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- Technical Paper -

ANALYTICAL STUDY ON SEISMIC BEHAVIOR OF FULL-SCALE CONCRETE PILES IN COHESIVE SOIL

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ABSTRACT

For the development of seismic response analysis method for the whole structural system including foundation and ground, it is first necessary to clarify the seismic behavior of pile. 3D finite element analysis was carried out to investigate the seismic behavior of concrete piles in cohesive soil. The study showed that the lateral capacity of pile degrades when subjected to cyclic loading compared to the monotonic loading. With proper consideration of interface element between pile and soil, and the degradation of soil stiffness with cyclic loading, the 3D analysis was found to simulate well the behavior of pile and soil.

Keywords: Concrete pile, lateral loading, pile-soil interaction, seismic behavior

1. INTRODUCTION

Damages sustained in recent earthquakes, such as the 1995 Hyogoken-Nanbu (Kobe) earthquake, have highlighted that the seismic behavior of the structures is highly influenced by the response of the foundation and the ground. Hence, the modern seismic design codes [1] recommend more detailed analysis of the whole structural system including super-structure, foundation and ground. However, for the development of seismic response analysis method for the whole structural system including superstructure, foundation and ground, it is imperative to first clarify the behavior of soil and pile during earthquakes.

There are simplified approaches to analyze laterally loaded piles by modeling surrounding soil by discrete springs and dashpots [2,3]. These discrete models, however, do not take into account the soil continua, and hence, cannot model the damping and inertial effects of soil media. Moreover, it is difficult to properly model the soil-pile interface in these discrete methods.

With the advancement in computation capability, 3D finite element analysis has become more appealing, as it can realistically model the soil as a continuum media and takes into account the damping and inertial effects of soil. Nevertheless, successful implementation of finite element models depends on appropriate use of various parameters such as: soil constitutive models, soil-pile interface and stiffness degradation in soil in cyclic loading. There are some studies carried out to investigate the behavior of pile and soil by finite element analysis [4,5]. The studies, however, lack proper calibration with the full-scale experimental studies.

Authors carried out full-scale monotonic and reversed cyclic lateral load tests on instrumented concrete piles embedded into the ground. One test pile was subjected to monotonic loading whereas another test pile was subjected to reversed cyclic loading. The experimental details and results have already been published in JCI [6]. In this study, three-dimensional finite element analysis was carried out to study the behavior of those experimental specimens. The main purposes of this paper are to use 3D finite element analysis to clarify the effect of interface element, effect of method of piling technique, and degradation of soil stiffness during cyclic loading on the response of the pile.

2. FULL SCALE LATERAL LOADING TEST

The experimental program [6] consisted of lateral loading tests on two full scaled concrete piles embedded into the ground. Test pile SP1 was

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subjected to monotonic loading and test pile SP2 was subjected to reversed cyclic loading. Both of the test piles, were hollow precast prestressed concrete piles of diameter 300mm and thickness of 60mm. Six prestressing steel bars of 7mm diameter were used for longitudinal reinforcement and spirals of 3mm diameter and 100mm pitch were used for confining the concrete (Fig. 1a). Strain gages were attached to the prestressing bars up to 12m depth from the pile head, whereas, for the bottom 14m sections of the piles, strain gages were not attached (Fig. 1b). Compressive strength of concrete was f_c' = 69MPa and yielding stress of longitudinal steel was f_y = 1325MPa. Effective prestress on concrete was 5MPa.

Piling was carried out by drilling method. Drilling was done using auger of 450mm diameter. The shaft was then filled with bentonite-cement slurry to stabilize the soil and to facilitate piling. Pile was then inserted into the shaft. Test piles were embedded up to 24.8m from the ground level (GL), where sand layer exists.The head of the pile and the loading point was 1.2m and 0.6m from the ground level (GL) respectively.

From the bending test carried out on the 8m long pile with same cross-sectional properties as the test piles, yielding moment and ultimate moment of the section was obtained as M_y = 42kNm and M_u = 51.2kNm respectively.

2.1 Subsurface Investigation

The standard penetration test (SPT) was carried out at the experimental site to investigate the relevant soil parameters. The NSPT values obtained from the test are shown in Fig. 2 along with the soil type. The depth of water table was 1.3m from the ground level.

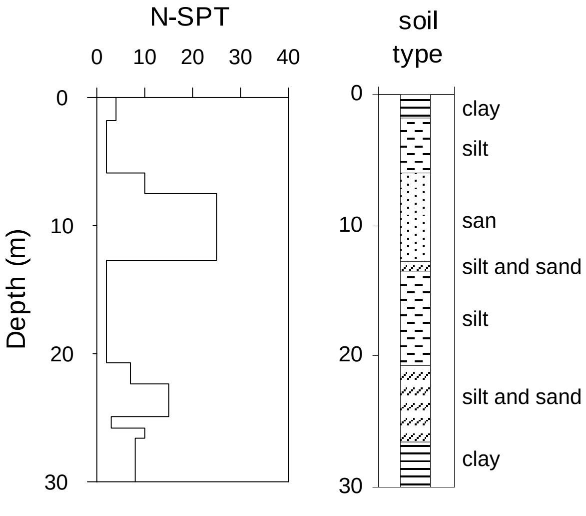


Fig. 2 Soil profile at test site

2.2 Experimental Observations

In the case of monotonic loading, SP1, yielding of the pile occurred at V_y = 44kN and maximum load achieved was V_u = 51kN. Here the yielding of the specimen is defined as the yielding of longitudinal bars. The maximum displacement at the failure was 160mm.

For reversed cyclic loading, SP2, yielding of PC bars occurred at depth of 1.2m from ground level (GL) at load of V_y = 30.5kN and maximum displacement of 170 mm at loading point.

For monotonic loading maximum moment was observed at 0.6m from ground level, whereas for reversed cyclic loading, maximum moment was observed at 1.2m from ground level. Gap of 100mm was formed between soil and pile on the face opposite to the loading direction for case SP1. Whereas, for case SP2, gap of 150mm and 170mm were observed between the soil and pile at each sides.

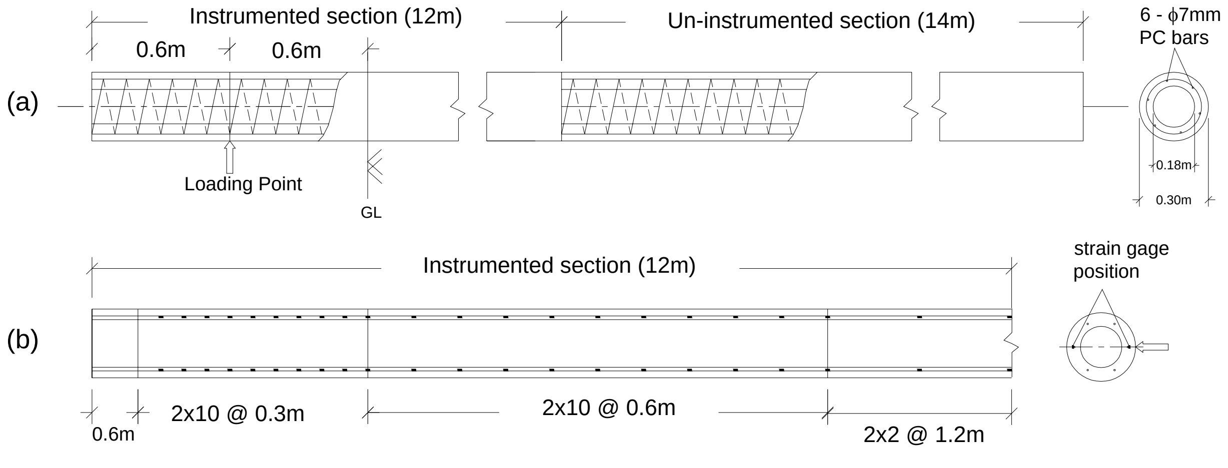


Fig. 1 (a) Test pile details (b) position of strain gages

3. 3D FINITE ELEMENT ANALYSIS

3D finite element analysis was carried out to make clear the behavior of experimental specimens, details of which are published in JCI [6]. Soil and pile were modeled as 20-node isoparametric solid elements. Soil and pile were modeled up to 12.5m depth, and 6.1m and 2.1m in width (Fig. 3). The soil properties used in the analysis are shown in Table 1. The base was fixed in all X, Y and Z directions. The two lateral faces of soil model, perpendicular to the direction of loading were fixed in X direction and the remaining two lateral faces were fixed in Y direction.

Table 1 Soil properties used in the analysis

Depth from GL (m)	Soil type	Unit weight (kN/m^3)	Shear strength (kPa)	Shear Modulus (kPa)
0–6	Clay	26	33	20.4
6–12.5	Sand	27	140	154.3

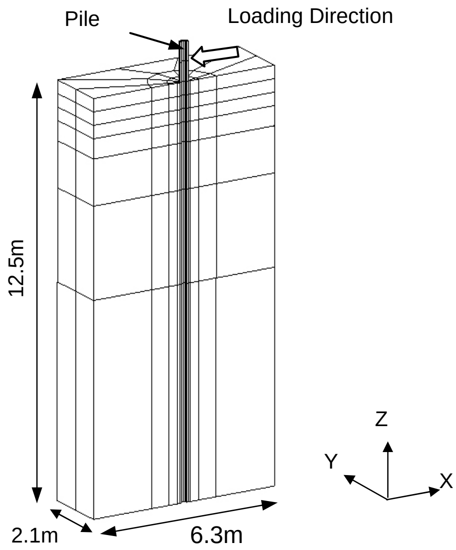


Fig. 3 Finite element mesh for 3D analysis

3.1 Nonlinearity of pile

The nonlinearity of concrete is model by compression and tension model proposed by Maekawa et al. [7], were used.

For reinforcement, nonlinear path dependent constitutive model proposed by Fukuura and Maekawa [8] was used.

3.2 Nonlinearity of soil

The non-linear path dependency of soil in shear was modeled by Ohsaki model (Eq. 1) [9].

$$\frac{J_2'}{M} = \frac{J_2}{2G_0 M}\left\{1 + \left(\frac{G_0}{100S_u} - 1\right)\left|\frac{J_2}{S_u M}\right|^B\right\} \tag{1}$$

where,
G_o = Initial shear modulus (N/mm^2)
J_2 and J'_2 = 2nd deviatoric invariant of stress (N/mm^2) and strain
S_u = shear strength at 1% shear strain (N/mm^2)
B = material parameter (1.6 for sand and 1.4 for clay)
M = loading parameter (1.0 when loading and 2.0 when unloading or reloading)

3.3 Interface element

To incorporate the gap formation between soil and pile during loading, 16 node interface element is used between soil and pile surface (Fig. 4). In this opening-closure model, there is no stress transfer between pile and soil during opening or tension. However, during closure or compression, high rigidity (K_n) is assumed between pile and soil element to avoid the overlapping of soil and pile element.

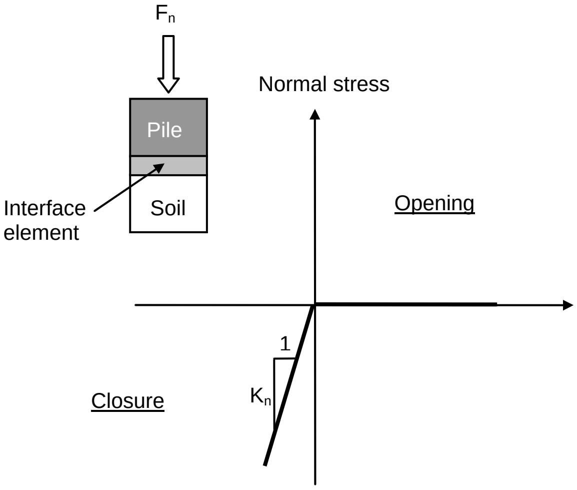


Fig. 4 Opening-closure model for interface element between pile and soil

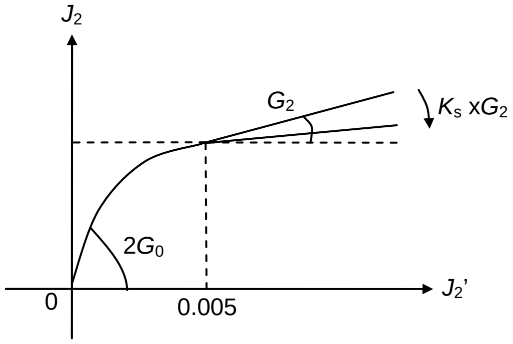
3.4 Bentonite-cement layer modeling

As discussed earlier, the piling was carried out by drilling method. Auger of 450mm was used for drilling the shaft. The pile diameter was only 300mm, and the remaining 75mm gap between soil and pile was filled with bentonite-cement slurry. Unit weight of bentonite was 11.7 kN/m^3. Unconfined compressive strength (q_u) of the bentonite cement paste was obtained as 19.6 kPa from the unconfined compressive test of the specimen. Shear strength (S_u) was obtained as 9.8 kPa and initial shear modulus was 5.8 MPa. In the analysis the effect of considering the bentonite cement layer around the pile on the lateral capacity of the pile was also investigated.

3.5 Degradation in stiffness of soil with cyclic loading

When cohesive soil is subjected to cyclic loading, it leads to degradation in soil modulus and undrained shear strength [10]. Thiers and Seed [10] observed from cyclic shear testing on clay specimen that shear modulus decrease approximately 20% for peak strain of 1% while reduction was about 50% for peak strain of 3%. Degradation in soft clay due to cyclic loading has thus been recognized for many years; however, it has not been explicitly incorporated into finite element analysis for pile soil interaction.

In the current Ohsaki model used in the analysis, the deviatoric stress-strain relationship has been tested only up to 0.005 deviatoric strain level. After this strain, constant shear modulus (G_2) is assumed as shown in Fig. 5. To incorporate the degradation in the soil stiffness due to cyclic loading, the shear modulus after 0.005 deviatoric strain was reduced parametrically using stiffness degradation factor (K_s = 0.2) considering the experimental result.



K_s = Stiffness degradation factor

Fig. 5 Incorporating stiffness degradation factor in Ohsaki soil model

3.6 Analysis Parameters

In the monotonic loading, three different cases were analyzed (Table 2). In case Mon1, interface element and bentonite cement layer were not modeled. In case Mon2, interface element between soil and pile surface was modeled using opening-closure model as discussed in the earlier section, however, bentonite cement layer around the pile was not considered. In case Mon3, interface element as well as bentonite cement layer was considered. In reversed cyclic loading, case Rev1 considers interface element and bentonite cement layer, however, it does not considers the degradation in stiffness due to cyclic loading. Whereas in case Rev2, stiffness degradation was also considered.

Table 2 3D Finite element analysis cases

Loading condition	Name	Descriptions		
		Interface element	Bentonite-cement layer	Stiffness reduction factor
Monotonic	Mon1	No	No	No
	Mon2	Yes	No	No
	Mon3	Yes	Yes	No
Reversed cyclic	Rev1	Yes	Yes	No
	Rev2	Yes	Yes	Yes

4. FINITE ELEMENT ANALYSIS RESULTS

4.1 Monotonic loading

Load-displacement curves obtained from 3D finite element analysis for different cases in monotonic loading are shown in Fig. 6. Case Mon1, in which interface element is not considered, highly over-estimates the lateral capacity of the pile. In case Mon2, where interface element has been considered, the load-displacement curve is improved and tends to agree with the experimental result. However, case mon2 still overestimates the capacity.

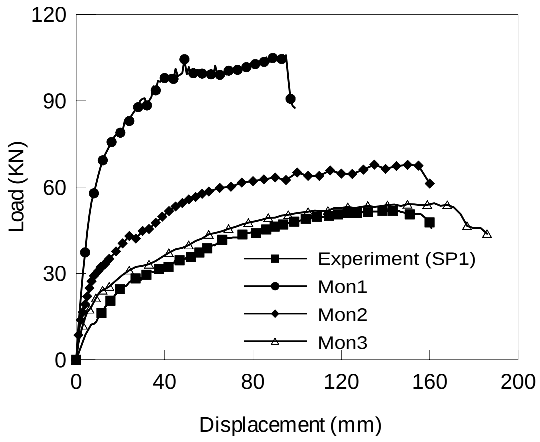
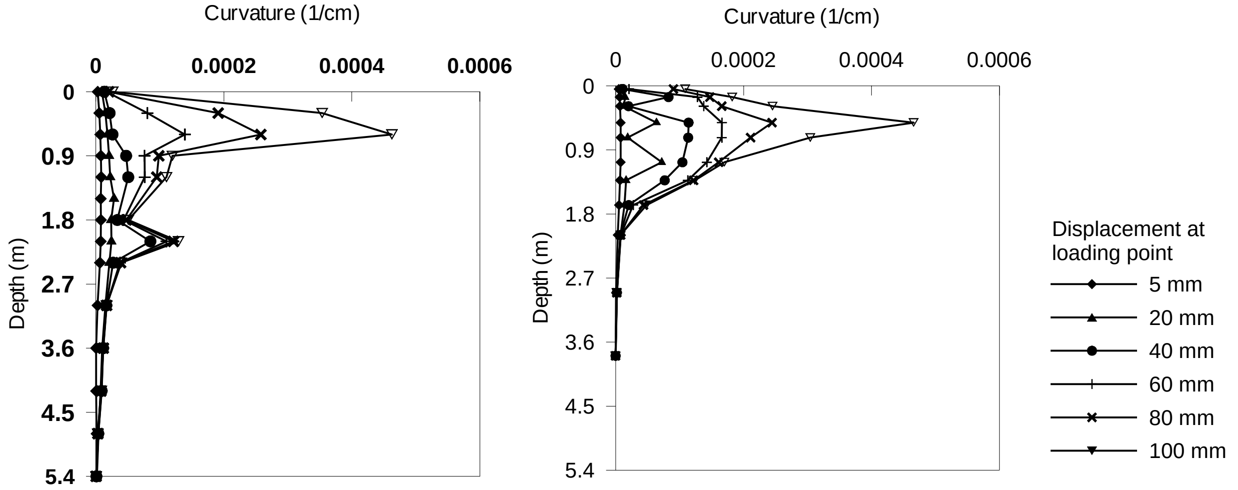


Fig. 6 Load displacement curves from experiment and 3D FEM analysis

In case Mon3, where bentonite-cement layer of 75 mm around the pile was also considered, the analytical results tends to correlate well with the experimental results. This shows that the disturbance caused around the soil during the drilling process has significant affect on the lateral capacity of the piles.

The curvature distribution along the pile shaft from experiment and case Mon3 are shown in Fig. 7 (a) and (b). The maximum curvature for case Mon3 is at the depth of 0.6m which correlates well with the experimental results.



(a) (b)

Fig. 7 Curvature distribution along the pile shaft for (a) SP1 (Experiment) and (b) case Mon3

4.2 Reversed cyclic loading

In the reversed cyclic loading, case Rev1 where interface element and bentonite cement layer around the pile is considered while the stiffness degradation is not considered, the analysis overestimates the lateral capacity of the pile (Fig. 8).

In case Rev2, degradation of stiffness curve was considered as shown in Fig 5. Stiffness reduction factor was considered parametrically and it was observed that for the stiffness reduction factor of 0.2, the analytical results tends to agree with the experimental results (Fig. 9). This shows that there is degradation in stiffness of soil due to reversed cyclic loading.

Fig 10 and Fig 11 shows the curvature distribution along the depth of the pile for experiment and case Rev2, respectively. The maximum curvature for case Rev2 is at the depth of 1.2m which correlates well with the experimental results. The depth of plastic hinge is lowered for reversed cyclic case (Rev2) compared with the monotonic case (Mon3).

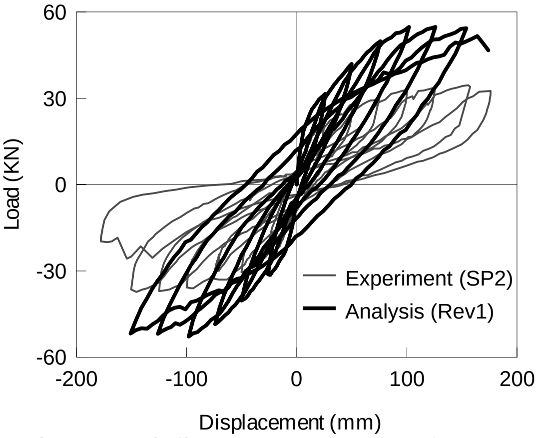


Fig.8 Load displacement curve for case Rev1

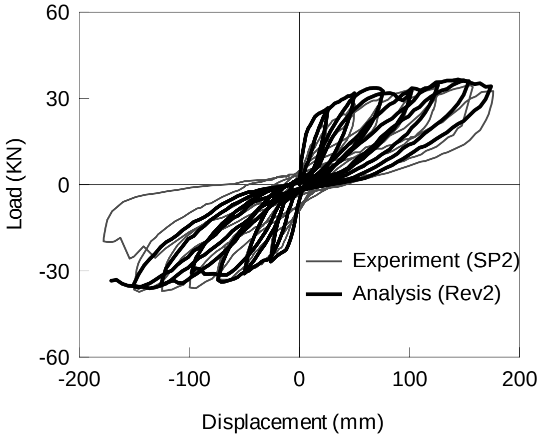


Fig.9 Load displacement curve for case Rev2

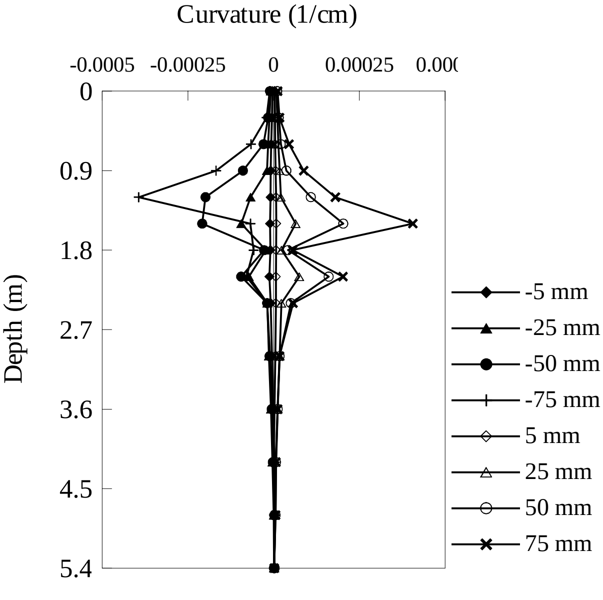


Fig.10 Curvature distribution for SP2 (Experiment)

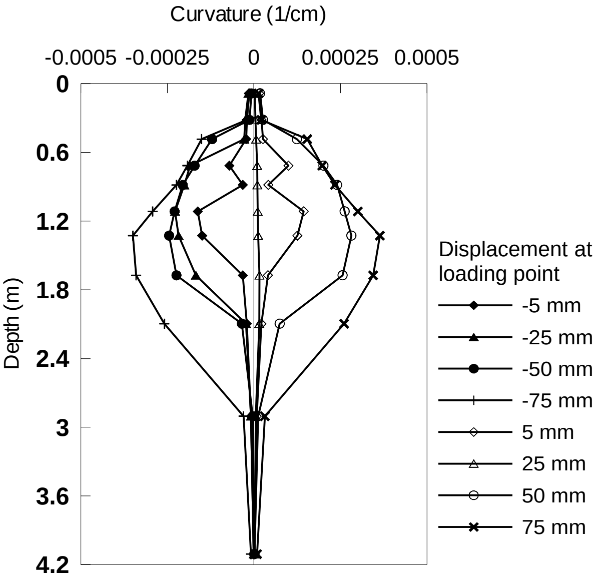


Fig.11 Curvature distribution for case Rev2

5. CONCLUSIONS

From the 3D finite element analysis carried out on piles in cohesive soil subjected to lateral loading, following conclusions can be drawn.

1. When the pile embedded in cohesive soil is subjected to lateral loading gap occurs between the pile surface and soil. Gap formation significantly reduces the lateral capacity of the pile.

Proper interface element should be considered between pile surface and soil to incorporate the gaping effect. The interface element used in this study can realistically consider the gap formation.

2. Significant degradation in lateral capacity of pile occurs in reversed cyclic loading compared to the monotonic loading. The reduction observed was around 40% in the experiment. The degradation in reversed cyclic loading is due to the degradation of shear modulus of clay due to cyclic loading.

The degradation in shear modulus with cyclic loading should be considered for the analysis as well. In this research stiffness reduction factor of 0.2 was considered parameterically. It shows that without considering the degradation in shear modulus due to cyclic loading, the analytical results highly overestimates the lateral load carrying capacity of pile in reversed cyclic loading.

3. Presence of layer of bentonite-cement slurry around the pile has significant effect on the lateral capacity of the pile. This should be considered for the analysis for pre-boring piles.

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