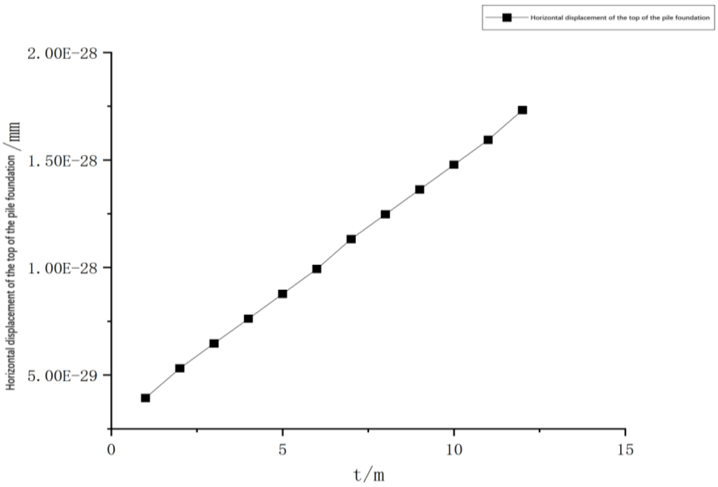

Fig. 11 Horizontal displacement map at the top of the pile foundation

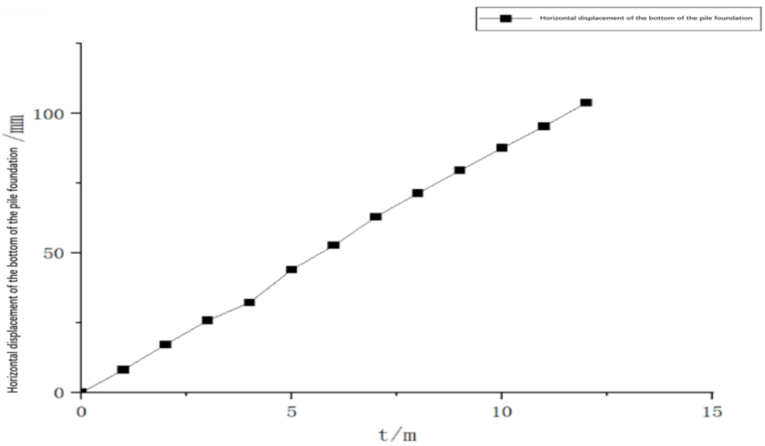

Fig. 12 Horizontal displacement map at the base of the pile foundation

From the above figure, it can be seen that the displacement at the bottom of the pile foundation is relatively large, but the displacement at the top is very small and almost negligible. The reason is that the bottom of the pile foundation is deeper and closer to the recharge point, and the horizontal displacement of the soil around here is larger due to the recharge effect, while the top of the pile foundation is farther away from the recharge point, and the effect of the soil around here by the recharge effect can be almost ignored. From this, it can be argued that the pile foundation did produce relatively large horizontal displacement due to recharge, and as the depth of recharge becomes larger, the wider the range of soil layer affected by recharge, the horizontal displacement of the soil body also becomes larger, which also leads to a greater inclination of elevated pile foundation along with the surrounding soil body, resulting in the reduction of its vertical uplift.

3.2. Impact of recharge flow rate

The above model is still used, but change the recharge flow rate, the irrigation volume were $Q1 = 5 \times 10^{-6} m^3/s$, $Q2 = 4 \times 10^{-6} m^3/s$, $Q3 = 3 \times 10^{-6} m^3/s$, $Q4 = 2 \times 10^{-6} m^3/s$, $Q5 = 1 \times 10^{-6} m^3/s$, the time of recharge is one year, and the depth of the recharge wells is set to 60m, and the results are shown in Fig. 13.

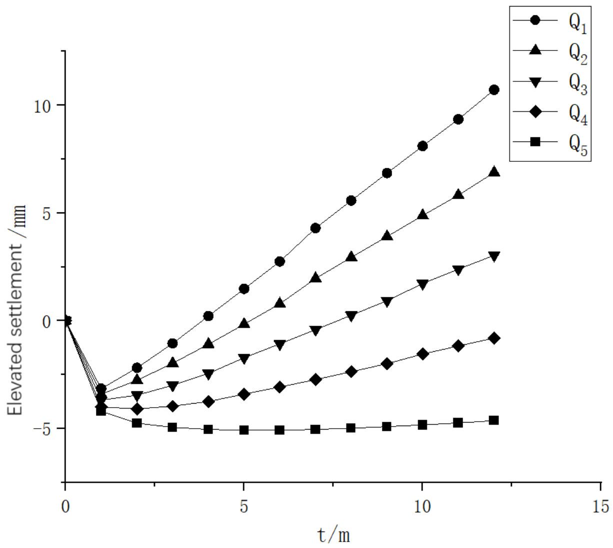

Fig. 13 Elevated settlement map with different recharge flow rates

Based on the figure, it can be observed that under the influence of recharge load, the elevated pile foundations exhibit a gradual uplift deformation characteristic. Among these, the maximum uplift occurs at the 12th month when the recharge flow rate is $Q1 = 5 \times 10^{-6} m^3/s$. It can be inferred from this figure that as the recharge load flow rate increases, its effect on the deformation of the elevated pile foundations also increases. Specifically, the pile foundations will experience greater uplift under the influence of higher recharge load. Conversely, when the recharge load flow rate is relatively small, its impact on the pile foundations is minor. In such cases, the pile foundations still undergo settlement under the combined effects of self-weight and superimposed loads. There exists a critical value for the uplift and settlement of the elevated pile foundations, approximately at $Q5 = 1 \times 10^{-6} m^3/s$.

4. Summary

From the above analysis, the following conclusions can be drawn:

Firstly, as time progresses, the impact of recharge becomes increasingly evident. Under the combined influence of upper load and recharge, the elevated pile foundation and the shallow soil layer experience a sequence of settlement followed by uplift. Notably, the deformation of the elevated pile foundation is predominantly governed by the deformation of the deep soil layer, specifically the soil beneath the pile foundation retaining layer.

Secondly, as the depth of the recharge point increases, it leads to a broader scope of influence on the deep soil layer, consequently resulting in a greater magnitude of uplift in the deep soil layer. Correspondingly, the uplift of the elevated pile foundation also increases proportionally.

Thirdly, with the increase in depth of the recharge point, the influence on the soil layer expands, resulting in a larger horizontal displacement of the soil mass. Consequently, the elevated pile foundation tilts along with the surrounding soil mass, leading to a reduction in the uplift amount. The final uplift magnitude is determined by the interplay of these two factors, typically with the former being predominant. However, the influence of the latter should not be disregarded.

Lastly, in addition to the settlement of the elevated pile foundation being influenced by the depth of the recharge point, it is also affected by the magnitude of the recharge load flow. A higher recharge flow rate results in a greater amount of bulging. There exists a critical value of recharge load flow at which neither bulging nor settlement occurs in the vicinity of the elevated pile foundation. This critical value provides valuable insights for predicting and controlling the settlement of the elevated pile foundation.

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