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LATERAL RESISTANCE OF PILES WITHIN CORRUGATED METAL SLEEVES: FINAL SUMMARY REPORT #3 FOR STUDY TPF-5(272)

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Final Summary Report #3
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16. Abstract

Pile foundations supporting bridge abutments are often driven inside corrugated metal pipe sleeves (CMS) which extend through the approach fill to reduce downdrag or for construction expediency. The annular space between the pile and the sleeve is typically filled with uncompacted pea gravel. Designers often assume that the lateral resistance of the pile within the sleeve will be minimal; however, no test results are available to confirm this assumption. To investigate the lateral resistance of piles driven within a CMS, full-scale lateral load tests were performed. The test pile configuration included a 32.4 cm (12.75 in.) pipe pile within a 60 cm (24 in.) CMS with uncompacted pea gravel or clean sand filling the annular space. Results indicate that after small pile displacements, the lateral pile resistance was similar to that provided by an individual 12.75-in. diameter pipe pile and was even greater at larger displacements. As the pile displaced laterally, the gravel within the annular space became engaged and displaced the CMS into the compacted fill. Back-analyses indicate that the ultimate lateral pile resistance for this case can be approximated by treating the pipe-infill-CMS as a composite pile having an elastic modulus (E) and moment of inertia (I) equal to the pipe pile but with a diameter equal to the 24-inch CMS.

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UNIT CONVERSION FACTORS

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. (Adapted from FHWA report template, Revised March 2003)

EXECUTIVE SUMMARY

Pile foundations supporting bridge abutments are often driven inside corrugated metal pipe sleeves (CMS) which extend through the approach fill to reduce downdrag or for construction expediency. The annular space between the pile and the sleeve is typically filled with uncompacted pea gravel or sand. Designers often assume that the lateral resistance of the pile within the sleeve will be minimal; however, no test results are available to confirm this assumption. To investigate the lateral resistance of piles driven within a CMS, full-scale lateral load tests were performed. The test pile configuration included a 32.4 cm (12.75 in.) pipe pile within a 60 cm (24 in.) CMS with uncompacted pea gravel filling the annular space in one test and uncompacted clean uniform sand in another. Results indicate that after small pile displacements, the lateral pile resistance was similar to that provided by an individual 12.75-in. diameter pipe pile and was even greater at larger displacements. As the pile displaced laterally, the gravel within the annular space became engaged and displaced the CMS into the compacted fill. The lateral resistance for the test pile with pea gravel infill was slightly higher than that for the sand infill, but the overall behavior was consistent in both cases. Back-analyses using the computer model LPILE indicate that the ultimate lateral pile resistance for this case can be approximated by treating the pipe-infill-CMS as a composite pile having an elastic modulus (E) and moment of inertia (I) equal to the pipe pile but with a diameter equal to the 24-inch CMS.

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1.0 INTRODUCTION

Pile foundations supporting bridge abutments are often driven inside corrugated metal pipe sleeves (CMS) which extend through the approach fill. These sleeves may be used to reduce downdrag from settlement of the approach fill or simply to preserve a hole through a Mechanically Stabilized Earth (MSE) fill so that construction of the fill can commence before the pile is driven. Typically, the annular space between the CMS and the pile is back-filled with uncompacted sand or pea gravel. For piles supporting integral abutments, the pile-sleeve methodology is meant to provide reduced stiffness for lateral loading of piles while reducing the potential for buckling under axial load. Because these sleeves are placed near the head of the pile where much of the resistance to lateral loading is gained (Duncan et al. 1994, Russell 2016), designers often assume that the lateral pile resistance is minimal.

A nation-wide survey of state Departments of Transportation (DOTs) and construction companies indicated that 11 of the 20 responding agencies use the practice of placing a CMS around piles in the design of integral abutment bridges (Arenas et al. 2013). Although the survey indicates that CMS composite piles are being used by multiple agencies, a review of the published technical literature does not provide any full-scale test results indicating how these pile-sleeve systems actually react to lateral loads. However, numerical analyses of the pile-sleeve system suggest that significant lateral resistance might still develop (Arenas et al. 2013). This report details the results of full-scale lateral pile load tests on pipe piles within a CMS to define the failure mechanisms involved. Simplified approaches to simulate the lateral resistance using p-y curve procedures are also presented.

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2.0 TEST LAYOUT

Three pipe piles were installed, instrumented and tested in similar soil conditions. Two of the pipe piles were encased in a CMS surrounded by compacted fill (CMS composite piles) while an identical pipe pile was surrounded by the same compacted fill to provide a comparison or control. Each of the pipe piles measured 12.2 meters (40 ft) long with a diameter of 32.4 cm (12.75 in.) having the properties shown in Table 1. Each pile was driven 5.5 m (18 ft) into granular native soil, leaving 6.7 m (22 ft) of pile stickup above native ground. A 6.1-meter (20-ft) section of corrugated sleeve was placed over two of the piles. Then a backfill, consisting of silty sand with gravel, was compacted to 6.1 meters (20 ft) above native soil, leaving 0.6 meters (2 ft) of the pipe piles above grade. The annular space for the CMS encased piles was filled from the top with pea gravel in one case and sand in another case, without any compaction. Particle size-distribution curves for each infill material are shown in Figure 1. The grain size curves are relatively uniform in both cases. The pea gravel actually consists of 30% gravel and 70% sand, but will be referred to as pea gravel for simplicity.

Table 1. Material Properties for Pipe Piles and CMS.

Type	Diameter	Wall Thickness	Cross Sectional Area	I	E	F_y
	cm (in.)	cm (in.)	cm^2 (in^2)	cm^4 (in^4)	MPa (ksi)	MPa (ksi)
Pipe Pile	32.4 (12.75)	0.89 (0.35)	94 (14.57)	13,070 (314)	200,000 (29,000)	393 (57)
CMS	60 (24)	0.16 (0.064)	31 (4.8)	18.9 (0.454)	200,000 (29,000)	393 (57)

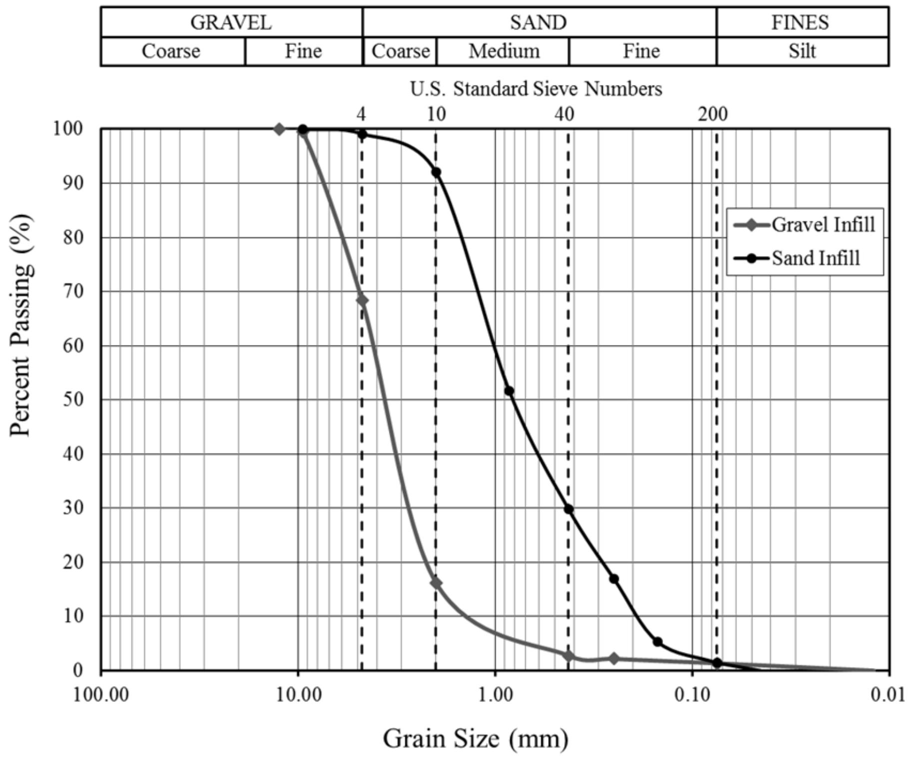

Figure 1. Particle size-distribution curve for pea gravel and sand infill material.

3.0 LOAD TEST PROCEDURE AND INSTRUMENTATION

A static lateral load was applied to each pile 30 cm (12 in.) above the ground surface by a hydraulic jack. The lateral load was applied incrementally by pushing the pile first to 3.175 mm (0.125 in.) of lateral deflection and then in 6.35 mm (0.25 in.) increments of lateral deflection. After the specified deflection increment had been reached, the fluid pressure in the jack was locked off while load and deflection came into equilibrium over a 5-minute period.

The loads were measured with a load cell while lateral deflection was recorded by string potentiometers. Bending moment with depth was calculated using readings taken from strain gauges placed along the length of the pile prior to installation. Soil displacement around the piles was recorded using a digital image correlation system as well as string potentiometers attached to fixed markers.

4.0 RESULTS OF LATERAL LOAD TESTS

Initial pile response was observable from the surface shear cracks which developed in the soil surrounding the loaded piles. These cracks are a result of soil failure as a passive failure wedge began to mobilize in front of the pile. Figure 2 shows the surface cracks around piles with and without the CMS sleeve. The cracks were highlighted in red paint for better visibility.

Figure 2. Surface shear cracks around a laterally loaded pipe pile (left) and CMS composite pile (right).

The apparent failure wedge shown around the pipe pile within a CMS gives insight into the soil-pile interaction of this composite pile system. As the applied load increases, the pipe pile displaces the loose annulus infill until a wedge of gravel eventually engages and displaces the CMS. The CMS then transmits this pressure onto a larger wedge of soil radiating outward from the edges of the CMS which has been idealized in Figure 3. This is a simplified representation of how the use of a CMS increases the effective width of the pile. This failure wedge will be further investigated in a following section from measurements of vertical soil movement at increasing distances from the pile. An observation of the surface shear cracks indicates the approximate extent of the failure “wedge” or “bulb” in front of the CMS composite pile.

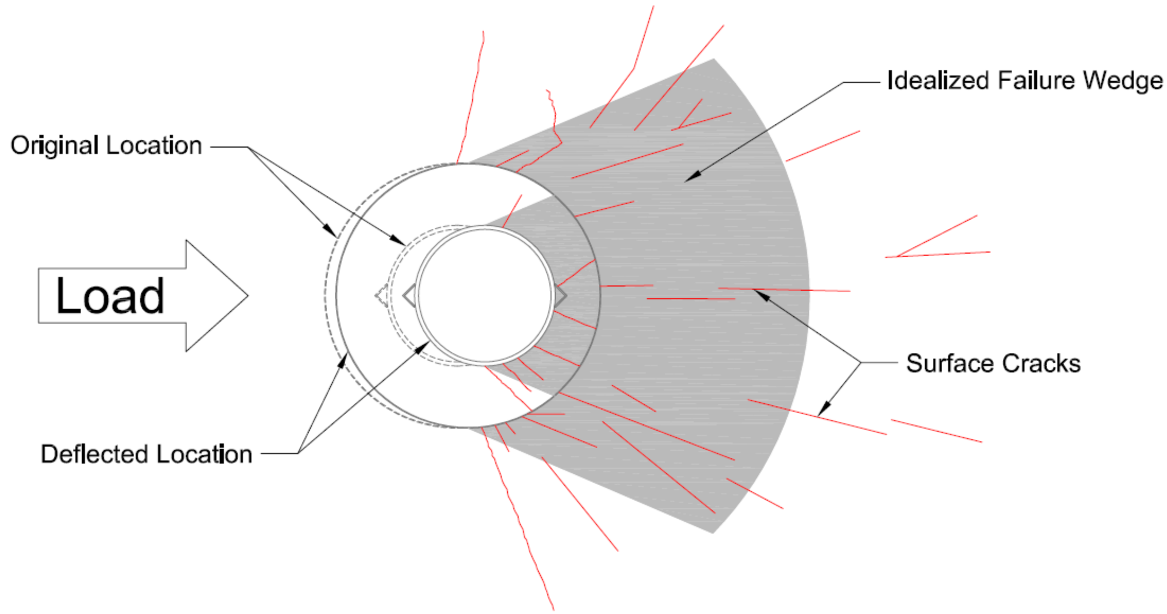

Figure 3. Idealized failure wedge geometry around a CMS composite pile system.

4.1 Ground Heave

As each pile deflected laterally under the applied loads, the compacted soil within the passive failure wedge would displace vertically. Measurements of this vertical soil displacement, or soil heave, with increasing distance from the pile can indicate the zone of influence in front of the pile itself. With the use of a level survey and a Digital Image Correlation (DIC) camera-based system, measurements were collected to observe magnitudes of soil heave at a distance from the pile. The DIC consists of two video cameras at a fixed distance apart with over-lapping fields of view connected to a laptop computer. Computer algorithms track the movement of thousands of points within the field of view to evaluate elevation changes similar to the methods employed by aerial photogrammetry.

Quantitative observations can be made from DIC contour plots created through the data analysis package, Istra-4D Q-400 (Dantec Dynamics 2014). Figure 4 was created by assigning colors to various levels of vertical soil displacement in front of the pile. The contour intervals range from hot to cool colors as displacement values decrease in magnitude. The contours show the progression of ground heave within the failure “wedge” or “bulb” surrounding the loaded pile. An idealized stress bulb has been outlined on Figure 4 representing the boundary of 1.27 cm (½ inch) of vertical ground deflection.

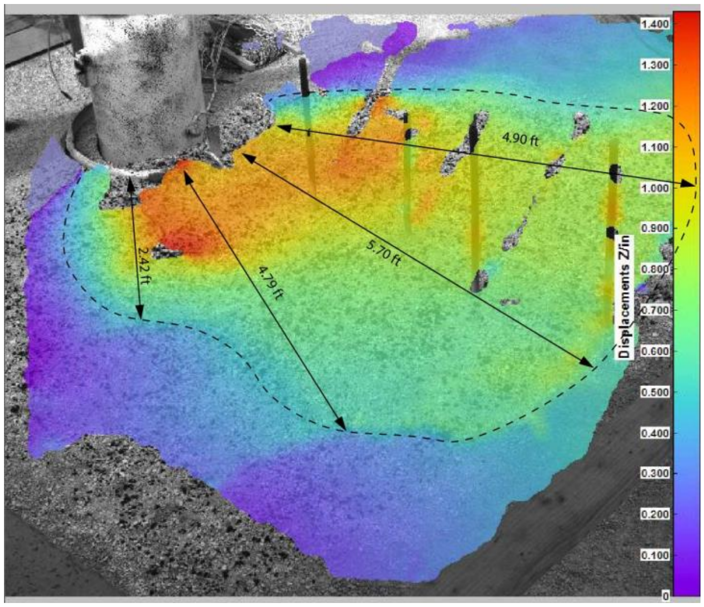

Figure 4. Vertical soil displacement contour plot for a laterally loaded CMS composite pile.

Based on the soil heave measurements of both piles, the CMS composite pile has a larger zone of influence in the surrounding soil. Survey measurements showed that ground heave around the control pipe pile is greatest at the pile face and reaches zero near a distance of 1.2 to 1.5 m (4 to 5 ft). According to the stress bulb shown in Figure 4, the zone of influence for the CMS composite pile reaches approximately 1.85 meters (6.2 ft) or more from the face of the central pile. Although the heave between the pipe pile and the CMS was not perceived from the DIC cameras, survey measurements showed the ground heave increased from the pile face to the edge of the CMS, presumably as the loose fill in the annular space gradually compressed under load. Maximum heave occurred at the CMS face and then decreased with distance. This information can influence the design of pile groups, bridge abutments, or structures near deep foundations. Three-dimensional relationships, such as these, can be more helpful in creating a realistic model of the failure surface than the simplified failure wedge method (Reese and Van Impe, 2001)

4.2 Lateral Load-Deflection

A plot of the lateral load-deflection performance of the pipe pile in compacted fill (control pile) and the pipe pile within a CMS is provided in Figure 5. Lateral deflection measurements were taken at 30 cm (12 in.) above the ground. This also was the point where the load was applied and will be referred to as the pile head.

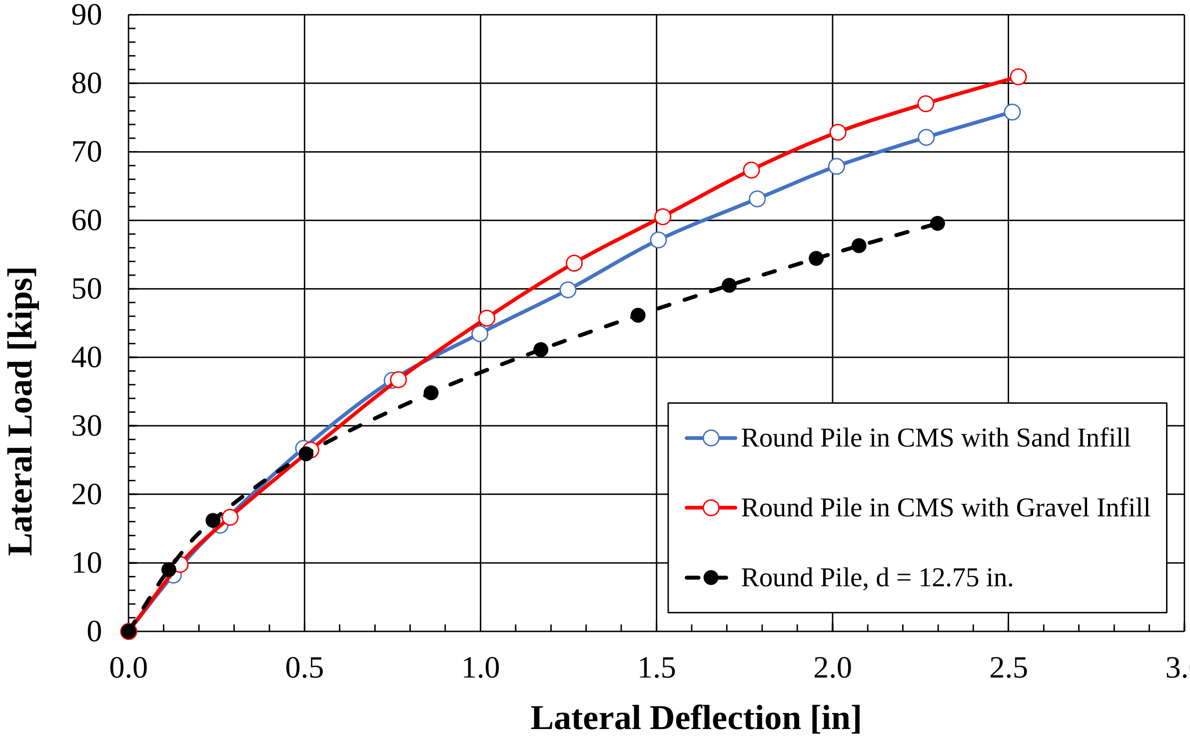

Figure 5. Lateral load-displacement performance for a pipe pile in compacted backfill and a pipe pile within a CMS surrounded by compacted backfill.

These deflection measurements represent pile performance under static loading conditions. For deflections less than 1.27 cm (½ in.), the lateral load is very similar for both test pile conditions, except the CMS composite pile shows slightly more deflection in the early stages of loading. For deflections greater than 1.27 cm (½ in.), the CMS composite pile shows more resistance to loading than the control pipe pile. These test results indicate that although the annular void between the pipe pile and the sleeve is filled with loose material, the infill densifies after approximately 1.27 cm (½ in.) of deflection and is capable of transferring stress to the CMS. This in turn increases the effective pile width providing a similar or greater amount of resistance than the individual control pile. Of course, this behavior is completely contrary to the common design assumption that the pile within the sleeve will have very little lateral resistance. However, it is generally consistent with the results of numerical studies reported by Arenas et al. (2013). Additional tests are necessary to determine if this failure mechanism is only valid for pea gravel or if is applicable to other infill materials.

4.3 Bending Moment vs. Depth Curves

Bending moment versus depth curves are shown in Figure 6 for the single pile and the two identical piles within the CMS pipe with sand and gravel infill. The moment vs. depth curves were plotted for a load of 222 kN (50 kips) applied to each pile. The maximum moment typically occurs at a depth of about 1.2 m (4 ft) below the ground surface for the isolated pipe pile. The pipe piles in a CMS show maximum moments occurring at depths of 2.1 m to 2.4 m (7 ft to 8 ft) below the ground surface which is much deeper than for the isolated single piles. Typically, larger diameter piles develop maximum moment at greater depth. This suggests that the CMS composite pile is acting as a round pile of larger diameter. The moment versus depth plots indicate that a large part of the soil resistance of a single laterally loaded pile occurs in the top 1.2 m (4 ft) of soil which is in agreement with previous laterally loaded pile analysis (Duncan et al., 1994). It is also interesting to note that the maximum moment in these tests tended to occur at a depth of about four times the diameter of the pile or composite pile.

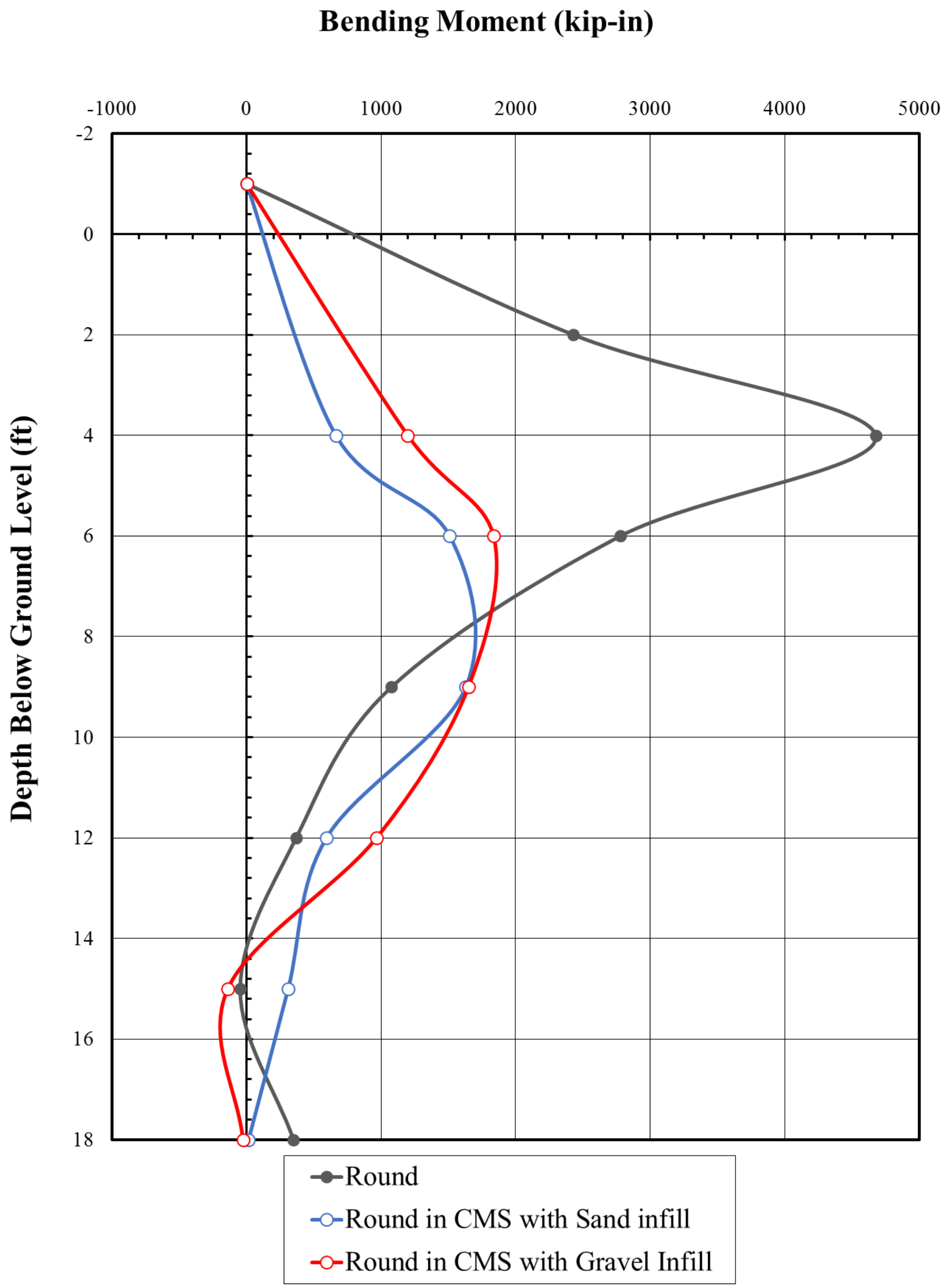

Figure 6. Bending moment versus depth curves for the individual pile and the pile in CMS with sand and gravel infill.

5.0 ANALYSES USING SIMPLIFIED MODELS

To better understand the results of the lateral load tests, analyses of several simplified pile geometries were performed using the computer program LPILE (Ensoft, 2014). Initially, a geotechnical profile was calibrated in the LPILE model using the results from the pipe pile load test. Further investigations were then made using the calibrated geotechnical properties to develop a simplified model in LPILE that could describe the lateral resistance of the pipe pile within the CMS.

The soil properties required for an LPILE analysis in non-cohesive soil include: the effective unit weight, γ'; the friction angle, ϕ; and the lateral soil stiffness or subgrade modulus, k. Soil properties were keyed into the model to represent the soil conditions at the test site including the native soil and the compacted backfill. The native soil and the backfill material, being silty sand and silty sand with gravel, respectively, were modeled using the API Sand (O'Neill) p-y curve model. Because the compacted fill was 6 m (20 ft) thick, lateral response was primarily governed by the fill (silty sand with gravel). Values for the effective unit weights of each layer in the fill were based on averaged nuclear density gauge measurements taken in each lift during construction. Measurements for the ϕ and k were not made during testing and were derived by calibrating the LPILE model of a 32.4 cm (12.75-in.) pipe pile to match the measured load test results. The measured load-deflection curve is compared with curves computed by LPILE using relative density compatible ϕ and k values in Figure 7. The calibrated soil properties are shown in Table 2. The back-calculated ϕ and k values are generally consistent with API recommendations for a relative density of 100% and match the measured load-displacement test results reasonably well. However, the back-calculated soil parameters are higher than might typically be assumed during design in engineering practice.

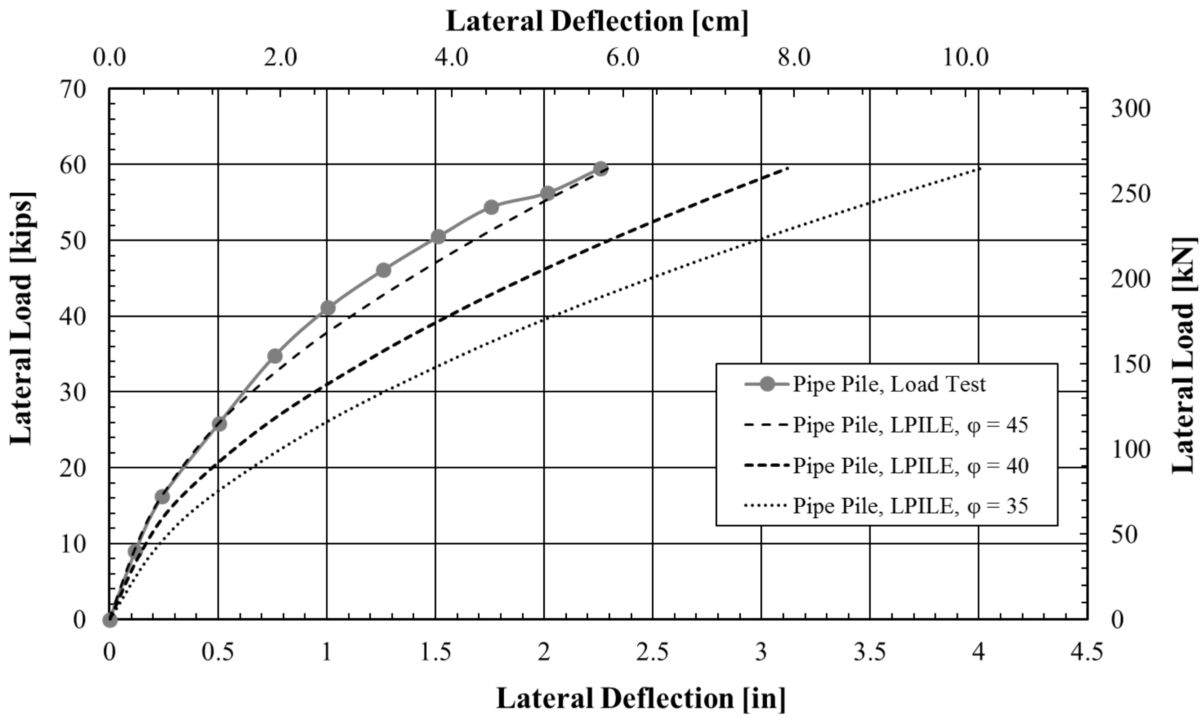

Figure 7. LPILE model calibration with load test results for pipe pile.

Table 2. Calibrated Soil Properties

Soil Layer	Effective Unit Weight, γ' kg/m³ (pcf)	Friction Angle, ϕ (degrees)	k kg/cm³ (pci)
Native Soil	2002 (125)	34	2.8 (100)
Backfill	2098 (131)	45	10.9 (394)

Ideally, the creation of a simplified model for the CMS composite pile should be easy to replicate for standard design purposes. Therefore, analyses using existing pile options in LPILE that may resemble a pipe pile within a CMS were investigated. Initially, a model was created using the moment of inertia of the inner pipe pile and assuming no resistance was provided by the infill or the CMS. This model idealized the annular fill material as being very loose. Using this model, lateral resistance was only about 18 kN (4 kips) for a pile head deflection of 75 mm (3 in.) because the applied load at the pile head had a moment arm of 6.4 meters (21 ft) above the native soil. Although it is a common assumption that this model can be conservatively assigned to sleeved piles in some cases, it does not appear to accurately represent actual soil response. The failure of this model to match measured response indicates that the annular fill, although initially loose, can still engage the CMS and provide significant lateral resistance during loading.

Another model was produced consisting of a pile with a permanent casing and core using the CMS properties for the casing, pipe pile properties as the shaft core and the soil infill as the "concrete" fill. Stiffness properties can be calculated for a pipe core with permanent casing assuming that the concrete has sufficiently bonded to the casing and core, to produce one composite member. However, the same model cannot be used for the CMS with cohesionless soil infill because the member does not act as a uniformly composite material. As the member is loaded, the cohesionless infill provides no contribution in tension and it is difficult to quantify the contribution in compression as the annular fill material continuously consolidates with increased load. These differences eliminate a pipe core with a permanent casing as a viable model for a pipe pile within a CMS even when using very low compressive strength values for the "concrete" fill.

The most comparable model was created for a composite pile with the diameter of the CMS, 0.6 m (24 in.), but with the moment of inertia of the 0.324 m (12.75 in.) pipe pile alone as it is the most significant contribution to flexural stiffness. Any contribution to the structural stiffness from the CMS was ignored. This model retains the structural properties (E and I) of the 0.324 m (12.75 in.) pile but with the benefit of an effective width of 0.6 m (24 in.) from the CMS. The same ϕ and k were used to define the backfill soil around the CMS as was determined by back-analysis for the pipe pile in compacted fill. For comparison purposes, load versus deflection curves were computed using two LPILE models. One model is for the 0.324 m (12.75 in.) diameter pipe alone, while the second is for the stiffness of the 0.324 m (12.75 in.) pile but with a diameter of 0.6 m (24 in.) as explained previously. The load versus deflection curves for the LPILE models have been plotted along with the curve from the load test in Figure 8.

According to this analysis, the lateral resistance of the composite pipe-CMS pile can be defined within the bounds of a 0.324 m (12.75 in.) and a 0.6 m (24 in.) diameter pipe pile with the moment of inertia of the 0.324 m (12.75-in.) diameter pile as shown in Figure 8. For pile head displacements less than 1.27 cm (0.5 in.), the model based on the pipe pile alone provided acceptable agreement with measured results. For pile head displacement greater than about 4.45 cm (1.75 in.), the pipe pile model with the 0.6 m (24 in.) effective width provides reasonable agreement with the measured response. Fitting a linear transition between the two models at 1.27 cm (0.5 in.) of deflection and 4.45 cm (1.75 in.) of deflection creates a load-deflection curve that fits the measured curve for the pipe-CMS composite pile in this interval very well. This model indicates that initial resistance is provided by the inner pipe pile, and eventually the benefit of the larger effective width of the CMS is developed as the stress is transferred to the surrounding soil at greater pile head deflections.

Additional testing and analysis are necessary to develop a more generalized model to account for different geometries, but this simple model provides preliminary guidance. Lastly, group interaction factors (p-multipliers) are often specified in terms of the center-to-center pile spacing divided by the pile diameter. For the case of sleeved piles where the effective pile diameter changes, additional study will be necessary to properly consider these effects. For example, at larger pile head deflections the “pile diameter” used for group interaction may need to be the diameter of the sleeve, not the actual diameter of the pile.

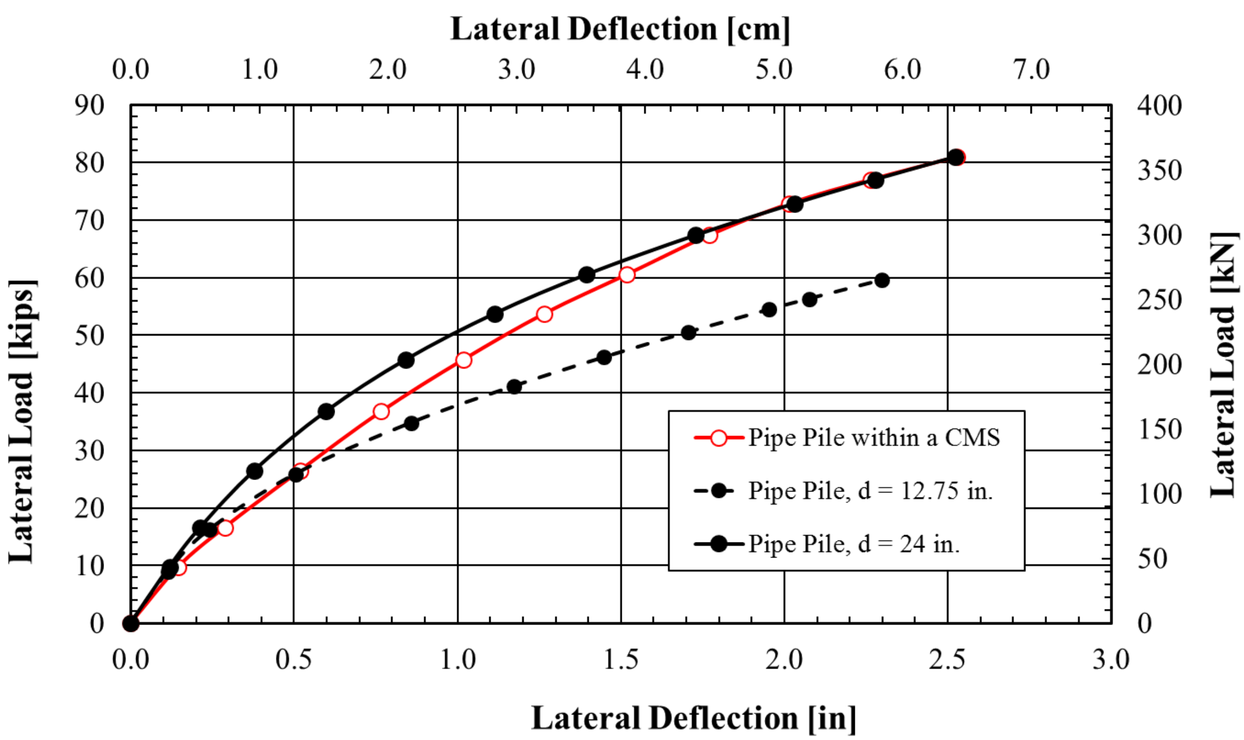

Figure 8. Lateral load-defection curve for 0.324 m (12.75 in.) pipe pile in 0.6 m (24 in.) CMS in comparison with LPILE models for pipe piles of 0.324 m (12.75 in.) and 0.6 m (24 in.) diameter.

6.0 CONCLUSION

Based on the field testing and analyses of the test data, the following conclusions have been made:

1. Placing a CMS around a pipe pile with uncompacted granular fill in the annular space does not lead to a pile with little to no lateral resistance as is sometimes assumed in design applications.
2. The size of the observed failure wedge, the shear crack patterns, and the lateral load versus deflection curve for the CMS composite pile indicate that placing a sleeve of a larger diameter around a pile has the effect of increasing the effective width of a pile when it is laterally loaded.
3. The use of a CMS can increase the lateral resistance of the central pile as stresses propagate through the loose granular annulus infill and engage the CMS. This increase in lateral resistance was observed after about 1.27 cm (0.5 in.) of lateral pile head deflection.
4. At larger deflections, the lateral resistance of a CMS composite pile can be approximated by using the structural stiffness (EI) of the interior pipe pile but with an effective pile diameter equal to the width of the CMS to account for increased soil resistance on the CMS.

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