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THE RESEARCH OF THE VARIATION LAWS OF SETTLEMENT AND INTERNAL FORCE OF PILE GROUPS OF RAILWAY BRIDGE CAUSED BY PUMPING BRINE

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ABSTRACT

Taking Yingzigou Bridge of Dezhou-Dajiawa railway as the engineering background, the three-dimensional fluid-solid coupling models of pile group caps were established on the basis of five-stage field monitoring data of the settlement and groundwater level drop by using FLAC3D software. On the basis of the field monitoring data checking, the variation of axial force and skin friction of piles at different positions under the condition of water level drop was simulated. The results show that with the underground water level dropped, the axial force of pile along the shaft increased first and then decreased. The cross section of maximum axial force moved down constantly. In the same ground water levels drop, the distance between the maximum axial force and neutral point of each pile and the top of the pile was corner pile > side pile> near borehole center pile > center pile. The size of the pile axial force and negative skin friction resistance was corner pile > side pile> near borehole center pile > center pile. The upper part of the pile was subjected to negative skin friction resistance. The skin friction resistance of each pile along the shaft increased first and then decreased. The lower part of the pile was subjected to positive skin friction resistance. The skin friction resistance of each pile along the shaft increased. The location of the maximum negative friction resistance was about 10m distance from the top of the pile. The maximum negative friction resistance of corner pile was -36.5kPa. The distance of neutral point of center pile from the top was 35.2m. The neutral point of each pile was in accordance with the position of the maximum axial force of the pile. A reliable basis was provided for high-speed railway survey and design and the prevention and control of land subsidence along the railway.

KEY WORDS

Skin friction, Pile groups, Pumping water, Groundwater level drop, Neutral point, Axis force

INTRODUCTION

The brine wells were densely distributed along Dezhou-Dajiawa railway. The regional subsidence in DK228+800-DK257+500 of Dezhou-Dajiawa railway resulted from the over mining of underground brine in the adjacent area of pile foundation of railway bridge. The skin friction resistance was produced on the pile groups of the bridge (XIA et al 2012, WU et al 2008). It would adversely affect the bearing performance and settlement control of the pile and even the geometry of the line and the running quality of the train. To ensure the safety and efficiency of high-speed railway operation, it was very important to calculate the settlement and internal force of the pile caused by the groundwater level drop. At present, the main methods of calculating the settlement of the foundation pile are elastic theory method (ZHAO et al 2004, SHEN 2008), shear displacement method (ZHAO et al 2008), load transfer method (JIA et al 2015, HONG et al 2004), numerical analysis method (XIA et al 2012, COMODROMOS et al 2005), model experiment(YANG et al 2008, LIU 2015, HE et al 2002), field test (CHEN et al 2000, XIA et al 2009), and more[1-4]. According to the generation mechanism of skin friction resistance of the pile, the estimation of skin friction resistance could be attributed to the determination of the depth of neutral point and the strength of skin friction resistance. However, there were many factors that influenced the skin friction resistance of piles [5-8]. The current methods were approximate or empirical, and it was impossible to consider the fluid-solid coupling process of the foundation settlement of piles caused by pumping (WANG et al 2014, LIU et al 2013, and XU et al 2013). There are little literatures on the internal force of piles in field tests. Based on the measured settlement data in the field, it was an important method to study the settlement and internal force of pile foundation under pumping conditions by using numerical analysis method, which could consider various influencing factors. The reference could be provided for survey and design and the ground subsidence control along the high-speed railway [9-12].

MONITORING ANALYSIS OF PILE FOUNDATION OF BRIDGE DURING BRINE WELL MINING

The construction of Dezhou-Dajiawa railway started in November 2010. The monitoring of ground subsidence started on 21 April 2014. The settlement value was set at 0. The monitoring values for subsequent periods were added. The five stages of monitoring were conducted by 15 September 2015. The accumulated ground subsidence of DK246~DK249 and DK252~DK257 sections along Dezhou-Dajiawa railway was serious. The central distance of Yingzigou Bridge in the serious settlement area was DK247+724.0. The length of the bridge was 132.6m. The span of bridge was 5 spans. Each span was 24m. The upper structure of the bridge was continuous pre-stressed concrete T beam. The lower bridge deck adopted rib deck. The layout of settlement marks of the bridge piers was shown in Figure 1. The piers was cylindrical and the piers were frictional pile foundation. The piers contained nine single piles with 45m length and 1m diameter. The distribution of piles was rectangular distribution. The spacing of piled was 3.4m and 4.1m. The distance between the centers of the pile with the edge of the bearing bed was 1.15m. The pile and the bearing bed were rigid connection. The size of pile groups and bearing bed was shown in Figure 2.

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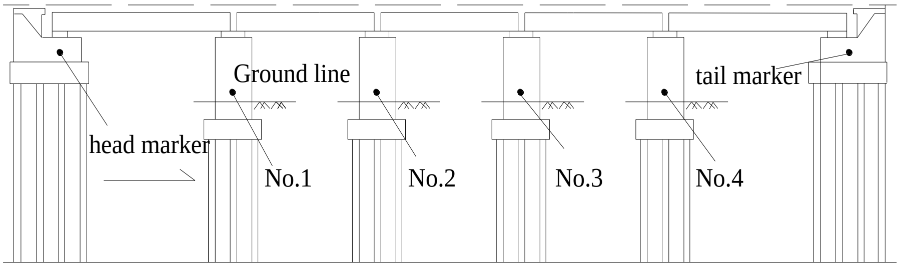

Fig. 1- Arrangement diagram of pier settlement observation mark

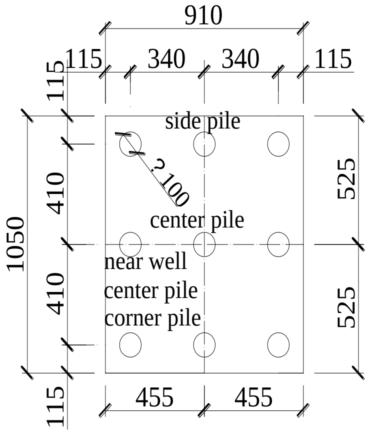

Fig.2 - The size of pile groups and bearing bed (unit: cm)

The settlement curves of the bridge piers at each stage were shown in Figure 3. The subsidence of the bridge piers was about -26mm in August 2014 to December. The maximum difference settlement between the two piers was 5.2mm and the difference settlement at the head and end of the bridge was 12.5mm and 17.7mm respectively. The settlement of bridge piers was relatively low in December 2014 to March 2015, and there was a trend to accelerate the settlement of bridge piers in March 2015 to September 2015. The maximum cumulative settlement was 106mm by September 2015. The bridge piers showed a trend of uneven settlement with a maximum difference of $3^{\#}$-$4^{\#}$ and a difference of 5mm. The brine mining is mainly carried out in the form of water well pumping. With the increase of the exploitation of brine water resources, the dynamic and static water level of brine continues to decline. The water level drop value reached -47.5m on September 15, 2015.The settlement values of $3^{\#}$ bridge piers and the monitoring values of the nearby groundwater level were shown in Table 1. With the decline of the groundwater level, the funnel-like settlement of the ground gradually increases, and the regional land subsidence along the railway seriously weakens the stability of the pile foundation of the railway bridge and makes the differential settlement of the bridge.

The three-dimensional fluid-solid coupling models of group piles with pile cap were established on the basis of five stage field monitoring data of the settlement and groundwater level drop by using $FLAC^{3D}$ software [13-17]. On the basis of the field monitoring data checking, the variation of axial force and skin friction of pile bodies at different position under different conditions of water level drop of pumping well was simulated.

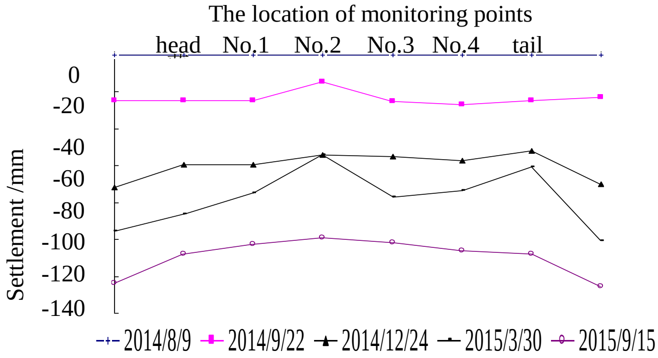

Fig.3 - Settlement curve of Yingzigou bridge piers

Tab.1 - Settlement of 3# pier and groundwater level at different time

Date	2014/8/9	2014/9/22	2014/12/24	2015/3/30	2015/9/15
Settlement/ mm	-6.6	-25.2	-55.2	-77.0	101.8
Groundwater level drop/m	-9	-26.7	-33.1	-40.2	-47.5

NUMERICAL SIMULATION OF SETTLEMENT AND INTERNAL FORCE OF PILE GROUPS DURING GROUNDWATER PUMPING

The fluid-solid coupling models of group piles with pile cap

The dimension of fluid-solid coupling models of pile group caps was 350m× 350m × 80m. The elastic-plastic material was used to simulate the behaviour of non-linear soil. The elastic model was adopted for concrete pile. The physical and mechanical parameters of soil and pile were shown in Table 2.

The pumping well was a square with 2m long and the depth was 80m. The center of well group was 47m away from the center pile groups. The pile-soil interface uses displacement method to establish the contact surface. The meshes of the soil and well under the bearing platform were closely divided. The meshes of the soil on both sides were sparse. The pile adopted the gradient radiation grid, and the finite difference model of soil and pile groups was shown in Figure 4.

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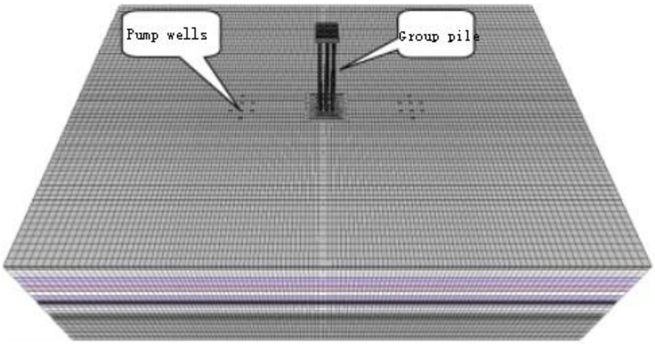

Fig. 4 - Finite difference model of soil and pile groups

Tab.2 - Calculation parameters of soil and pile group

The type of soil	Thickness/ m	Density / g/m³	Moisture content	Porosity	Cohesion /KPa	Internal friction angle /º	Bulk modulus /MPa	Shear modulus /MPa	Permeability coefficient; /m²/Pa-sec
silty clay	2.5	1.88	31.3%	0.47	28.5	7.9	7.79	4.59	2×10^{-12}
silt	6.5	1.96	21.6%	0.38	20.5	30.5	4.78	3.28	5×10^{-11}
silty clay	7.9	1.88	23.3%	0.39	27.7	9.0	5.6	3.76	2.2×10^{-12}
silt	9.8	2.03	21.6%	0.36	20.5	30.5	4.95	3.56	3.2×10^{-12}
silty clay	6.4	1.91	23.1%	0.37	27.0	8.9	5.6	3.77	2.2×10^{-12}
silt	7.1	1.93	20.3%	0.37	28.0	11.4	5.31	3.59	2.1×10^{-12}
silt	7.3	1.98	20.4%	0.36	21.5	25.8	4.68	3.18	4.6×10^{-11}
silt	32.5	2.07	21.1%	0.36	22.5	26.8	17.53	4.78	3.2×10^{-12}
pile caps	2.5	2.5	-	-	-	-	15600	11700	0
Pile	45.0	2.5	-	-	-	-	15600	11700	0

The permeability coefficient of the soil in Table 1 decreased gradually with the continuous pumping water.

The vertical constraint was set at the bottom boundary. The horizontal constraints were set at the boundary along the side face direction. The bottom of the model was non-permeable boundary. The side and top of the model were permeable boundaries. When pumping simulation was carried out, the pore water pressure above the water level line in the well was fixed at 0. The Initial ground stress was obtained by applying gravity loads on the model. The pore water pressure was applied to the model according to the groundwater level. A uniform load of 2000kN was applied to the top of the platform. The groundwater level reduced from -9m to -47.5m in simulation, then remained stable. Since the pile foundation has been settled under the action of load and groundwater level drop from construction completion of the Yingzigou Bridge to the arrangement of monitoring points. The initial settlement was set to 0. The cumulative settlement value of the bridge pile foundation was fitted by adjusting soil parameters, permeability coefficient and precipitation

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depth. On this basis, the groundwater level monitored on September 15, 2015 was taken as the final water level, the final settlement of pile foundation was predicted, and the settlement of pile and its internal force were analysed by considering the influence of water level drop of brine well and the quantity of pumping well. The calculation time of seepage flow in FLAC^{3D} software was consistent with the monitoring interval.

The effects of water level drop of brine well on the pile foundation of bridge

The research programme was as follows. Eight wells were arranged on each side of the pile foundation. The center distance of two wells was 6m. The water level in the well dropped to -9m, -26.7m, -33.1m, -40.2m, -47.5m respectively. The pressure above the water level line was set to 0Pa and the pore water pressure in the soil surrounding the group well was set according to the actual head. By reducing the water level to a specified level, the settlement of piles tended to be stabilized as the standard for the calculation of termination fluid solid coupling. The variation law of settlement and internal force of pile foundation under different water level was analysed.

The effects of water level drop of brine well on the surface settlement of well groups

The pore water pressure at the bottom of the well was converted to the height of water surface. The infiltration curve of soil at different groundwater level drop was shown in Figure 5. It can be seen that the water level in the well and the soil layers was the same. The infiltration curve was funnel-shaped. The influence range of water pumping increased. And the water level in the soil layers at the same location decreased with the continuous drop of water level in the well.

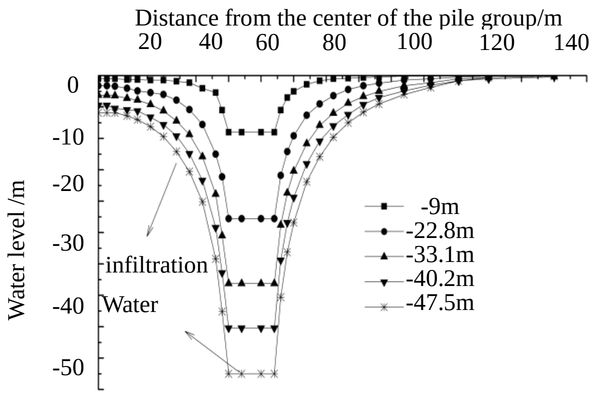

Fig. 5 - The infiltration curves of soil layer around the well groups at different water level drop

The ground subsidence curve within 100 m of the center of well groups at different groundwater level drop was shown in Figure 6. It can be seen that the ground subsidence at the same position increased, the range of ground subsidence increased with the continuous drop of water level in the well. The ground subsidence curve was funnel-shaped. The settlement of the ground in the center of the group well was severe and the settlement was large.

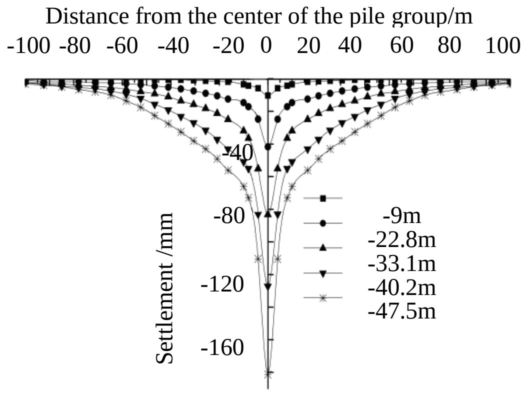

Fig. 6 - Ground settlement curve at different water level drop in wells

The effects of water level drop of brine well on the initial force of pile groups

The settlement curve of the top of pile groups at different groundwater levels drop was shown in Figure 7. It can be seen that the settlement of the piles increased gradually with the decrease of the water level in the pumping well. When the water level in the well is lower than 9m, the settlement of the pile was smaller. The settlement of the top of pile groups was proportional to the drop depth of water level in well.

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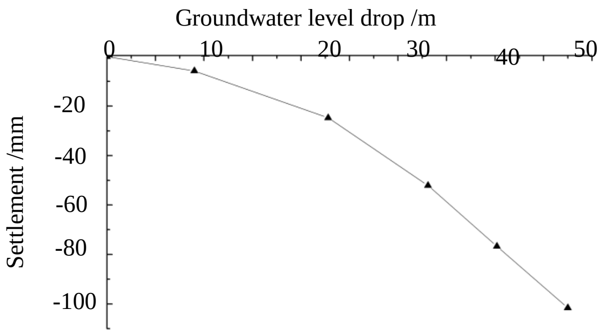
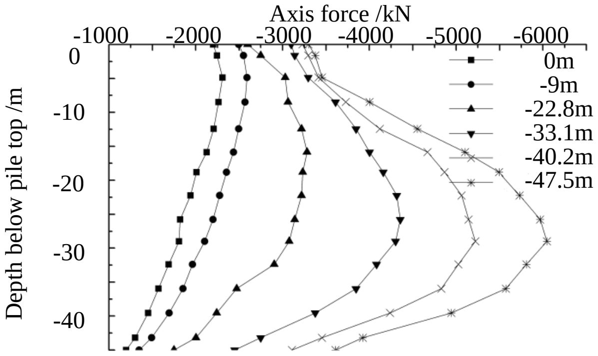
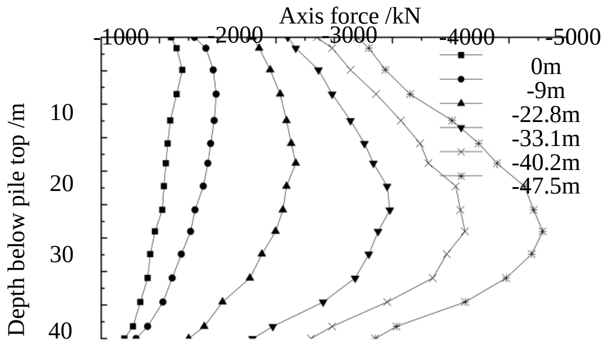


Fig. 7 - The settlement curve of the top of pile groups at different groundwater levels drop

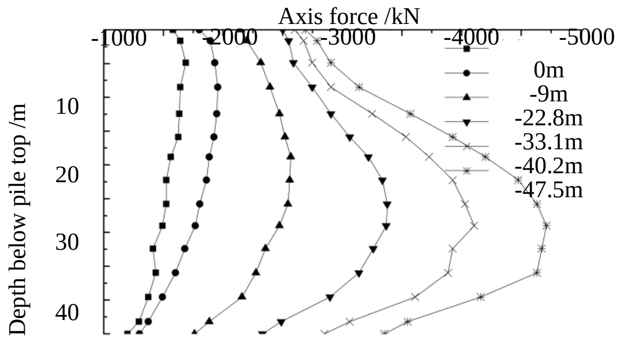
The variation curves of axial force of different piles at different groundwater levels drop were shown in Figure 8. It can be seen that with the continuous drop of groundwater level in the well, the axial force of the piles along the shaft increased first and then decreased. The axial force of the piles increased and the position of cross section of the maximum axis force moved downward. When the groundwater level drop was -47.5m, the axis force of corner pile was the largest. The maximum axial force was 6054.8kN. In the same groundwater level drop, the size of axial force of the file was corner pile>side pile>near borehole center pile > center pile. The order of the distance from the cross section of maximum axial force to the top of the pile was center pile>near well center pile> side pile >corner pile. When the groundwater level drop was -47.5m, the maximum distance from the cross section of maximum axial force to the top of the center pile was 36.1m.



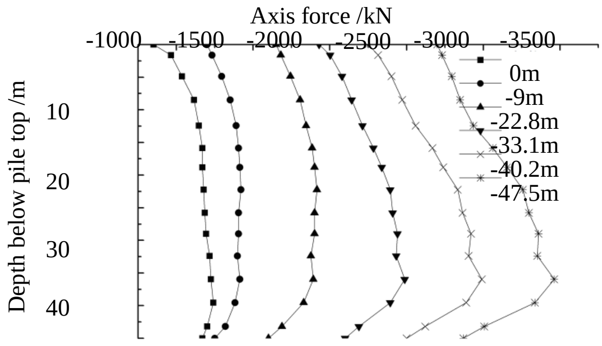
(a) Corner pile



(b) Side pile



(c) Near well center pile



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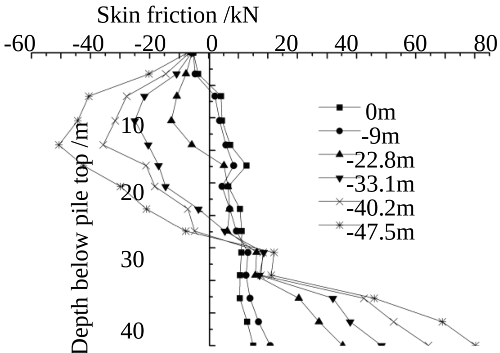
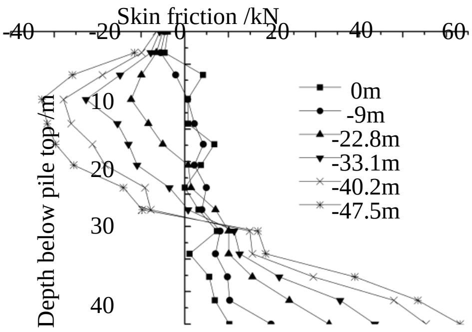
(d) Center pile

Fig.8 - The variation curve of axial force of different piles along the pile shaft at different groundwater levels drop

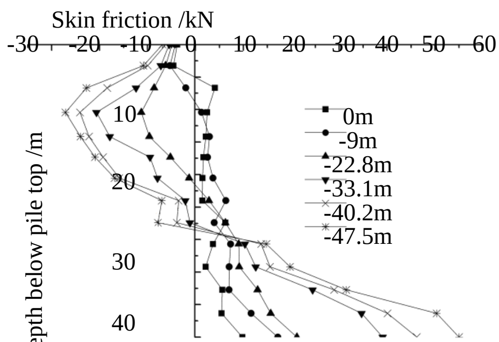
The variation curve of the skin friction resistance of the corner pile along the pile shaft along the pile shaft at different water level drop was shown in Figure 9. It can be seen that:



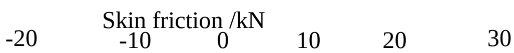
(a) Corner pile

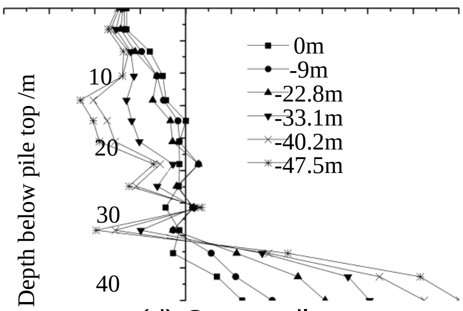


(b) Side pile



(b) Near well center pile





(d) Center pile

Fig.9- The variation curve of the skin friction resistance of different piles along the pile shaft at different groundwater levels drop

The pile around the top of the pile was subjected to negative skin friction resistance at different water level drop. When the water level drop in the well was lower than 9m, the pile was mainly affected by positive skin friction resistance, which increased gradually along the pile shaft. With the constant drop of water level in the well, the scope of the negative friction resistance in the upper part of the corner pile became larger and larger. In the negative friction resistance area, the negative friction resistance increased firstly and then decreased with the increase of depth of the pile. The position of the maximum negative skin friction resistance of corner pile, side pile and near well center pile was about 10m below the top of the pile. The order of negative friction resistance of corner pile was -36.5kPa.

With the drop of the groundwater level, the neutral point of each pile gradually moved down, and each pile was affected by positive friction below the neutral point and increased gradually along the pile shaft, the skin positive skin friction resistance reached the maximum in the bottom of the pile. When the groundwater level drop was -47.5m, the maximum positive skin friction resistance of corner pile was 90kPa. In the same ground water levels drop, the size of positive skin friction resistance was corner pile > side pile> near well center pile > center pile. The order of the distance between neutral point of each pile and the top of the pile was center pile > near well center > side pile > corner pile. When the groundwater level drop was -47.5m, the maximum distance from neutral point to the top of the center pile was 35.2m. The position of the neutral point of each pile was basically the same as the position of cross section of the maximum axial force of the pile.

The central pile was mainly affected by negative skin friction resistance in the range of 0 ~ 35m below the top of the pile. The pile was mainly affected by positive skin friction resistance in the range of 35m ~ 45m below the top of the pile. The cross-section position of the neutral point of the central pile was less affected by the water level in the well. There were multiple neutral points in center pile.

CONCLUSIONS

1) The curves of infiltration and ground subsidence were funnel-shaped. The influence range of water pumping increased. And the water level in the soil layers at the same location decreased with the continuous drop of water level in the well. The ground subsidence at the same position

increased, the range of ground subsidence increased with the continuous drop of water level in the well. The settlement of the ground in the center of the group well was severe and the settlement was large.

2) With the continuous drop of groundwater level in the pumping well, the axial force of the piles along the pile shaft firstly increased then decreased. The axial force of the piles increased and the position of cross section of the maximum axis force moved downward. In the same groundwater level drop, the size of the pile axial force was corner pile > side pile> near borehole center pile > center pile. The order of the distance from the cross section of maximum axial force to the top of the pile was center pile > near well center pile > side pile >corner pile. When the groundwater level drop was -47.5m, the maximum distance from the cross section of maximum axial force to the top of the center pile was 36.1m.

3) With the drop of the groundwater level, the neutral point of each pile gradually moved down, and each pile was affected by positive friction below the neutral point and increased gradually along the pile shaft, the skin positive skin friction resistance reached the maximum in the bottom of the pile. In the same ground water levels drop, the size of positive skin friction resistance was corner pile > side pile> near well center pile > center pile. The order of the distance between neutral point of each pile and the top of the pile was center pile > near well center > side pile > corner pile. The position of the neutral point of each pile was basically the same as the position of cross section of the maximum axial force of the pile.

4) The central pile was mainly affected by negative skin friction resistance in the range of 0 ~ 35m below the top of the pile. The pile was mainly affected by positive skin friction resistance in the range of 35m ~ 45m below the top of the pile. The cross-section position of the neutral point of the central pile was less affected by the water level in the well. There were multiple neutral points in center pile.

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