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Field Test Study on Construction Disturbances of Driven Pile and PGP Pile

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Abstract: The pre-bored grouted planted (PGP) pile has been more and more used in recent years, but its precise disturbance effect in soft soil areas has not been studied deeply. Therefore, a comparative field test for the disturbances by PGP pile and driven pile construction in deep soft ground was carried out. It revealed that the excess pore pressure caused by the two kinds of piles decreases with the increase of radial distance, and the influence range is less than 7.5 *d* (*d* is pile diameter). The maximum excess pore pressure generated by PGP pile construction is about 100 kPa smaller than that generated by driven pile construction. The comparison of the soil pressure and lateral displacement between the two piles is related to the depth and soil type. The typical result is that the soil pressure caused by PGP pile construction is half that of the driven pile, and the maximum lateral displacement of the PGP pile is 50.7~53.8% of that of the driven pile. The noise generated during PGP construction was lower but continuous, and the maximum value at the same distance was reduced by 8 to 15% than the driven pile. The test results reveal the construction disturbance effect of PGP pile and provide a reference for the selection of pile construction method in soft soil areas.

Keywords: saturated soft clay; driven pile; pre-bored grouted planted pile; field test; pore water pressure; soil squeezing effect

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Citation: Shao, F.; Deng, Y.; Chen, S.; Zheng, R.; Zhang, R. Field Test Study on Construction Disturbances of Driven Pile and PGP Pile. *Appl. Sci.* **2023**, *13*, 11887. https://doi.org/10.3390/app132111887

Academic Editor: Syed Minhaj Saleem Kazmi

Received: 27 September 2023
Revised: 24 October 2023
Accepted: 28 October 2023
Published: 30 October 2023

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1. Introduction

Pile foundation is a deep foundation technique with a long history and wide engineering application due to its economic and stability advantages. Among the various types of piles, precast and cast-in-place piles are the most widely used. Precast piles have the benefits of consistent quality and inexpensive cost, but their application is restricted by construction noise and soil compaction. Cast-in-place piles do not produce soil-squeezing effects but usually have higher costs and longer pile formation times. Since the 1980s, Japanese scholars pioneered the precast nodular pile and prestressed high-strength concrete (PHC) nodular pile to increase the pile frictional resistance [1,2], and proved that these piles are a favorable foundation choice for deep soft soil sites [3]. In 2010, Chinese scholars developed the PGP pile method based on the above technology from Japan. The PGP pile technology uses a spiral drill to bore a hole into the design elevation and then constructs an enlarged head at the hole bottom; cement soil is formed by injecting a certain proportion of cement slurry into the borehole and mixing it with the ground soil; PHC pipe pile is then planted into the pile hole fully filled with cement soil [4]. The PGP pile has the advantages of low noise, high durability, and high load-bearing capacity characteristics, and is an environment-friendly pile foundation [5]. Compared to the driven pile construction method, it reduces the disturbance of the surrounding soil and environment; compared to the cast-in-place pile method, it minimizes slurry discharge [6].

Previous studies have shown that pile foundation construction inevitably causes changes in pore water pressure around the pile [7] and soil structure [8,9]. After the pile penetrates the soil layer, the excess pore water pressure of the relevant soil increases to its maximum value rapidly and then decays exponentially over time [10]. The dissipation trend of pore water pressure by different pile construction methods usually is different [11]. The generated pore water pressure decreases with the distance [12–14], and it takes a longer time to reach the peak value in a deeper position [13]. Moreover, radial drainage along the diameter of the pile also influences the dissipation of excess pore pressure [15]. The peak excess pore pressure generated by open-end piles with radial penetration is lower, and the dissipation rate is faster [14,16,17]. Closed-end piles are often subjected to high soil rebound, and their permanent deformation is very small [17]. However, the soil's mechanical properties and the distribution of soil layers also have an impact on changes in pore water pressure [16,18], but similar boundary-scale responses have been observed when piles are driven in non-typical soils, like diatomaceous earth, which has a high intra-particle porosity, complex particle shapes, and uniform mineralogy [19]. During pile driving, negative surplus pore pressure around the pile close to the ground surface and below a certain depth beneath the pile tip will increase effective stress, hence increasing penetration resistance [20].

Furthermore, nodular cylinder piles will cause more significant disturbance to the surrounding soil, resulting in significant excess pore pressure below 2 m beneath the pile bottom but not evident below 4 m beneath the pile bottom. Soft clay layers have delayed dissipation of excess pore pressure, but surface soil layers dissipate excess pore pressure more quickly than deep soil layers [21]. In the squeezed pile construction, if the speed of pile driving is too fast or the pile spacing is too small, it may cause the pile body to tilt significantly [13]. The consequent lateral displacement of the soil decreases with distance [9], and for a period after construction, the lateral displacement of the soil and the excess pore water pressure continue to rise. As the excess pore pressure dissipates, the soil recovers displacement towards the pile [12], but the rate of rebound decreases over time [10]. Using model testing and finite element back-analysis of saturated sand, some researchers have explored the disturbance induced by pile construction. By applying high-frequency imaging recording and digital image correlation (DIC) technology, they successfully evaluated soil displacement near the penetrating pile [22], and using field tests as an example, verified the pile construction on the excess pore pressure and deformation of the existing tunnel around and away from the pile through the superposition principle [23]. The acceleration generated by pile driving is a high-frequency vibration, and the peak ground acceleration caused by pile driving attenuation is unrelated to pile depth but falls fast with increasing distance from the pile [9]. The soil behind the piles would move away from the excavation pit if the earth pressure caused by the construction of the piles was not correctly regulated and was over its initial earth pressure [21]. The ground vibration and excess pore pressure caused by vibratory pile driving are smaller than those caused by impact pile driving. Low-frequency driving creates more vibration than high-frequency driving, but the response of ground motion is determined by the frequency, type, and interactions of produced stress waves [24]. In addition, some numerical models based on meshless methods (EFG, RKPM, and so on) have been developed for the vibration analyses of pile foundation [25].

However, during the construction of driven pile and PGP piles, both soil pressure and excess pore water pressure increase, which lead to a potential compression and harm to nearby structures. And the vibration and noise negatively impact workers and the public. For PGP piles, the cement slurry injection will reduce the disturbance. But the risk persists in sensitive areas like the subway and pipelines surrounding the construction site.

The relevant research about PGP pile disturbance in deep soft soil areas has not been reported at present.

For the coastal geological conditions, the construction disturbance and environmental impact of PGP piles and driven piles are qualitatively and quantitatively studied and compared in this paper. The disturbance effect evaluation factors, including earth pressure,

lateral displacement, excess pore water pressure with depth and radial distance, and the vibration and noise responses of the surrounding soil, are tested during the construction of different piles. Based on these test results, the construction disturbance effects of the two types of pile are compared and analyzed, which provides an assessment of the scope of application of PGP piles in the project.

2. Test Overview and Arrangement

2.1. Geological Conditions

This study is conducted at a site in Ningbo City (Show location in Figure 1), covering an area of 23,339.9 m^2 with an elevation of about 4.0 m. A six-story dormitory building with a planned pile foundation is to be constructed. The site is in the Ning-Shao Plain, known for flat terrain and easy access. Ground elevation ranges from 3.02 to 4.75 m.

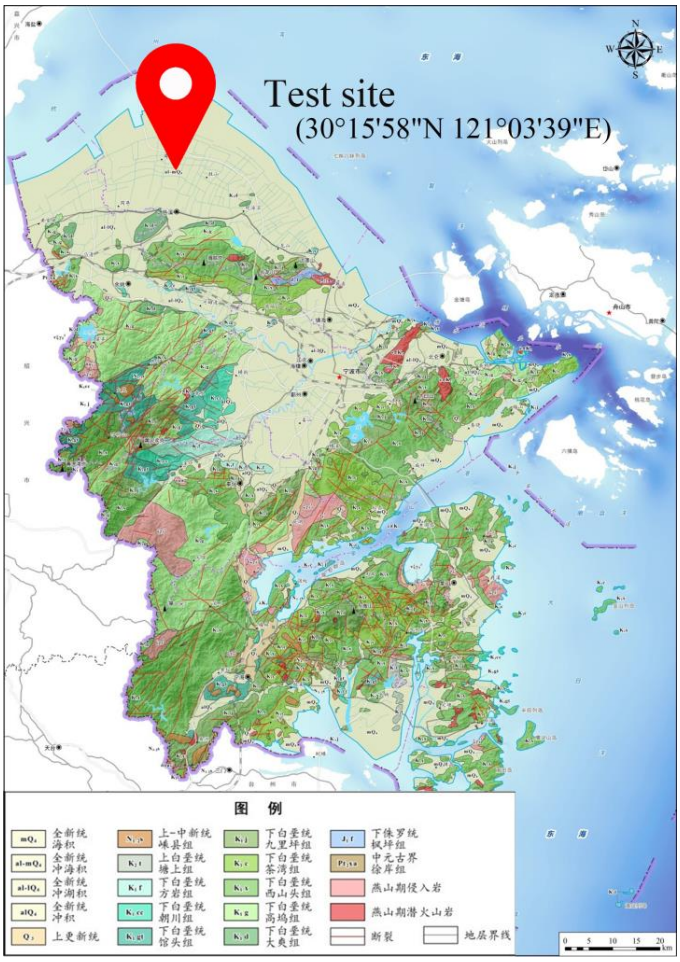


Figure 1. Location of the test site.

During the soil survey, standard penetration, borehole wave velocity, and other detection methods were used to test the physical parameters of the soil layer. And combined with indoor geotechnical testing, the foundation soil is divided into six main layers and twelve sub-layers. The physical and mechanical characteristics of these soil layers are presented in Table 1.

The site's upper section comprises various fill, clayey layers, and muddy soil layers. Close to the ground, vital transportation pipelines exist, and there is a factory building eastward and a mixing tower westward. If only prefabricated squeezed piles are used, construction's squeezing impact could cause soil lifting and lateral displacement, endangering nearby structures. Considering site data, building load, and environmental effects, driven and PGP piles were selected for the pile foundation design to mitigate these concerns.

Table 1. Soil layer and its basic parameters.

Soil Layer	Thickness (m)	w (%)	γ (kN/m^3)	e	w_L (%)	w_P (%)	Es (MPa)	c (kPa)	φ (°)
1-1 back-filling	1.7	-	-	-	-	-	-	-	-
1-2 clayey silt	2.3	28.8	18.9	0.809	33	24.3	6.3	12.7	17.8
1-3 muddy silty clay	2.1	40.2	17.7	1.124	36.9	21.5	3.29	11.3	10.2
3-1 clayey silt	2.9	27.8	19	0.783	33.1	24.1	9.1	12.6	20.5
3-2 clayey silt	7.3	28.6	18.9	0.809	33.3	24.3	8.9	12.6	20
3-3 sandy silt	3.2	26.8	19.1	0.761	32	23.4	11.4	12.4	20.9
4-1 muddy silty clay	8.7	39.6	17.7	1.107	36.5	21.5	3.32	11.7	10.4
4-1 silty clay	8.6	34.8	18.2	0.987	38.5	22.1	3.98	26	12.7
4-3 silty clay	6.1	34.9	18.2	0.978	38.2	22.8	3.9	25.4	14.3
6-1 clayey silt	0.8	25.7	19.3	0.734	31.1	22.6	8.3	12.3	21.5
6-2 fine sand	-	19.4	-	-	-	-	26	-	-

2.2. Pile Information

Two types of pile used: Driven pile with PHC500 (100) model, C80 concrete, L_1 = 44 m, assembled from 14 m and two 15 m sections. PGP pile with d = 600 mm, PHC400 (95) + PHDC500 (390) models, C80 concrete, L_2 = 45 m, assembled from 12 m bamboo joint pile and three 11 m prefabricated pipe sections, as shown in Figure 2.

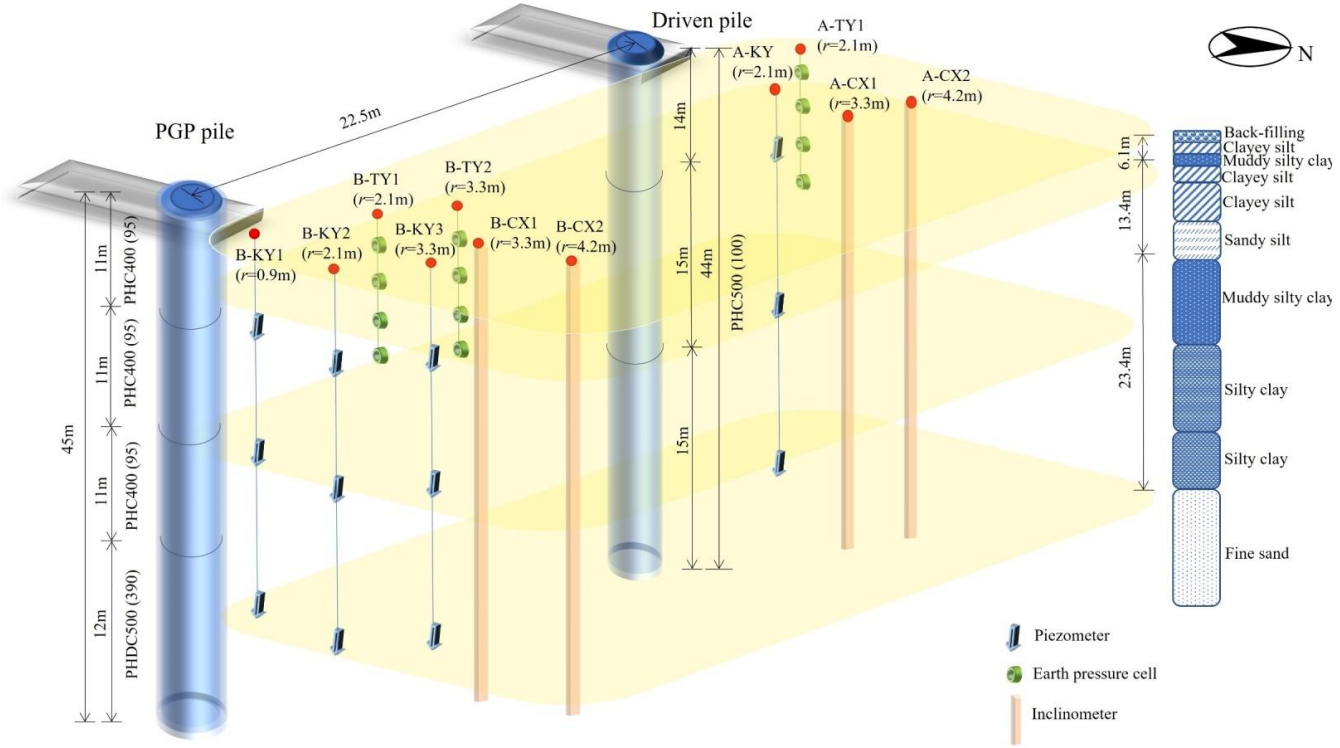


Figure 2. Measurement points.

2.3. Measurement Scheme

Trial piles were set up at two locations in the construction site's northeast corner to assess soil disturbance during pile construction. Tests included earth pressure, soil displacement, excess pore water pressure, vibration, and noise, as shown in Figure 3.

For the driven pile, one earth pressure hole was at 2.1 m from the pile axis, and two inclinometer points were at 3.3 and 4.2 m, respectively. A pore pressure hole was at 2.1 m. For the PGP pile, two earth pressure holes were at 2.1 and 3.3 m, respectively. Two inclinometer points were at 3.3 and 4.2 m, respectively, and three pore pressure holes were at 0.9, 2.1, and 3.3 m, respectively. Earth pressure cells were at depths of 4, 8, 12, 16 m,

respectively; inclinometer reaches a depth of 50 m; pore pressure gauges were at depths of 12, 22, and 32 m, respectively.

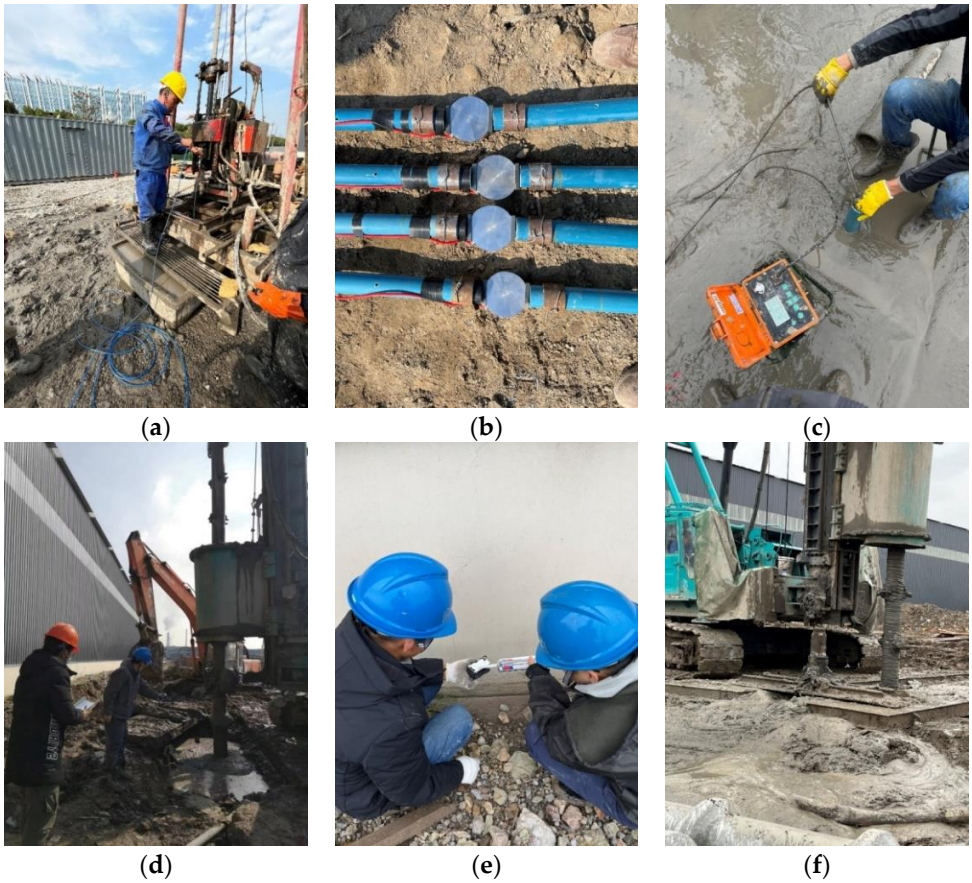


Figure 3. Sensors installation and monitoring. (**a**) Install the piezometer; (**b**) Install earth pressure cell; (**c**) Inclinometer measuring; (**d**) Noise monitoring; (**e**) Vibration accelerometer installation; and (**f**) The PGP pile construction.

Vibration accelerometers were placed on the pile driver, nearby building walls (r = 20 m), and a pipeline concrete column (r = 50 m) to measure driver vibrations. For the planting pile machine, accelerometers were on drilling and planting machines, building walls (r = 20 m), container workshop walls (r = 30 m), construction fence (r = 30 m), and pipeline column (r = 40 m). Noise levels were measured during construction at 1, 5, 10, and 20 m from the pile driver and planting machine.

3. Test Results

3.1. Earth Pressure

As pile components were pushed in, pressure shifted, highest at 12 m and lowest at 4 m. Post hammering, the pressure dropped, stabilizing in 2 h. Values of 4 and 8 m normalized in 24 h, 12 and 16 m stayed raised around 20 kPa. Figure 4 describes the entire process of earth pressure change. During the drilling operation, the radial earth pressure on the borehole wall steadily increases with depth, and each part of the drill rod has a varied effect on the soil pressure. During the planting of the pile, there is not much change in earth pressure because the diameter of the prefabricated pile is small. After grouting, the cemented soil moves upward, dissipating most of the extrusion force. At a radial distance of 3.5 m, the soil pressure change is most significant at 8 m during the drilling process, increasing by 50 kPa. During the withdrawal of the drill, the soil pressure also increases, but the increment is small, about 15 kPa. During the planting of the pile, the earth pressure changes at each point are less than 5 kPa. Overall, during the PGP pile installation process, it is important to consider the

influence of soil pressure on the surrounding soil during the drilling process and to pay close attention to the diameter of the prefabricated pile and the flowability of cemented soil after grouting to reduce the impact of extrusion force on the surrounding soil.

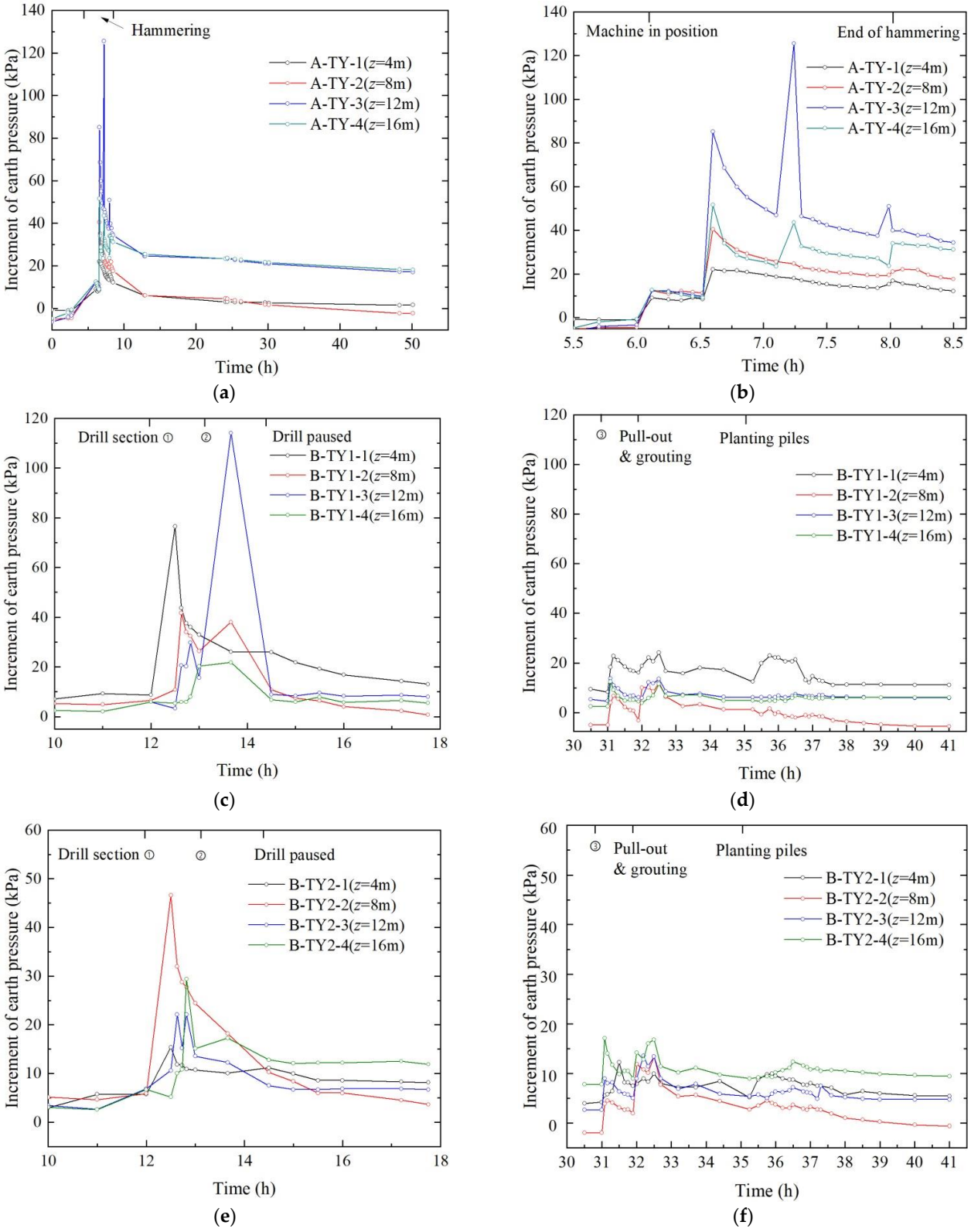


Figure 4. Comparisons of earth pressure. (**a**) A-TY before and after construction; (**b**) A-TY construction process; (**c**) B-TY1 Stage 1; (**d**) B-TY1 Stage 2; (**e**) B-TY3 Stage 1; and (**f**) B-TY3 Stage 2.

Earth pressure increases during initial pile construction due to pile penetration within 1/3 *L*. Soil extrusion mainly affects pile tip plane, influencing a 3 m range above and below. Above this, frictional force from pile shaft dominates over the tip's extrusion. Shallow soil has a smaller, quicker pressure rise and recovery than deep soil. Pressure from the pile machine weight recovers when removed, but construction-induced pressure can persist in deep layers for more than 2 days. It can be seen that the maximum earth pressure increment generated by PGP piles and driven piles is different at different depths, and the methods of generation are also different: driven piles are due to the driving of the pile body, while PGP piles are caused by agitation due to the rotation of the drill pipe.

Overall, at the same distance during construction, the earth pressure increment generated at different depths by the PGP pile is like the driven pile. At a depth of 4 m, the PGP pile generates greater earth pressure due to the larger mass of the pile-planting machine, which also affects the shallow soil. Since the measured earth pressure is not an instantaneous value during construction but the residual earth pressure after compression, the PGP pile exerts a more sustained pressure on the soil during construction.

3.2. Lateral Displacement of Soil

Before construction, the soil is in a static equilibrium state. After being squeezed by the pile, the soil is under passive pressure. After the construction is stopped, the soil is in an active state. Figure 5 depicts driven pile lateral soil displacement under different states. It can be seen that the shallow soil moved towards the pile on the machine setup. The first pile section led to a shallow soil backward shift, and the second section produced significant middle soil movement away from the pile. After the third section, the soil moved further, reaching 27 mm max.

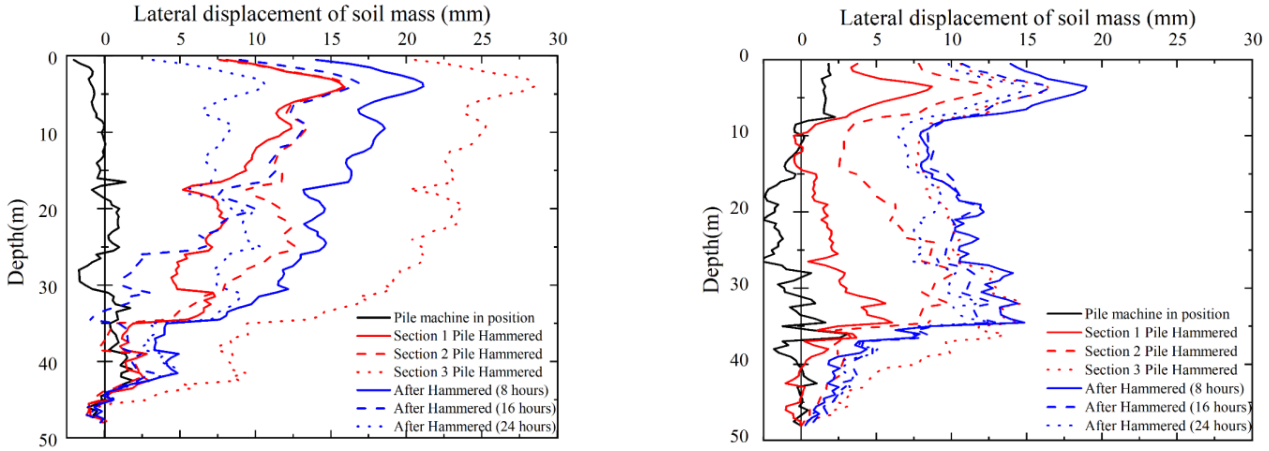


Figure 5. Comparisons of soil lateral displacement of driven pile. (**a**) A-CX1; and (**b**) A-CX2.

Deep displacement changed significantly at 40 m depth, around 10 mm. Soil started moving back towards the pile 8 h post-construction, and continued at 16 h, maxing at 10 mm after 24 h. The soil's peak lateral displacement appeared above the pile bottom plane (10~20 *d*). This trend relates to soil layer properties, resembling the "saddle-shaped" curve observed by Hwang et al. (2001) [9]. At A-CX1, the closer distance to the pile axis resulted in larger lateral soil displacement compared to A-CX2. The closer proximity to the pile axis led to greater radial soil displacement. A-CX2, further from the pile, experienced less overall compression than A-CX1 at the same depth.

Figure 6 illustrates lateral soil displacement around PGP piles with depth. During drilling, pile-side soil moved toward the pile axis. After a 12-h drill pause, the soil partly rebounded. Upon reaching max depth and erecting a larger head, pile-side soil continued moving toward the pile, peaking at −7.5 mm around 1/3 *L*. Drill withdrawal and grouting led the lower soil to shift toward the pile. After two pile sections, soil on the pile side

moved away from the body, with rapid changes around 30 m. After full implantation, max lateral displacement was about 10 mm, and there were notable bulges at 10 and 35 m. The soil gradually recovered post-construction, moving about 7.5 mm back to the initial displacement. For B-CX2, drilling shifted soil toward the pile. A 12-h pause showed less soil recovery on the pile side. Max depth and a larger head led the bottom pile-side soil to the pile. Max lateral displacement was −7.5 mm around 15 m depth. Drill withdrawal and grouting led to continued soil shift, −5.3 mm near the surface. Soil on the pile side moved away from the pile after two sections. Complete implantation had about 5 mm max lateral displacement. After construction, the soil rebounded to about −5 mm displacement.

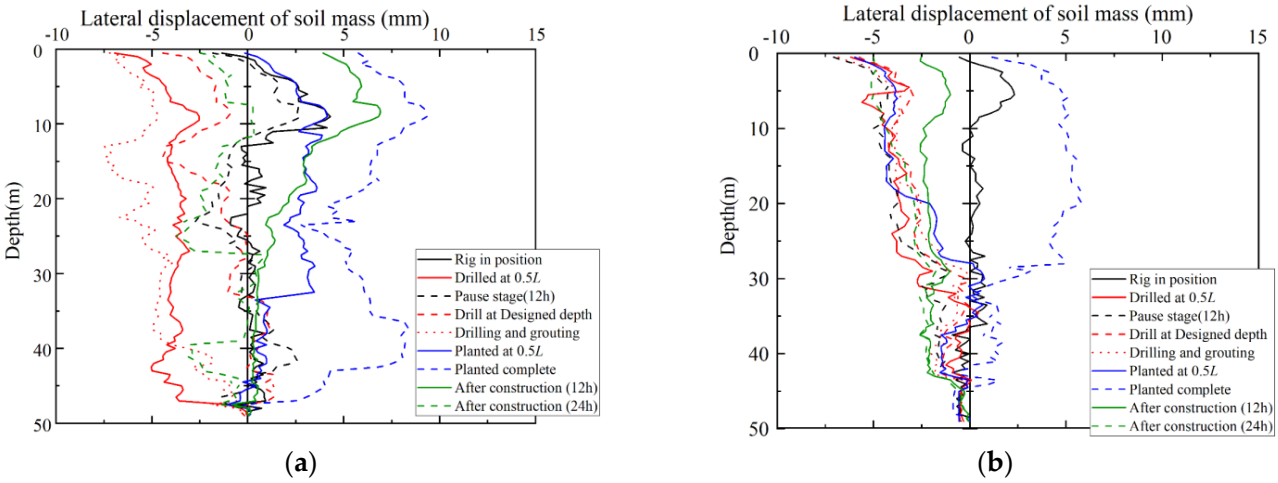


Figure 6. Comparisons of soil lateral displacement of PGP pile. (**a**) B-CX1; and (**b**) B-CX2.

After the soil is extracted by drilling, the surrounding soil will move towards the pile under the influence of active earth pressure, and after the prefabricated pile is implanted, the passive earth pressure will make it move back to the pile. The driven pile does not have the step of drilling, so the soil will not move towards the pile actively during the construction process.

Before and after construction, PGP piles' lateral soil displacement remains consistent. During construction, soil goes through three phases: toward, away, then back to the pile, aligning with the pile construction method. Soil near the piling hole loses stability during drilling, and moves due to lateral pressure. During pile installation, cemented soil filling and hole shrinkage cause soil extrusion, which is pushed aside by the pile. Pile-induced soil compression is minimal due to the hole. Post-construction, soil pore pressure dissipates, rebounding around the pile. The rebound is consistent across radial distances, maxing at 7.5 mm. The difference in the maximum horizontal displacement of the soil between driven piles and cast-in-place piles at typical depths is shown in Table 2.

Table 2. Comparison of lateral displacement difference of two pile types.

Pile Type	Depth (m)	Lateral Displacement/mm at r = 3.3 m (mm)			Lateral Displacement/mm at r = 4.2 m (mm)		
		Min	Max	Δ	Min	Max	Δ
Driven pile	10	−0.2	25.1	25.3	−0.5	8.3	8.8
	20	0.0	23.6	23.6	−1.8	12.1	13.9
	30	−0.8	19.1	19.9	−1.1	13.0	14.2
	40	0.0	8.2	8.2	−0.2	7.9	8.2
PGP pile	10	−5.1	8.6	13.6	−5.0	4.9	9.9
	20	−5.4	5.1	10.5	−3.8	5.8	9.6
	30	−4.5	5.6	10.1	−2.7	1.1	3.8
	40	−3.8	8.2	11.9	−2.0	1.5	3.5

Table 3 outlines soil's extreme displacement around the test pile. Driven piles show the greatest displacement away from the pile. For PGP piles, there is an initial displacement toward the pile, then away. After a one-day break, drilled and grouted piles rebound faster than driven piles. Contractions are observed at 4.2 m depth for drilled and grouted piles.

Table 3. Maximum horizontal displacement of soil around the pile.

No.	Min Displacement (mm)	Depth (m)	Max Displacement (mm)	Depth (m)	Displacement after 1 Day Rest (mm)	Rebound Rate (%)
A-CX1	−1.02	46.5	28.47	4.0	10.61	62.73
A-CX2	0.28	48	18.85	4.0	14.85	21.22
B-CX1	−7.48	13.0	9.39	8.5	0.26	97.23
B-CX2	−6.83	0.5	5.81	20.0	−2.87	149.40

During the construction of hammer piles, the soil is squeezed by the pile body and will only move away from the pile, and finally there will be a part rebound due to the dissipation of pore pressure and the consolidation of the soil. The maximum displacement of PGP piles is generally 50.7~53.8% of that of driven piles, but the displacement at the bottom of the pile is greater than 45.1% of that of driven piles.

3.3. Excess Pore Water Pressure

Figure 7a presents excess pore pressure over time during hammer-driven pile construction in three stages. In stage one, the first pile driving at 0.5 h raised the pore pressure by 100 kPa at 12 m, dissipating post-drive until the next stage. Stage two began at 1 h, driving increased excess pore pressure to about 150 kPa at 22 m. The pressure dropped after driving, and was slower in the shallow layer. There was a 50 kPa rise at 12 and 32 m. The third pile's construction saw a sharp 150 kPa increase at 32 m below 30 m depth. Half-hour post-construction, the excess pore pressure halved, further flattening in 8 h. At 24 h, 12 m pressure dissipated, and 22 and 32 m retained 25 kPa. At 48 h, the pressure at a depth of 22 m decreased. Increasing excess pore water pressure correlates with pile depth. Maximum increase: 100 kPa at 12 m, 150 kPa at 22 m, 200 kPa at 32 m. Mainly generated at pile tip. After the second pile section, 12 m depth pressure rises due to diffusivity of more than 3 m range. Pore pressure peaks post-hammering, then diminishes. The dissipation rate starts fast, slows, and stabilizes till gone. Dissipation time linked to depth: deeper soil, longer time for pressure to dissipate.

Figure 7b–g depict pore pressure changes around the PGP pile during construction. After drilling the first section of rod, the excess pore water pressure at z = 12 m with the distance increases by about 75 kPa, 60 kPa, and 30 kPa, respectively. During the drilling of the second section of rod, it can be seen that all the pore pressure gauges have a small increase. At this time, the drill pipe is about to reach a depth of 0.5 L, and B-KY1-2 generates an excess pore pressure of about 100 kPa, while the other pore pressure gauges have little change. There was a short pause in the construction at 13.5 h, and the excess pore water pressure began to dissipate, and then continued to increase due to the drill pipe. On the whole, the drill pipe in the first stage mainly causes the change of pore water pressure in shallow and middle soil, and the process is slow, continuous, and stable, with strong diffusion. When drilling the third section of rod, B-KY1-2 and B-KY1-3 increased the most, both reaching about 140 kPa, but when rotating the drill pipe for expanding head grouting, the excess pore water pressure of B-KY1-2 increased to about 180 kPa. B-KY2-3 increases by about 100 kPa, and B-KY2-2 also increases by about 90 kPa during the construction of the expansion head. B-KY3-3 increases the excess pore water pressure of about 45 kPa. At the depth of 12 m, the pore water pressure has only an increment of about 10 kPa. In the stage of drilling and grouting, the pore water pressure generally shows a dissipation trend.

During the process of pile planting, the pore water pressure at z = 12 m has no obvious change, because the cement soil is accumulated under the borehole, and the fluidity can make the pile flow upward when it is displaced, which is not enough to squeeze the surrounding. At z = 22 m, the increment of pore pressure due to pile planting increases with distance is 140 kPa, 50 kPa, and 15 kPa, respectively; z = 32 m, the pore water pressure increases with the distance of 130 kPa, 60 kPa, and 25 kPa, respectively.

At a radial distance of 2.1 m from the pile axis, the excess pore pressure generated during PGP pile construction is smaller than driven piles, and the pore pressure gradient is much smaller than driven piles. After a construction pause of one day, the pore pressure at a depth of 12 m has dissipated almost completely because the shallow pore pressure is more easily discharged from the upper surface. The pore pressure at a depth of 22 m dissipates more slowly because the water pressure in the middle of the pile cannot be quickly drained from the top and bottom ends, and the drainage conditions are worse than in the upper and lower parts.

Table 4 shows that the gradient of pore pressure changes at the same depth decreases with increasing radial distance. Generally, the greater the depth, the larger the gradient of pore pressure increases.

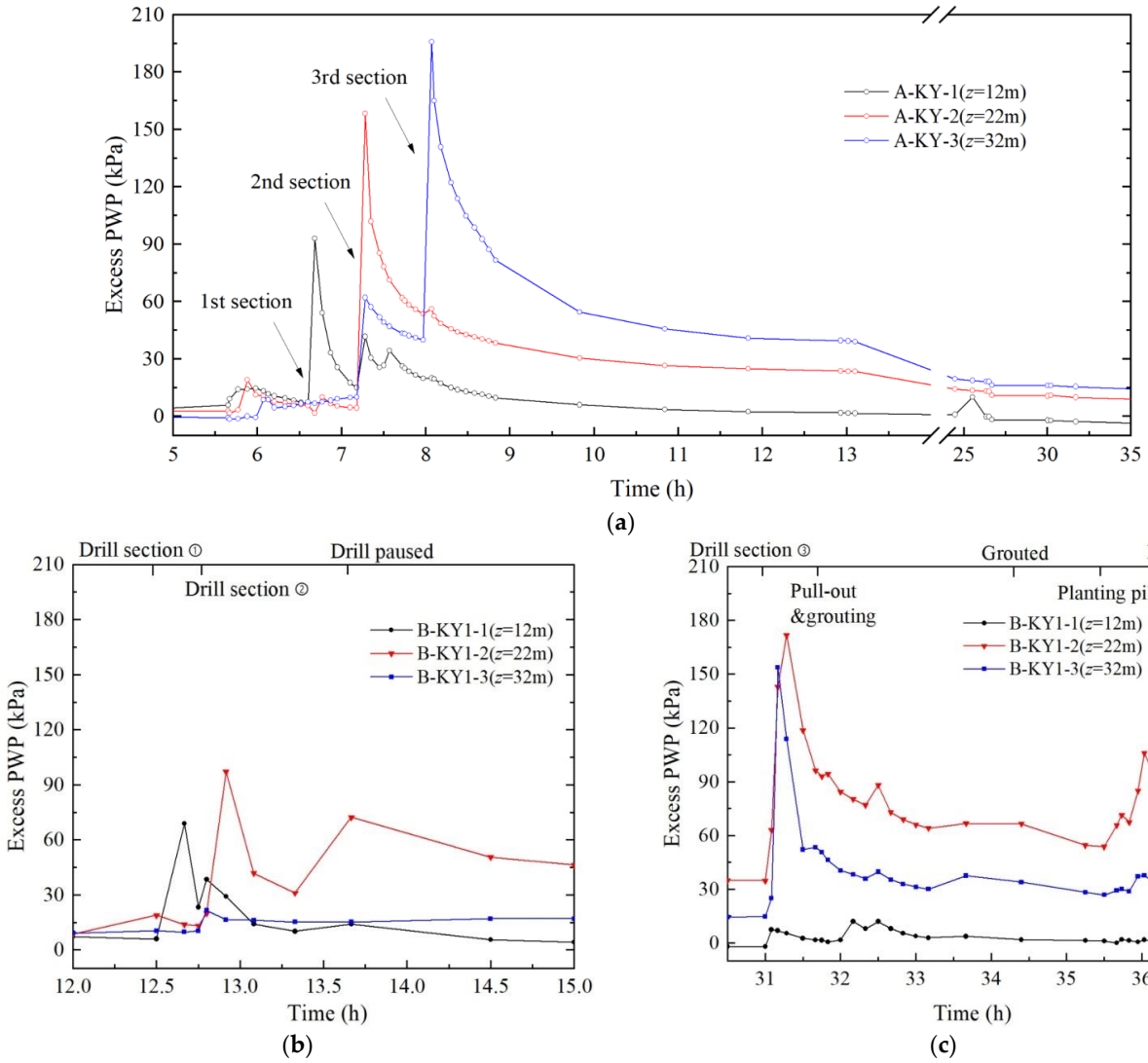


Figure 7. *Cont.*

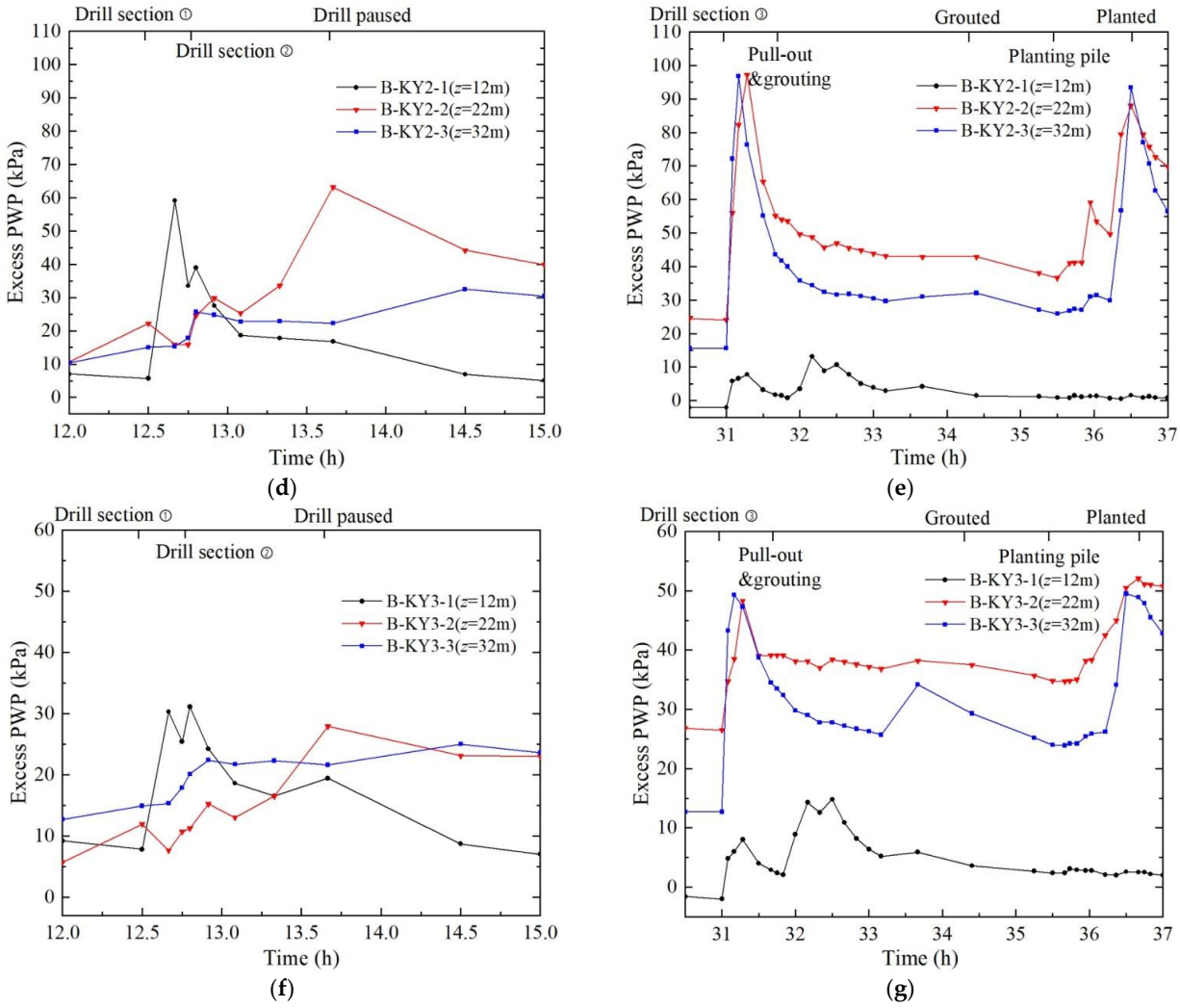


Figure 7. Variation curve of excess pore water pressure during the whole construction process. (**a**) Driven pile; (**b**) B-KY1 at stage 1; (**c**) B-KY1 at stage 2; (**d**) B-KY2 at stage 1; (**e**) B-KY2 at stage 2; (**f**) B-KY3 at stage 1; and (**g**) B-KY3 at stage 2.

Table 4. Rise and dissipation of excess pore pressure at different measuring points.

Number	Soil Layer	Depth (m)	Drilling Stage		Planting Stage		Resting 1 Day Dissipation Rate (%)
			u_{max} (kPa)	Average Gradient (kPa/min)	u_{max} (kPa)	Average Gradient (kPa/min)	
A-KY (r = 2.1 m)	③-2A clayey silt	12		-	92.9	18.0	100.0
	④-1 muddy silty clay	22		-	158.4	25.7	96.5
	④-2 silty clay	32		-	195.8	26.0	94.8
B-KY1 (r = 0.9 m)	③-2A clayey silt	12	68.9	6.3	1.9	1.1	100.0
	④-1 muddy silty clay	22	171.9	8.1	201.4	2.5	86.8
	④-2 silty clay	32	153.7	13.9	161.7	7.6	94.2
B-KY2 (r = 2.1 m)	③-2A clayey silt	12	59.1	5.4	1.6	1.0	100.0
	④-1 muddy silty clay	22	97.2	4.3	88	0.9	80.2
	④-2 silty clay	32	96.8	8.2	93.4	3.7	90.6
B-KY3 (r = 3.3 m)	③-2A clayey silt	12	31.1	2.3	3.1	0.5	100.0
	④-1 muddy silty clay	22	48.3	1.3	52.9	0.3	67.1
	④-2 silty clay	32	49.3	3.7	50.9	1.4	83.9

Furthermore, the soil layer is muddy silt clay with high porosity and low permeability. In contrast, pore pressure dissipates faster in clayey silt. At the same depth, the dissipation rate of excess pore water pressure decreases with increasing radial distance from the pile axis after a one-day pause.

The maximum excess pore water pressure u_{max} measured by each pore pressure gauge around the pile during the PGP pile construction is divided by the effective stress $\sigma_v(h)$ of the overlying soil at that point, and the distance of the pile axis r is divided by the diameter of the borehole d for normalization. As shown in Figure 8, when $r < 3.5\ d$, the pore pressure decays a little more rapidly than when $r > 3.5\ d$. The excess pore pressure has an almost linear relationship with the distance along the pile circumference compared to the average value, which can be expressed by the following equation.

$$\frac{u_{max}}{\sigma_v(h)} = -0.06\frac{r}{d} + 0.45 \quad (1)$$

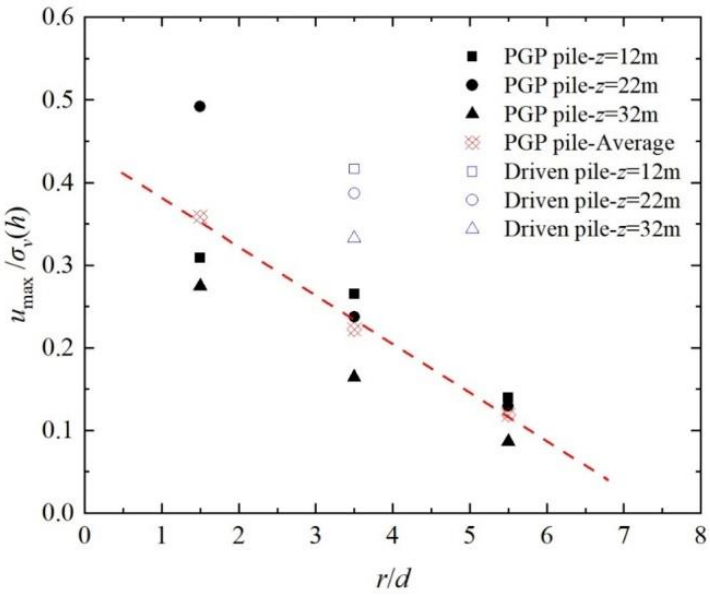


Figure 8. Radial variation of excess pore pressure ratio of PGP pile.

In the equation, u_{max} and $\sigma_v(h)$, respectively, represent the maximum measured excess pore water pressure at the point and the effective stress of the overlying soil. r is the distance between the measurement point and the pile axis, and d is the diameter of the pre-bored grouted planted pile.

It can be clearly seen from the figure that the excess pore pressure ratio at $r = 3.5\ d$ for the driven pile is significantly greater than that of the PGP pile. If the line is extended and intersects the horizontal axis at a certain location, the construction-caused excess pore pressure range can be determined. However, considering that, the change in excess pore pressure near the pile axis is gradually steep. In contrast, the change in excess pore pressure far from the pile axis is gradually gentle; it is inferred that the influence of excess pore pressure beyond the 7.5 d range is relatively small. Therefore, it can be concluded that the range of excess pore pressure influence implanted by the pile is much smaller than the 15 d range of excess pore pressure influence caused by the driven piles measured by Hwang [9].

3.4. Vibration Response around the Site

During construction, vibration acceleration is split into vertical and horizontal directions. Upward motion is considered positive on the z-axis, and horizontal vibration's maximum is grad (x, y). By subtracting initial bias, $\Delta\ z$ and Δ grad (x, y) are derived for change values, as depicted in Figure 9.

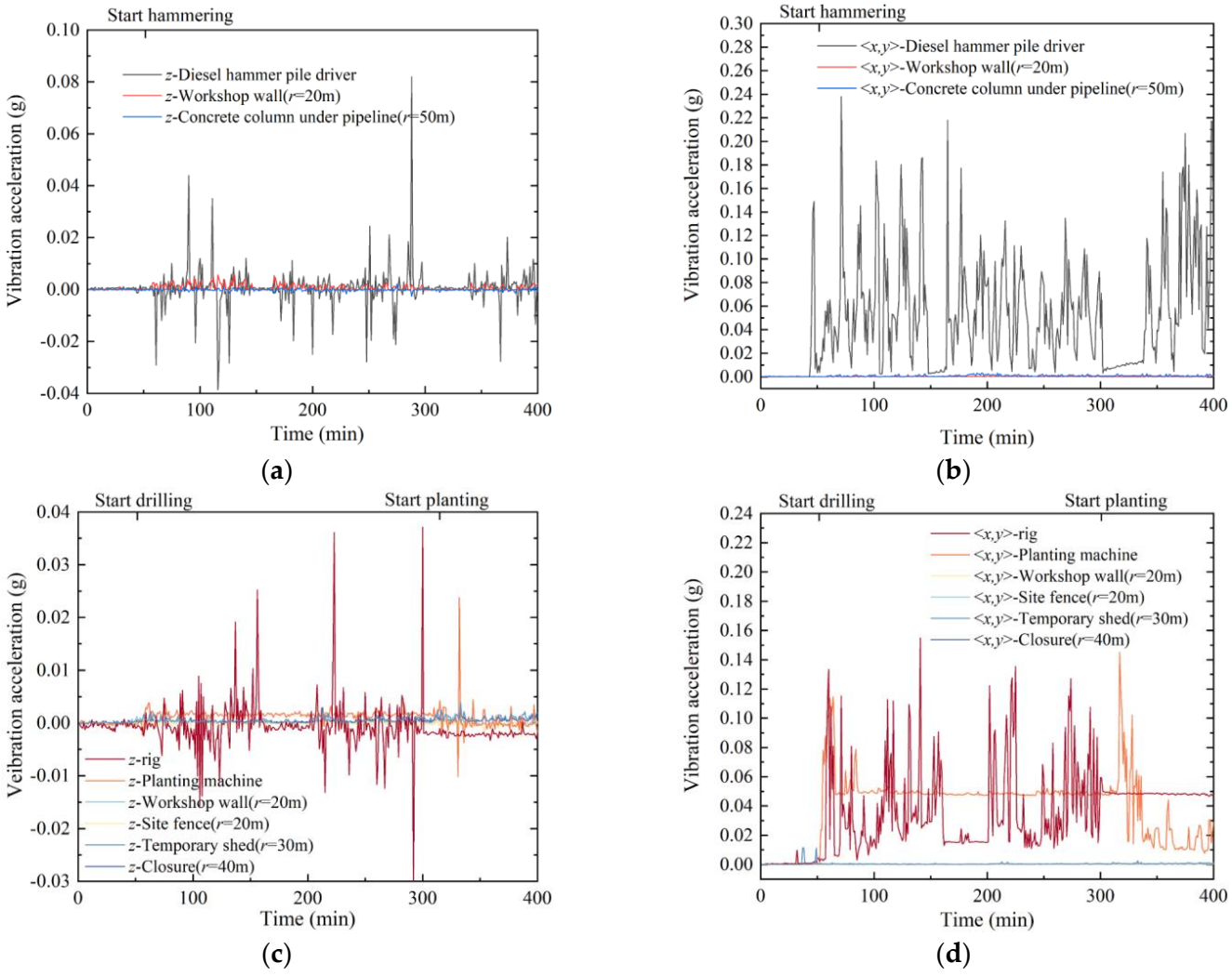


Figure 9. Vibration acceleration change curve during construction. (**a**) Vertical direction of driven pile; (**b**) Horizontal direction of driven pile; (**c**) Vertical direction of PGP pile; and (**d**) Horizontal direction of PGP pile.

It displays the vibration magnitude caused by two types of pile during construction. The driven pile produces a maximum vertical acceleration of 0.008 g at the pile driver, which can be uncomfortable. At 20 m, amplitude is 0.005 g, which is still perceptible. At 50 m, pipeline fluctuation is 0.001 g, which is affecting it. For driven piles, max horizontal acceleration at the driver surpasses 0.24 g, causing severe discomfort. At 20 m, horizontal acceleration is around 0.002 g. Horizontal vibration attenuates more quickly than vertical. Vertical vibration is significant at a factory wall 20 m away. At 50 m, 0.001 g fluctuation impacts transport pipelines.

The max vertical acceleration during PGP pile construction on the drill rig is 0.035 g, which is considered tolerable. Initial drilling causes a 0.0025 g vertical vibration on the pile driver situated 10 m from the pile driver. After 310 min, the drilling stops, and the pile driver starts, maintaining 0.0025 g of vertical vibration at 10 m. The highest horizontal acceleration of the PGP pile, measuring 0.15 g, is observed on the drill rig, below the maximum of 0.14 g from the pile driver. No vibration changes are observed at a 20-m distance. At the start of construction, the drill rig induces 0.05 g of horizontal vibration on the pile driver, 10 m away from the pile driver. Later, after 310 min, with the drilling ceased and pile driving initiated, the drill rig experiences 0.05 g of horizontal vibration at 10 m from the pile driver.

Figure 10 plots peak ground acceleration (PGA) against distance to demonstrate attenuation. The human body can feel the vibration at 0.003 g, feel uncomfortable at 0.05 g, and cannot tolerate it at 0.5 g. Considering that the horizontal vibration is greater than the vertical vibration, the driven pile construction should be 25 m away before the human body can tolerate it. If there is no perception, it should be 40 m away. However, the PGP pile only needs to endure at 15 m away. The vibration cannot be felt at 25 m away.

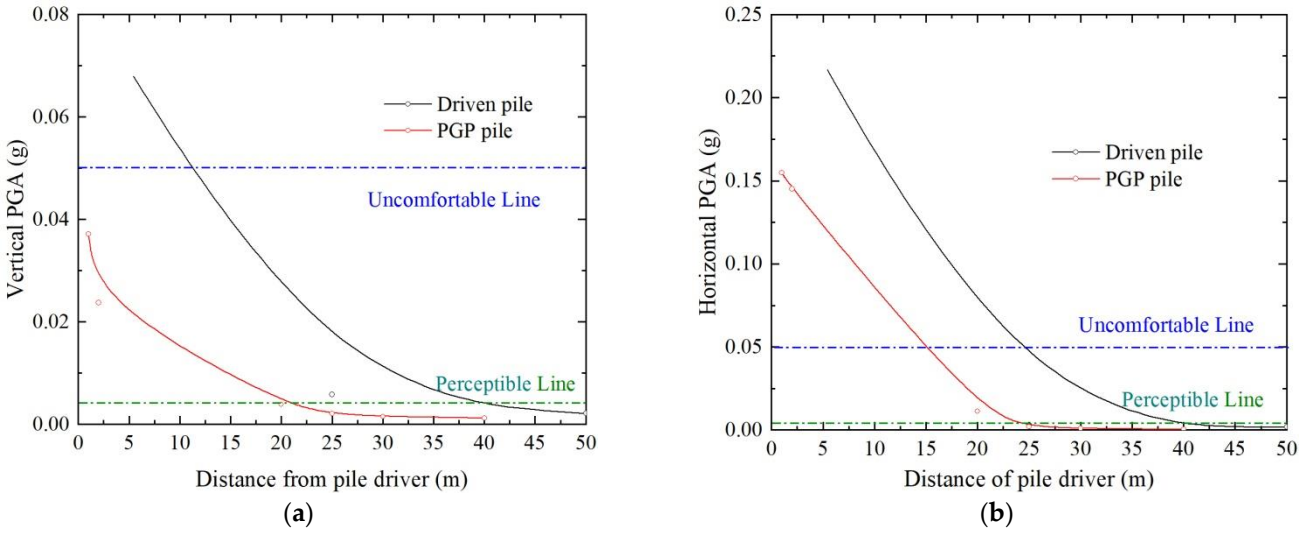


Figure 10. Comparison of PGA changes with distance during construction. (**a**) Vertical direction; and (**b**) Horizontal direction.

3.5. Construction Noise

In typical conditions, field noise ranges from 60 to 80 dB. Figure 11a displays noise during hammering, peaking at 110 dB close to the pile driver and increasing with hammering depth. Figure 11b shows noise from the PGP pile; drilling emits the most noise, then pile pressing, and drilling produces the least. Noise is higher near the pile driver and drilling generates around 100 dB at 1 m. PGP pile construction is slower than the driven pile, and the noise is mainly generated by the machine engine. When the drilling rod rotates and disturbs the soil during drilling, it produces much noise, less than 90 dB at 10 m.

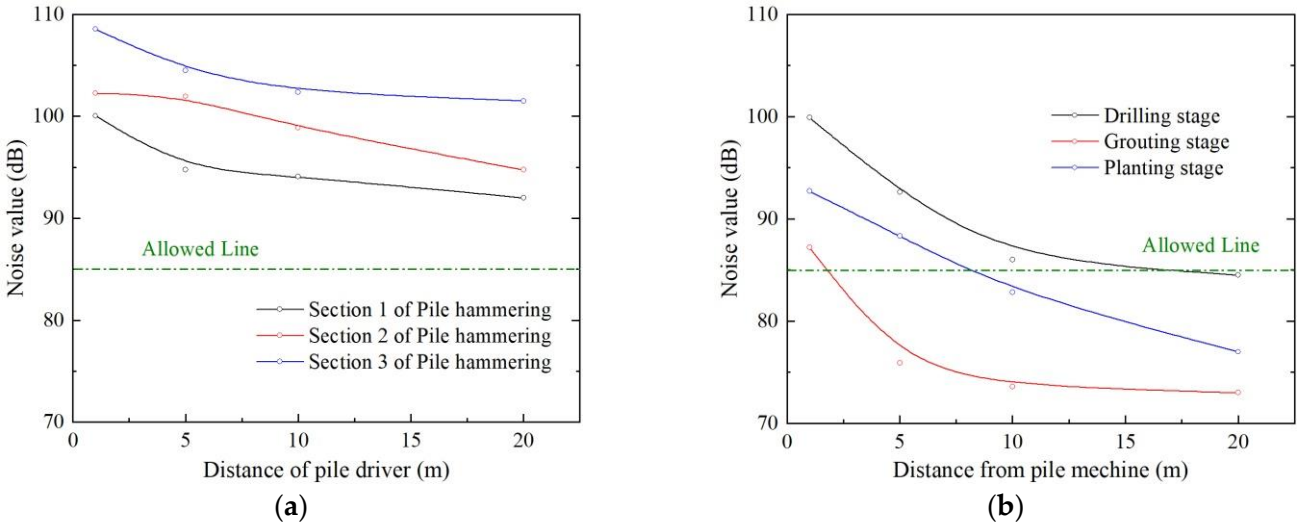


Figure 11. Comparisons of maximum noise during pile construction. (**a**) Driven pile; and (**b**) PGP pile.

During PGP pile construction, noise is over 10 dB lower compared to driven piles at the same spot. PGP pile noise diminishes notably with distance, while driven piles maintain 100+ dB at 20 m. PGP piles produce lower decibel noise, with minor attenuation. The maximum level at the same distance can be 8~15% lower than driven piles. The noise limit during the construction pile driving stage is 85 dB (Central urban area), and it is obvious that driven piles are not very compliant with regulations. If the distance from the PGP pile is 17 m, the noise can be controlled within a limited range.

4. Conclusions

This study examines soil disturbance and environmental impact caused by PGP piles and driven piles. The main findings are as follows:

(1) At a certain distance below, the soil is affected more by pile shaft friction than bottom squeezing. Shallow soil has a lower pressure increment and quicker recovery than deep soil. Planting drill generates substantial soil squeezing towards the pile body. Once the drill is below a layer, pressure stops increasing. More than 1/3 of pile body is not squeezed in the planting process;

(2) Driven piles displace soil away, compacting it due to pile impact. For PGP piles, the soil moves towards the pile during drilling, and it moves away during planting. Compaction and displacement are less distinct, with soil recovery. The lateral soil displacements by PGP piles are obviously less than by driven piles;

(3) Excess pore pressure by PGP pile construction reduces with the increase of radial distance. It mainly happens during drilling and planting, with minimal change in shallow soil during planting. The pore water pressure gradient at a depth decreases as radial distance increases. Deeper depths result in steeper pore pressure gradients. At r = 3.5 d, excess pore water pressure and its gradient are smaller than by driven piles. After a one-day break, the dissipation rate slows down. The maximum excess pore pressure value varies linearly with increasing radial distance, and the influence distance is no more than 7.5 d;

(4) Horizontal vibration exceeds vertical near the pile machine, and it decreases with radial distance. Vibrations from PGP piles are consistently smaller than by driven piles. The max vertical vibration is about 0.5 times that of driven piles, and the max horizontal vibration is about 0.58 times that of driven piles. The vibration by driven piles leads to discomfort, but this does not happen during PGP pile construction;

(5) The noise generated by PGP pile construction is lower than by driven piles, with a maximum value of 8 to 15% lower than by driven piles at the same distance. The noise generated during PGP pile construction decreases significantly with the distance increase, while driven piles still produce more than 100 dB of noise at 20 m away. The noise limit can be met 17 m away from the PGP pile;

(6) This study provides a reference for the selection of two pile types. In the future, more detailed tests can be carried out and compared with numerical simulations.

Author Contributions: Conceptualization, F.S. and Y.D.; methodology, Y.D.; software, F.S.; validation, Y.D., R.Z. (Rongyue Zheng) and R.Z. (Rihong Zhang); formal analysis, R.Z. (Rongyue Zheng); investigation, S.C.; resources, R.Z. (Rihong Zhang); data curation, F.S.; writing—original draft preparation, F.S.; writing—review and editing, Y.D.; visualization, F.S.; supervision, R.Z. (Rongyue Zheng); project administration, R.Z. (Rihong Zhang); funding acquisition, Y.D. and R.Z. (Rihong Zhang). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Key Project of Ningbo Natural Science Foundation (grant number 2023J004) and the Science and Technology Innovation 2025 Major Project of Ningbo, grant number 2022Z030).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used to support the findings of this study are currently under embargo while the research findings are commercialized. Requests for data, 12 months after publication of this article, will be considered by the corresponding author.

Acknowledgments: We acknowledge the funding support from Key Project of Ningbo Natural Science Foundation (grant number 2023J004) and the Science and Technology Innovation 2025 Major Project of Ningbo, grant number 2022Z030). The authors want to express gratitude to Wei Ming and Junfeng Gao for their valuable advice on this study; this paper could not have been completed well without them.

Conflicts of Interest: The authors declare no conflict of interest.

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