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Lateral resistance of piles in a group under E-Defense shaking-table tests

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ABSTRACT: Large-scale E-Defense shaking table tests were performed using a 3 × 3 pile group in sand layers to investigate the lateral resistance of piles in a group during an earthquake. The bending moments and shear force on the parts of the front-row piles shallower than G.L. −2 m were larger than those of the other rows. In contrast, the bending moments and shear force on the parts of the piles deeper than G.L. −2 m did not vary with the pile-location. Further, the horizontal subgrade reaction on piles varied with the depth and pile location. The development of lateral resistance in piles was investigated in terms of earth pressure acting on piles, soil displacement in the pile vicinity, and soil displacement in free field. The earth pressure was found to be influenced by the soil displacement in the pile vicinity, rather than that in the free field.

1 INTRODUCTION

The lateral resistance of pile groups is one of the most fundamental problems in geotechnical engineering. Brown et al. (1987) reported that the response of a single pile within a pile group differs from that of an isolated pile, and that the lateral loads at pile heads depend on the pile positions. To consider this effect, the concept of a p-multiplier was developed (Brown et al. 1988). Many experimental studies have been conducted to clarify the lateral resistance of a pile group. Full-scale static loading tests have been conducted on a 3 × 3 pile group at three pile diameter spacing in clay (Rollins et al. 1998), as well as on a 3 × 3 pile group at 3.3 pile diameter spacing in sand (Rollins et al. 2005). Centrifuge static-loading tests were conducted on 3 × 3 to 7 × 3 pile groups at three-diameter spacing in sand (McVay et al. 1998). These previous studies reported on p-multipliers with various pile spacing and soil conditions.

The lateral resistance of a pile group during an earthquake has been investigated by dynamic centrifuge tests. Specifically, seismic behaviors of a 3 × 3 pile group at four diameter spacing in a soft clay layer overlying a sand layer were investigated based on dynamic centrifuge tests and numerical analysis using a method employing a dynamic beam on a nonlinear Winkler foundation (BNWF) (Curras et al. 2001). The experiment showed no notable difference between the recorded bending moments at the pile heads of the inner piles and those of the other piles. Centrifuge tests on a 2 × 3 pile group at four-diameter spacing in laterally spreading ground (Brandenberg et al. 2005) showed p-multipliers for liquefied ground.

The lateral resistance of a pile group has been investigated by full-scale static loading tests and centrifuge tests; however, the paucity of full-scale shaking table test results is significant. In light of this, large-scale E-Defense shaking table tests were performed using a 3 × 3 pile group in sand layers to investigate the lateral resistance of piles in a group during an earthquake. The earth pressure acting on piles, the soil displacement in the vicinity of the piles, and the soil displacement in the free field on the lateral resistance of piles in a group were studied.

2 E-DEFENSE SHAKING TABLE TEST

2.1 *Test model*

Large-scale shaking table tests (Funahara et al. 2016) were performed using the E-Defense shaking table facility at the National Research Institute for Earth Science and Disaster Resilience (NIED) in 2015. The tests formed a part of the "Special Project for Maintenance and Recovery of Functionality in Urban Infrastructures," financed by MEXT in Japan. Figure 1 illustrates the model layout. The inner dimensions of the laminar shear box were 8.0 m in diameter, and 6.5 m in height. The soil model on the shaking table consisted of a dry Kakezu silica sand layer (emax = 1.085, emin = 0.720, Uc = 1.59) of thickness 2.0 m and relative density D_r = 60 %, overlying a 4.0 m thick layer of wet Albany silica sand (emax = 0.803, emin = 0.544, Uc = 1.76) of a moderately high relative density. Two pile foundation groups of different types, a 3 × 2 reinforced mortar pile group and a 3 × 3 steel pipe pile group, were installed in the laminar shear box. This study focused on the behavior of the steel pipe pile group, as the shaking test results of the reinforced mortar piles is described in Shibata et al. (in press).

The steel pipe piles had a diameter of 152.4 mm with a 5.0 mm wall thickness. The bending stiffness of the piles was 1.29 MN·m^2. The center-to-center distance of the piles was 620 mm, which was 4.07 times the pile diameter. The pile heads were rigidly linked to the footing (pile cap). The pile tips were set on the container base with slippage-stop plates. The mass of the superstructure and footing models were 14 × 10^3 kg and 10 × 10^3 kg, respectively. The superstructure was supported by four laminated rubbers. The natural period of the superstructure under the fixed base was 0.12 s, which was evaluated from Fourier spectrum ratio of the superstructure and footing during a small shaking. The footing was embedded approximately 500 mm into the dry sand layer.

The response of the soil-pile-structure system was monitored by many sensors including accelerometers, displacement transducers, strain gauges, and earth pressure transducers. Figure 2 shows sensor locations near the steel pipe pile model. The 6-mm-diameter earth pressure transducers were placed on the pile surface at G.L.−0.8 m and −2.25 m. The vertical array of the accelerometers was set at GP1, GP2, and GP3 with GP1, and GP2 at depths of G.L. −0.8 m, −1.5 m, and −2.25 m, and GP3 at depths of G.L. −0.8 m and −2.25 m. Strain gauges were placed on the piles every 250–500 mm. Three types of input motions were used: artificial ground motion for aseismic design in Japan called Kokuji wave, JR Takatori Kobe EQ wave, and sinusoidal waves. This study focuses on the use of a 5 Hz sinusoidal wave with a maximum acceleration of 0.46 m/s^2.

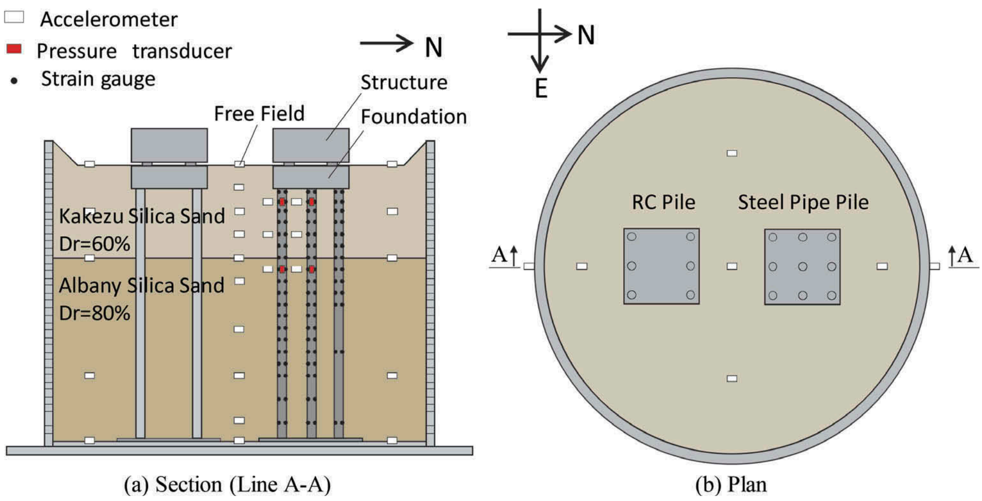

Figure 1. Test model and sensor locations.

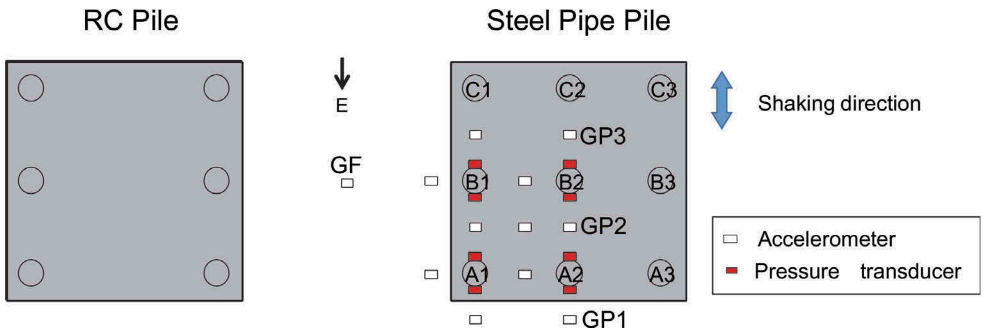

Figure 2. Sensor locations around steel pipe piles at depths of G.L. −0.8 m, and −2.25 m.

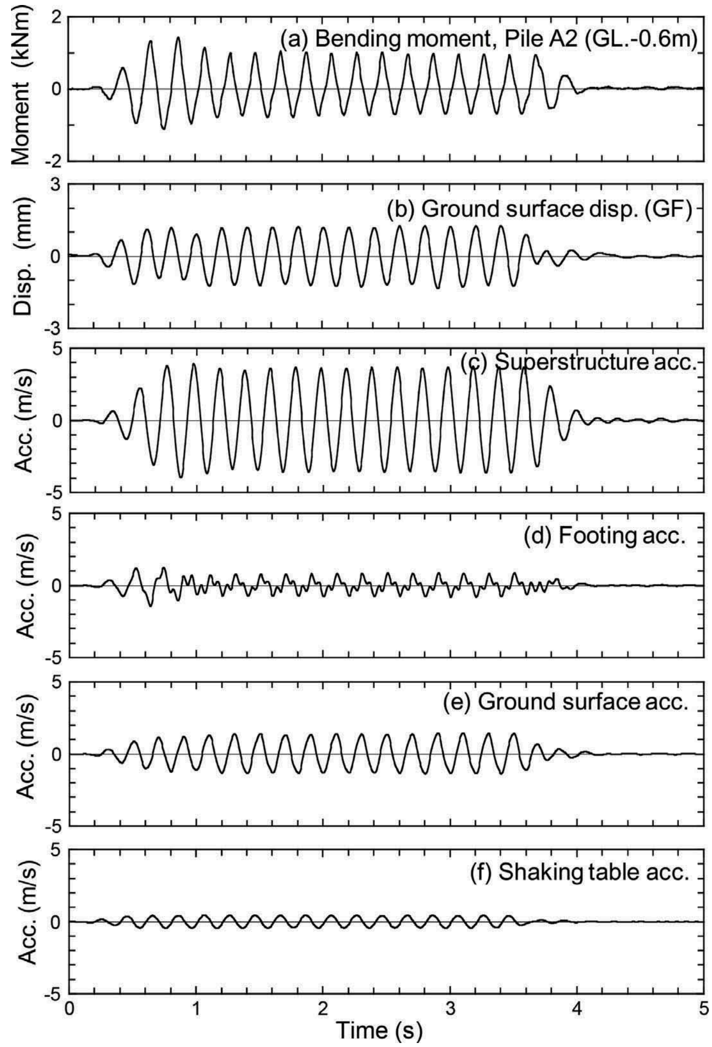

Figure 3. Time histories of (a) bending moment at pile head (Pile A2), (b) ground surface displacement, (c) superstructure accelerations, (d) footing accelerations, (e) ground surface accelerations, and (f) shaking table accelerations.

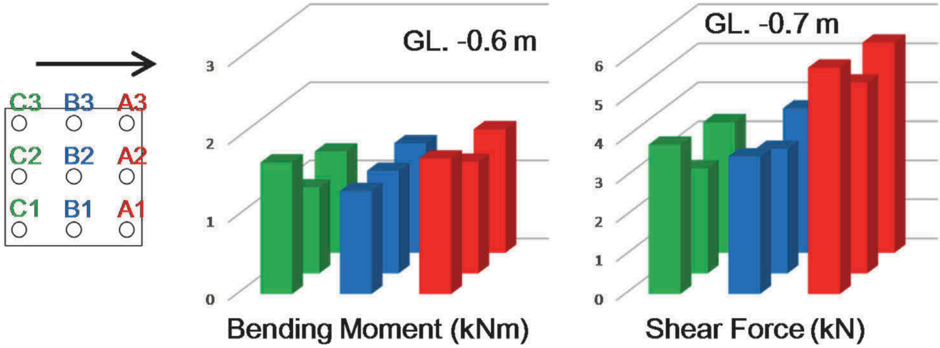

Figure 4. Measured bending moments and shear force at pile heads when the superstructure acceleration reached its maximum (at t = 0.865 s).

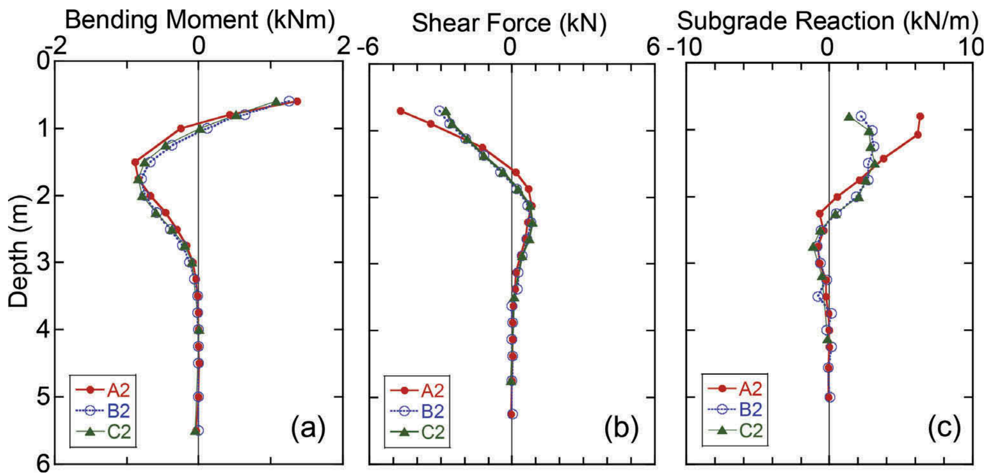

Figure 5. Measured depth distributions of bending moments, shear force, and subgrade reactions at Piles A2, B2, and C2 at t = 0.865 s.

Figure 3 shows the time histories of the shaking table, ground surface, footing and superstructure accelerations, ground surface displacement, and bending moment at the pile head (for Pile A2). The peak acceleration at the ground surface, footing, and superstructure were 1.45 m/s^2, 1.41 m/s^2, and 3.97 m/s^2, respectively. The peak acceleration of the superstructure was 8.6 times larger than that of the shaking table. The superstructure acceleration reached its maximum at t = 0.865 s, which was immediately after the shaking commenced.

To demonstrate the difference in pile behavior caused by the pile location, the measured bending moments and shear force at all the pile heads when the superstructure acceleration reached its maximum (t = 0.865 s) are shown in Figure 4. At this time, Piles A1–A3 were in the front row. Because of a malfunction that occurred in a strain gauge at the top of Pile A1, the bending strain data at the top of Pile A3 was used as a substitute for the missing data, by consideration of the symmetry of the pile location. The bending moments and shear force were evaluated by the bending strain data. The bending moments and shear force at the pile heads in the front row, i.e. Piles A1–A3, were found to be larger than those at the piles in the middle and back rows. This tendency is consistent with previous studies based on full-scale horizontal static loading tests (Brown et al. 1987, Rollins et al. 1998) and centrifuge tests (McVay et al. 1998). In addition, the bending moments and shear force at the center piles (Piles A2, B2, and C2) in each row were smaller than those at the peripheral piles.

Figure 5 shows the depth distributions of bending moments, shear force, and subgrade reactions along Piles A2, B2, and C2 at t = 0.865 s. The bending moments and shear force of the part of the front row pile (Pile A2) that was shallower than G.L. −2 m were found to be larger than those of the other piles (Piles B2 & C2). In contrast, the bending moments and shear force of the parts of all the piles that were deeper than G.L. −2 m were found to be independent of the location of the piles. The subgrade reactions of the part of the front row pile (Pile A2) that was shallower than G.L. −1.5 m were much larger than those of the middle and back-rows piles (Piles B2 & C2). The subgrade reactions of the part of all the piles that was deeper than G.L. −2 m were very similar. This indicates that the reduction factors, p-multipliers, are not independent of the depth.

3 PILE LOCATION AND HORIZONTAL SUBGRADE REACTIONS

3.1 p-y curves

The relation between the relative displacement and horizontal subgrade reactions is shown in Figure 6. The reactions were estimated by the measured bending strains on Piles A2 and B2 at G.L. −0.8 m. The relative displacement was the difference between the pile displacement estimated by the acceleration of each pile and the soil displacement at GF, which was assumed to be free field considering that the shaking was in the EW direction (Figure 2). The positive sign of the relative displacement corresponds to the location of Pile A2 in the front row. The stiffness of the p-y curve of Pile A2 depended on the sign of the relative displacement. This p-y loop indicates that high stiffness appeared along the pile in the front row, and lower stiffness was observed when the pile under consideration was in the back row. Conversely, the stiffness of the p-y curve of Pile B2, which was the middle row pile, did not depend on the sign of the relative displacement.

The horizontal subgrade reactions were also evaluated by the earth pressure transducers on the piles. Figure 7 shows the relation between the relative displacement and horizontal subgrade reactions estimated by the earth pressure transducers placed on Piles A2 and B2 at G.L. −0.8 m. The horizontal subgrade reaction P_{Ep} was calculated by

$$P_{EP} = (E_e - E_w) \times B, \qquad (1)$$

where E_e and E_w were the measured earth pressures on the east and west sides of piles, respectively, and B was the pile diameter (152.4 mm). The subgrade reactions were set to zero before the shaking. The p-y curves estimated by the earth pressure transducers indicated fairly good agreement with those estimated using the bending strains (Figure 6). This indicates the validity of the measured earth pressure.

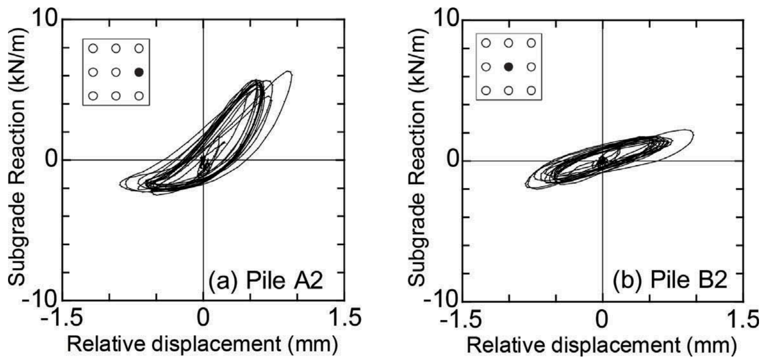

Figure 6. The relation between the relative displacement and horizontal subgrade reactions at G.L. −0.8 m estimated by the measured bending strains of Piles A2 and B2.

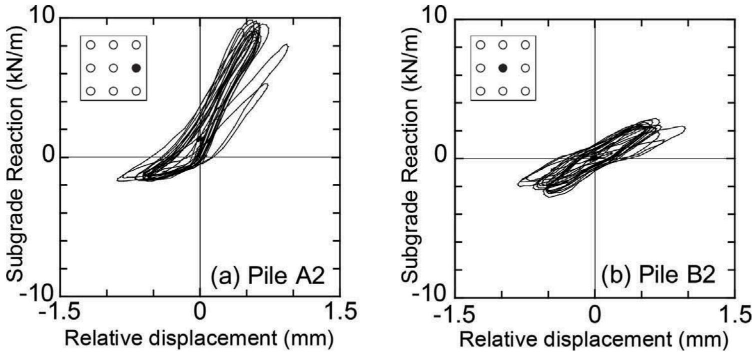

Figure 7. The relation between the relative displacement and horizontal subgrade reactions at G.L. -0.8 m estimated by the measured earth pressure of Piles A2 and B2.

3.2 *Earth pressure acting on a pile*

To investigate the mechanism of horizontal subgrade reactions, Figures 8a, b show the measured earth pressure at G.L. -0.8 m and the relative displacement between the piles and the free field (GF). The baseline of the earth pressure before the shaking was corrected to be earth pressure at rest, as estimated by Jaky's solution. A2E corresponds to the earth pressure on the east side of Pile A2. The earth pressure on both the piles increased with an increasing relative displacement. To compare the earth pressure loop of Piles A2 and B2, all the loops are plotted in Figure 8c in the same plane. In this figure, the positive and negative signs of the relative displacement were defined to be the passive and active sides, respectively. This figure indicates that the stiffness of the measured earth pressure loop was dependent on the locations of the measurement. The stiffness of the earth pressure loop at A2E, outside the front row pile, was much larger than that at A2W. Therefore, the p-y stiffness at the positive sign is significantly larger than that at the negative sign, as shown in Figure 7a. However, in the case of the middle row piles, B2E and B2W have almost the same stiffness of the earth pressure loop. This corresponds to the fact that the p-y stiffness of the negative and positive signs is almost the same, as shown in Figure 7b. These results are consistent with the concept of p-multiplier.

Figure 9 shows the measured earth pressure and the relative displacement between the piles and the soil in the vicinity of the pile. The soil displacements were calculated using acceleration data in the vicinity of each pile, which were GP1 for A2E, GP2 for A2W and B2E, and GP3 for B2W, as shown in Figure 2. The stiffness of the earth pressure loop was almost identical at all the locations, indicating that the earth pressure was more influenced by the soil displacement in the vicinity of a pile than that of the free field. This fact indicates that the group effects result from the relative displacement between piles and soil in their vicinity, rather than soil in the free field.

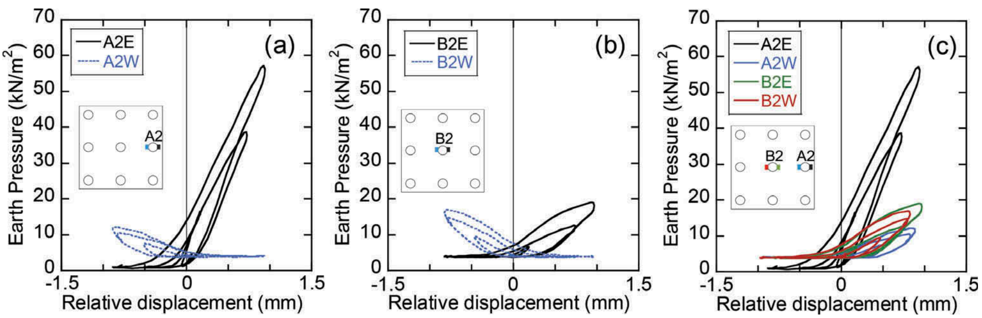

Figure 8. Measured earth pressure and relative displacement between the piles and the free field (GF).

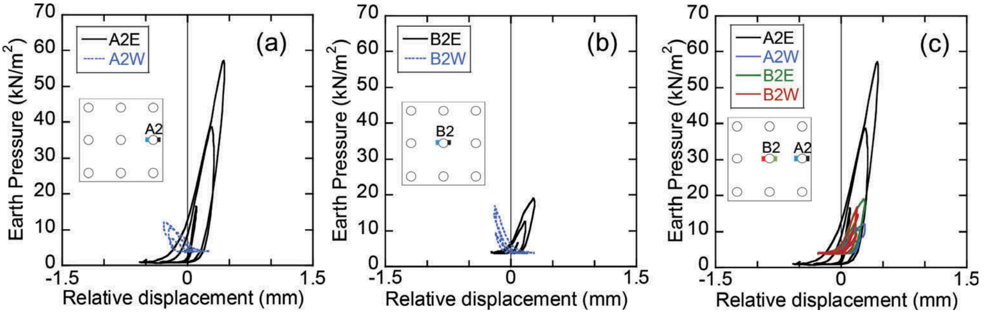

Figure 9. Measured earth pressure and relative displacement between the piles and the soil in the vicinity of the piles.

4 CONCLUSIONS

Large-scale E-Defense shaking table tests were performed using a 3 × 3 pile group in sand layers to investigate the lateral resistance of piles in a group during an earthquake. The effects of earth pressure acting on the piles, the soil displacement in the vicinity of the piles, and the soil displacement in the free field were studied in this regard. The following conclusions were drawn:

1. The pile behavior in the group is dependent on the depth. The bending moments and shear force of the part of front row pile that is shallower than G.L. -2 m were larger than those of the other rows' piles. In contrast, the bending moments and shear force of the part of all piles that was deeper than G.L. -2 m was independent of pile location.
2. The subgrade reactions of the part of front row pile that was shallower than G.L. -1.5 m were much larger than those of the middle and back rows' piles. Conversely, the subgrade reactions of the part of all piles that was deeper than G.L. -2 m were very similar.
3. The subgrade reactions at G.L. −0.8 m were clarified by means of the relation between earth pressure on the piles and relative displacement. When the relative displacement was calculated between the piles and the free field, the stiffness of the earth pressure loop on the outside of the front row pile was much larger than that on the inside of the front row pile. These results were consistent with the concept of a p-multiplier. In contrast, when the relative displacement was calculated between the piles and the soil in the vicinity of a pile, the stiffness of the earth pressure loop at all the locations was almost identical, indicating that earth pressure was influenced by the soil displacement in the vicinity of a pile, not that of the free field. This indicates that the group effects result from relative displacement between the pile and the soil in the vicinity of the pile, rather than the soil in the free field.

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