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Lateral load resistance of piled raft foundation - A case study of District Jail, Saidu Sharif, Swat Pakistan

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***Abstract* - Piled raft foundations under lateral loads are usually designed as a pile group, ignoring the contribution of the raft to resisting the lateral loads. In this paper, a case study was performed to determine the raft's contribution to the lateral load resistance. This study analyzed a pile-supported reinforced concrete retaining wall for two different foundation conditions, i.e., pile group foundation and pile raft foundation. Pile group supported reinforced concrete retaining wall was analyzed by following the standard code practice while pile raft supported reinforced concrete retaining wall was analyzed with the help of up-to-the-minute finite element-based software, PLAXIS 3D. It was revealed that by considering the contribution of the raft in the pile raft foundation system subjected to lateral loads, a great deal of economy can be achieved in terms of the small diameter of piles, short pile lengths and less number of piles. The maximum moment on piles was decreased about 2.5-3 times while the maximum shear was decreased about 2-3 times. A decrease in demand also results in reducing the lateral deflection of piles to about 50 %.**

Index Terms – Piled raft, Pile group, Lateral load, shear force, bending moment

INTRODUCTION

Piled raft is one of the effective types of foundation from a bearing capacity and settlement point of view. Usually, pile foundations are designed for vertical loads, however, cases like the foundation of bridges, transmissions towers, offshore structures, wind turbines and pile-supported reinforced concrete retaining walls, are also properly analyzed and designed for lateral loads. Lateral load resistance of pile foundations in these structures is critically important for their design under lateral loads, resulting from earthquakes, water waves, wind and soil movements [1,2]. [2] performed finite element analysis on a group of piles under lateral load and concluded that the piles' top is critical to load and deflection. Moreover, the pile's deflection decreases with an increase in the L/D ratio. The effect of the L/D ratio on the capacity of piles under lateral load was also studied by [3].

Pile foundation under lateral loads has been studied by various researchers [4-8] who studied single piles under lateral loads whereas many researchers [9-12] studied pile group foundation under lateral loads. [13] conducted 1g-experimental testing and found that the lateral capacity of the piled raft was about 2-6 times as compared to the pile group which indicates that the raft also contributed to resist lateral loads and should be considered for design purposes. To simulate the lateral behavior of piles, [14] performed a study and compared the numerical results using ABAQUS and LPILE with full-scale tests. The results obtained were close enough with FE software ABAQUS. Load deflection behavior of piles in groups under lateral load also depends on group size, pile spacing and relative density [15]. [16] also studied the group piles under lateral load and concluded that raft contribution to lateral load was due to friction and raft contact pressure with the soil. They also proposed simplified equations using Mindlin's method to determine shear forces and bending moments produced in a pile due to lateral load. [17] performed finite element analysis to determine the load contribution ratio of different components of piled raft foundation under combined V-M-H loading. [18] concluded from current experimental findings that rafts contribute to the applied lateral load in piled raft foundations.

A case study was evaluated for piled raft and pile group as a deep foundation for retaining wall in the current work. Piled raft foundation comes out to be more economical due to raft contribution in resisting lateral and vertical load.

CASE STUDY

District Jail, Saidu Sharif is located at 34°44'51.22"N, 72°21'33.00"E in District Swat, Khyber Pakhtunkhwa, Pakistan. A snapshot of the project site taken from the Google Map is provided in Fig. 1. Generally, the topography of the site is composed of hilly terrain, with a non-perennial drain flowing beside.

FIGURE 1
SITE LOCATION MAP (GOOGLE EARTH)

I. Soil Profile

Soil investigation consisted of two (02) geotechnical test boreholes of 60 feet deep each, executed at the top (BH-1) and bottom (BH-2) of the slope Fig. 2. Standard penetration tests were performed in each borehole at 5 feet intervals. All other relevant fields and laboratory tests were performed in each geotechnical test boreholes. The following soil properties were used for the analysis and design of the RCC cantilever retaining wall. The soil strata are composed of different soil layers, as can be identified in Table 1.

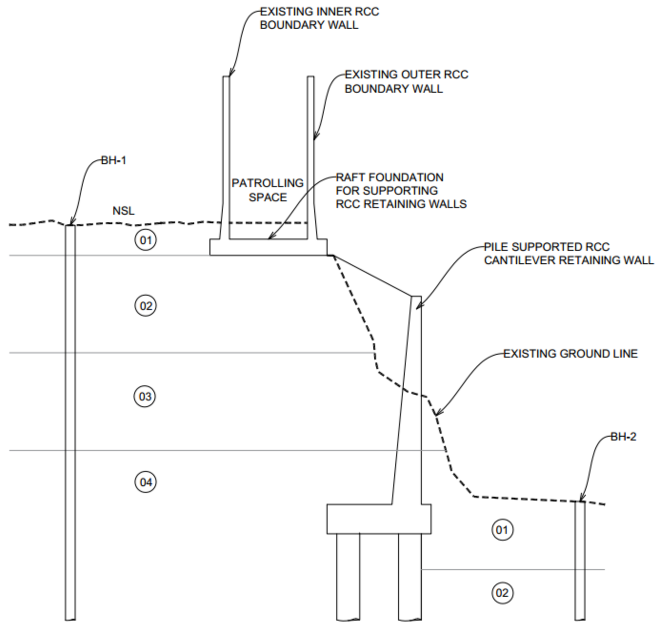

FIGURE 2
SOIL PROFILE

II. Topography Survey

The topography of the site is shown in Fig. 3. Six different sections were evaluated for the height, slope and surcharge loads to determine a critical section. Section 3 was observed as a critical section because of the maximum height, steep slope and maximum load. Therefore, section 3 was selected as a critical section as shown in Fig. 4, for the design and analysis of the proposed RCC retaining wall.

TABLE 1
DESIGN SOIL PARAMETERS

Bore Hole ID	Soil ID	Description	Design Parameters	Remarks
BH-1	01	Compacted Fill	-	These soil properties are used for slope stability analysis and retaining wall analysis.
	02	Silty Sand with Gravels	c = 250 psf., φ = 39.5°	
	03	Sandy Silt	c = 385 psf., φ = 36°	
	04	Silt with Sand	c = 776 psf., φ = 20°	
BH-2	01	Silty Clay	c = 4000 psf., φ = 0°	These soil properties are used for the analysis of piles.
	02	Silty Clay with Gravels	c = 0 psf., φ = 38°	

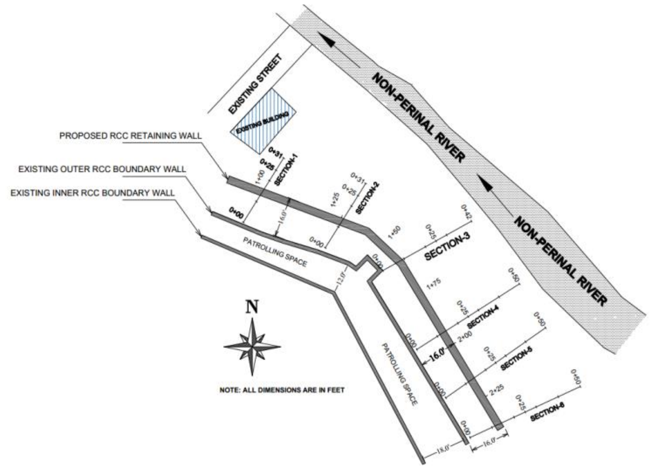

FIGURE 3
GENERAL TOPOGRAPHY OF SITE AND SECTIONS

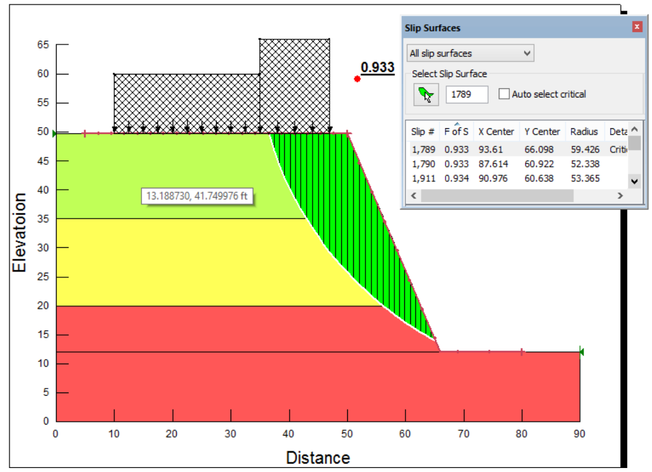

FIGURE 5
SLOPE STABILITY ANALYSIS OF ACTUAL SLOPE (ASSUMED 16 FT PROJECTING AT BASE)

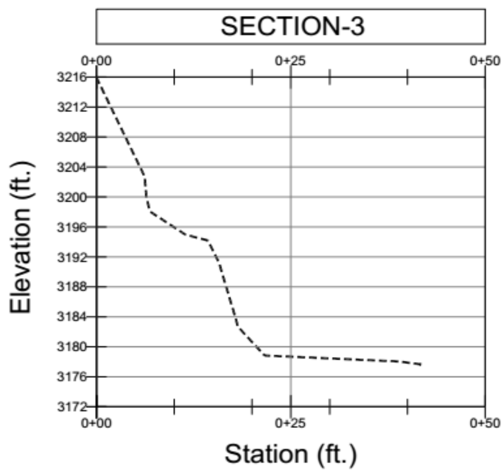

FIGURE 4
SECTION 3 CRITICAL SECTION

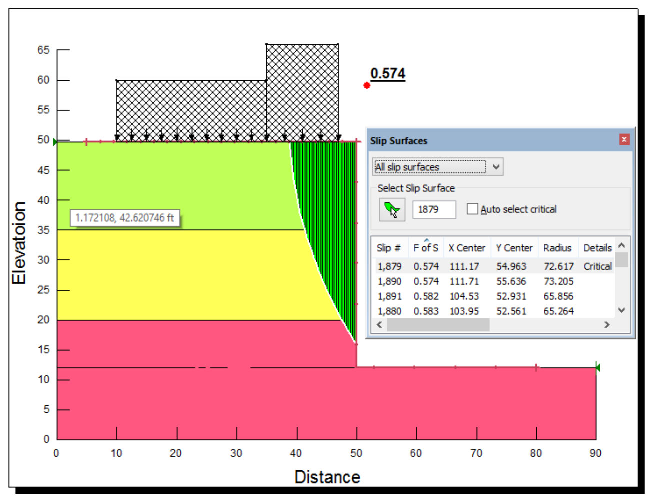

FIGURE 6
STABILITY ANALYSIS OF VERTICAL CUT

SLOPE STABILITY ANALYSIS

The following two different types of slope stability analyses were performed on the slope.

I. Analysis of actual slope

The actual slope condition with surcharge loads was modelled using soil properties provided in Table 1. In dry soil conditions factor of safety of the existing slope was almost equal to 1 from the analysis using Geo Studio software (Fig. 5).

II. Stability analysis of vertical cut

For the construction of a pile-supported RCC retaining wall, a vertical cut of the existing slope, with a width of 16 feet, will be carried out to get sufficient working space. The vertical cut slope was analyzed, resulting in a factor of safety equal to 0.5 (Fig. 6). This means that temporary support will be required to stabilize the slope before starting construction work.

RETAINING WALL ANALYSIS

Before the piles were examined, the retaining wall was analyzed for various failures and to transmit loads from the wall to the foundation. At the first attempt, the RCC cantilever retaining wall without piles was analyzed, which results in less factor of safety than the minimum required. Therefore, piles were provided beneath the base of the retaining wall.

The retaining wall was modelled in the Geo-Structural Analysis software and resultant load actions were calculated at the middle of the base of the retaining wall. Further, the resultant load actions were transferred to the supporting piles and piles were analyzed for that load (axial and lateral loads).

I. Analysis of retaining wall with and without piles

The analysis of the retaining wall with and without piles was carried out for all possible LRFD load combinations. LRFD load factors for all the relevant limit states considered in the retaining wall analysis are provided in Table 2.

TABLE 2
LRFD LOAD COMBINATIONS

Limit State	DC	EV	LS_v	LS_h	EH	Probable USE
Service I	1.00	1.00	1.00	1.00	1.00	Settlement
Strength I (a)	0.90	1.00	1.75	1.75	1.50	BC/EC/SL
Strength I (b)	1.25	1.35	1.75	1.75	1.50	BC (max value)
Extreme Event I	1.00	1.00	0.00	0.00	1.00	BC/EC/SL

DC: Dead load of Concrete
EV: Vertical Pressure from Dead load of Earth Backfill
LSv: Live Load Surcharge (Vertical Component)
LSh: Live Load Surcharge (Horizontal Component)
EH: Horizontal Earth Pressure

A dimension of the proposed retaining wall and the piled foundation is shown in Fig. 7. The diameter of the piles was taken as 3.5 ft and the thickness of the raft as 4 ft. A piled foundation was analyzed as a group and piled-raft foundation.

A surcharge load from the existing 12 ft retaining wall (2150 psf) and compacted fill (1200psf) were also calculated and taken into account for the retaining wall analysis as shown in Fig. 8.

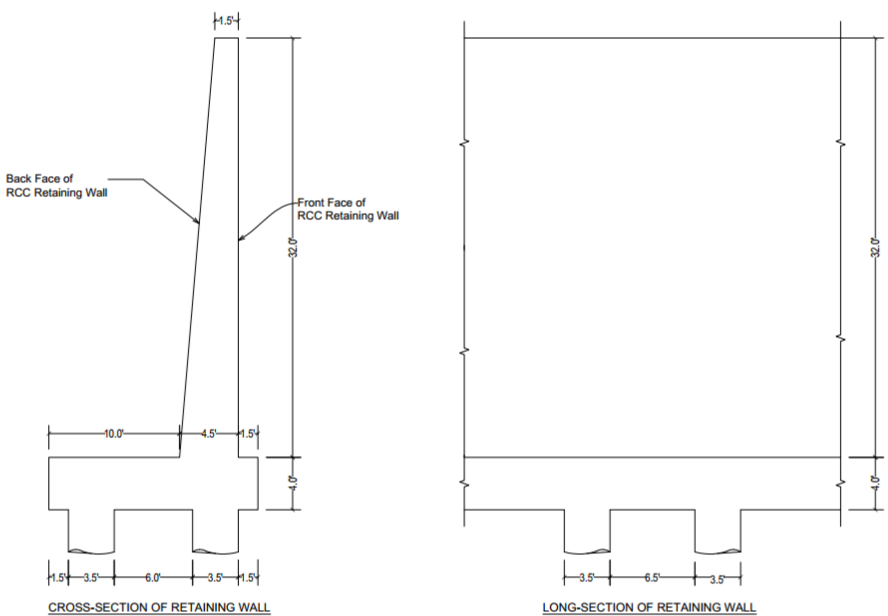

FIGURE 7
RETAINING WALL GOEMETRY

Results from the analysis using different limit states are summarized in Table 3. Analysis of the wall and foundation is to be carried out for the worst case. So, the maximum moment was obtained from the extreme event while the maximum normal force and shear force was obtained from the strength 1b case.

TABLE 3
RETAINING WALL ANALYSIS SUMMARY

No.	Limit State	Moment (lbf-ft/ft)	Normal force (lbf/ft)	Shear Force (lbf/ft)	Remarks
1	Service I	218759.3	89478.69	28629.24	Retaining Wall without piles
2	Service I	218759.3	89478.69	28629.24	Retaining Wall with Piles
3	Strength I (a)	319788.8	94163.90	39461.10	
4	Strength I (b)	302050.1	**113548.69**	**42943.87**	
5	Extreme Event I	**452037.2**	91400.10	41072.94	

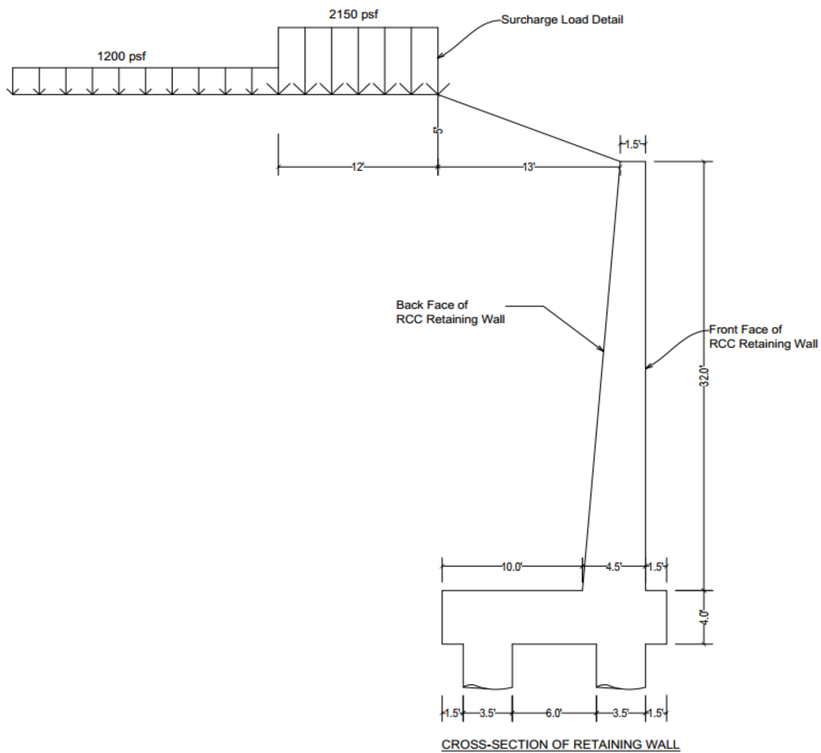

FIGURE 8
SURCAHRGE LOAD DETAIL ON RETAINING WALL

The factor of safety against overturning and sliding obtained from Geo 5 retaining wall analysis without piles is given in Table 4. The retaining wall is safe against overturning as FOS > 1.5 (recommended). However, the wall is not safe against sliding as FOS is on the verge of recommended FOS i.e., 1.5. FOS against sliding can be controlled by providing a key beneath the footing but we provided piles because bearing pressure was also exceeded much more than the allowable bearing capacity i.e., 1.5 tsf.

TABLE 4
FOS FOR RETAINING WALL WITHOUT PILES

Description	Factor of Safety	Remarks
A factor of safety against overturning	2.23	These factors of safety are only for Service-I limit state (Retaining Wall without Piles).
A factor of safety against sliding	1.44	
Bearing pressure	$q_{max.}$ = 10.7 ksf $q_{min.}$= 0.47 ksf	The following equation is used for bearing pressure q = N/B ± My/I

ANALYSIS OF PILES

Piles were analyzed for both axial and lateral loads considering the resulting loads (axial load, lateral load and moment) from the retaining wall, applied to the center of the pile cap as shown in Fig. 9. Demand for the piles is given in Table 5.

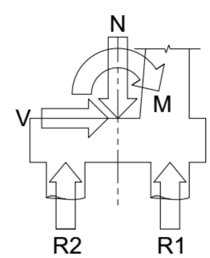

FIGURE 9
RESULTANT LOADS FROM THE RETAINING WALL ON THE CENTER OF THE PILE CAP

I. Code based analysis

A pile foundation was first analyzed as a pile group which means that all the loads will be transferred to piles and the raft does not contribute to resist the demand. Reactions of piles were determined using finite different analysis software i.e., ALLPILE for each limit state and tabulated in Table 6.

TABLE 5
DEMAND ON PILES

No.	Load Condition	Moment (lbf-ft/ft)	Normal force (lbf/ft)	Shear Force (lbf/ft)
1	Service	218759.3	89478.69	28629.24
2	Factored (Governing)	452037.2	113548.69	42943.87

TABLE 6
SUMMARY OF PILE REACTIONS

Load Cases	Moment (lbf-ft/ft)	Normal force [lbf/ft]	e (ft)	Shear Force (lbf/ft)	Pile Spacing [ft]	R1 [lbf/ft]	R2 [lbf/ft]
Service-1	221244.9	89861.64	2.5	28629.24	9.5	**68219.76**	**21641.88**
Strength-1(a)	346029.2	96292.86	3.6	39461.10	9.5	84570.56	11722.3
Strength-1(b)	331202.8	121562.78	**2.7**	**42943.87**	9.5	95644.84	25917.94
Extreme Event-1	462034.1	93982.87	4.9	41072.94	9.5	**95626.6**	**-1643.73**

II. Axial analysis of piles

The maximum pile reaction due to applied loads for a tributary length of 10 feet, in the service load combination, is 682 kips whereas the safe axial capacity of 45 feet long pile is 700 kips.

III. Lateral analysis of piles

The maximum lateral load resulting in the pile cap from the superstructure was equally distributed between the two piles. A lateral load applied on the single pile for a tributary length of 10 feet wall, in-service load condition is equal to 286/2 = 143 kips and in the case of governing factored load condition is equal to 430/2 = 215 kips. Detail of lateral loads is provided in Table 7.

For both cases i.e., service load condition and factored load condition, the lateral response of the pile was analyzed (Table 7).

Lateral analysis was carried out using ALLPILE for the pile group and shear forces calculated for back and front piles were tabulated in Table 8. Back piles were taking less load as compared to front piles. This is because of the less stiff soil in the vicinity of the back pile.

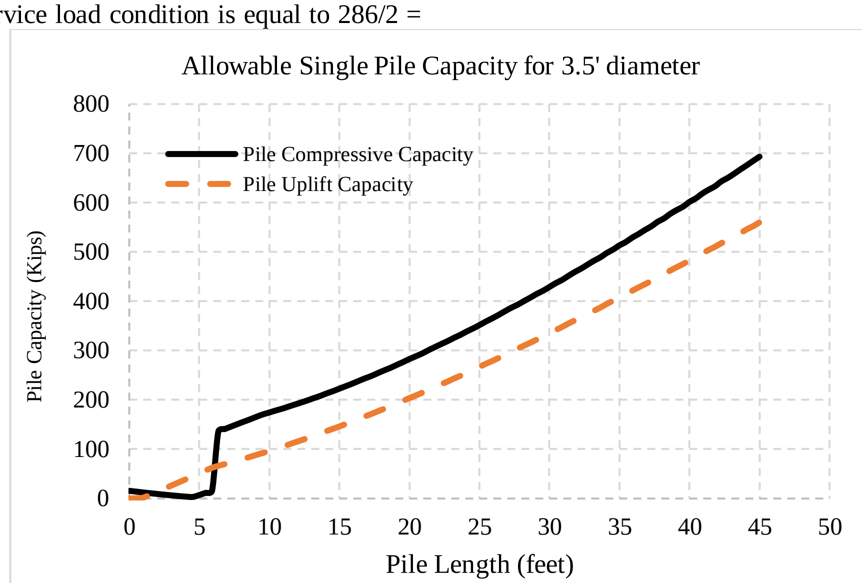

FIGURE 10
AXIAL SINGLE PILE CAPACITY

TABLE 7
LATERAL ANALYSIS OF A SINGLE PILE IN PILE GROUP

Service Load Condition	Governing Factored Load Condition
Max. Moment = 950 k-ft.	Max. Moment = 1508 k-ft.
Max. Shear = 157 k	Max. Shear = 220 k
Lateral Deflection = 0.15 in.	Lateral Deflection = 0.28 in.

TABLE 8
LATERAL ANALYSIS OF PILE GROUP

Load cases	Lateral load (kips)	Load resisted (kips)	
		Back Pile	Front pile
Service-I	286	130	156
Strength-1(a)	394	184	210
Strength-1(b)	430	208	228
Extreme Event-1	410	193	219

III. Plaxis 3D Analysis

PLAXIS 3D models were used for the analysis of piles under both axial and lateral loads using pile group and pile raft approaches. The failure criteria of Mohr-Coulomb were used to model the soil. The model's sides were laterally constrained to prevent it from moving. To calculate the bending moment caused in piles when a load was applied, a 10-noded tetrahedral embedded pile element was used. The raft was represented by a 6-noded plate element. The properties of concrete were assigned to the piles and raft. With 146608 elements and 210820 nodes, a fine mesh is constructed with a relative element size of 0.60. A fine mesh was provided in the foundation vicinity while away from the foundation, a coarser mesh was provided. A soil model of 100ft x 100ft x 200ft was developed. The Ko technique was used to simulate the initial stress scenario in the staged construction mode. Hereafter, a pile was activated followed by the raft in the second and third stages. In the final stage, a vertical and lateral load were applied simultaneously. In the case of the pile group, a raft was kept above the soil surface.

IV. Plaxis 3D Results

Piles were analyzed for the axial force, shear force and bending moment along the length of piles as shown in Figure 10. From the curves, it is observed that both back and front piles are under compression and the least load is transferred to the back pile of the piled raft. In the case of shear force profile, the top of the piles is in negative shear while at some depth, positive shear forces are produced. Additionally, the bending moments in a piled raft and pile group are negative along the pile length. Moreover, active pile length in the front pile is greater than back pile in both piled raft and pile group.

From the Table 9 and Figure 11, as can be seen, the load and moment demand for piles were higher in the pile group foundation than in the piled raft foundation. This is because of the raft's contribution to resist the external applied loads and moments in the case of a piled raft. The maximum bending moment on the pile group was about 2-3 times that of the piled raft. Considering this reduction in moment demand may result in an economical foundation by reducing the reinforcement, pile diameter, or length. Moreover, in both deep foundations, front piles were taking more demand i.e., loads and moments than back piles.

V. Lateral analysis of piles

To compare piled raft with pile group, lateral analysis of piles in the piled raft was also carried out and the results are shown in Table 10. A demand for piles was decreased to a great extent. The maximum moment was decreased about 2.5-3 times while the maximum shear was decreased about 2-3 times. A decrease in demand also results in reducing the lateral deflection to about 50 %. A detail of shear force resisted by back and front piles is tabulated in Table 11.

CONCLUSION

The foundation of the retaining wall was investigated in the aforementioned case study. For the lateral load, two types of foundations were investigated: pile group and piled raft. ALLPILE was used for pile group analysis, and PLAXIS 3D was used for piled raft lateral load analysis. The analyses were compared, and the discussion yielded the following conclusions:

In piled-raft foundation, load transfer to the piles was reduced significantly because of the increased stiffness beneath the raft and the raft thus contributes to the load resistance. While in the pile group, all the loads were resisted by the piles.

In a piled raft, the maximum moment on piles was reduced by 2.5-3 times, while the maximum shear was reduced by 2-3 times. Reduced demand also leads in a 50% reduction in lateral deflection of piles. A foundation design based on raft contribution to resist load can reduce the pile diameter, length, pile's number or reinforcement. This will lead to a more economical foundation.

In both deep foundations, front piles carried more demand than back piles due to stiffer soil in front piles' surroundings.

TABLE 9
LATERAL ANALYSIS OF PILED RAFT AND PILE GROUP

Analysis Type	**Pile Location**	**Max. Axial Load (kips)**	**Max. Shear Load (kips)**	**Max. Bending Moment (kips-ft)**
Pile Raft Analysis	Front Pile	459.80	112.19	561.71
	Back Pile	183.76	85.30	607.39
Pile Group Analysis	Front Pile	566.04	184.89	1534.96
	Back Pile	425.57	100.54	1404.87

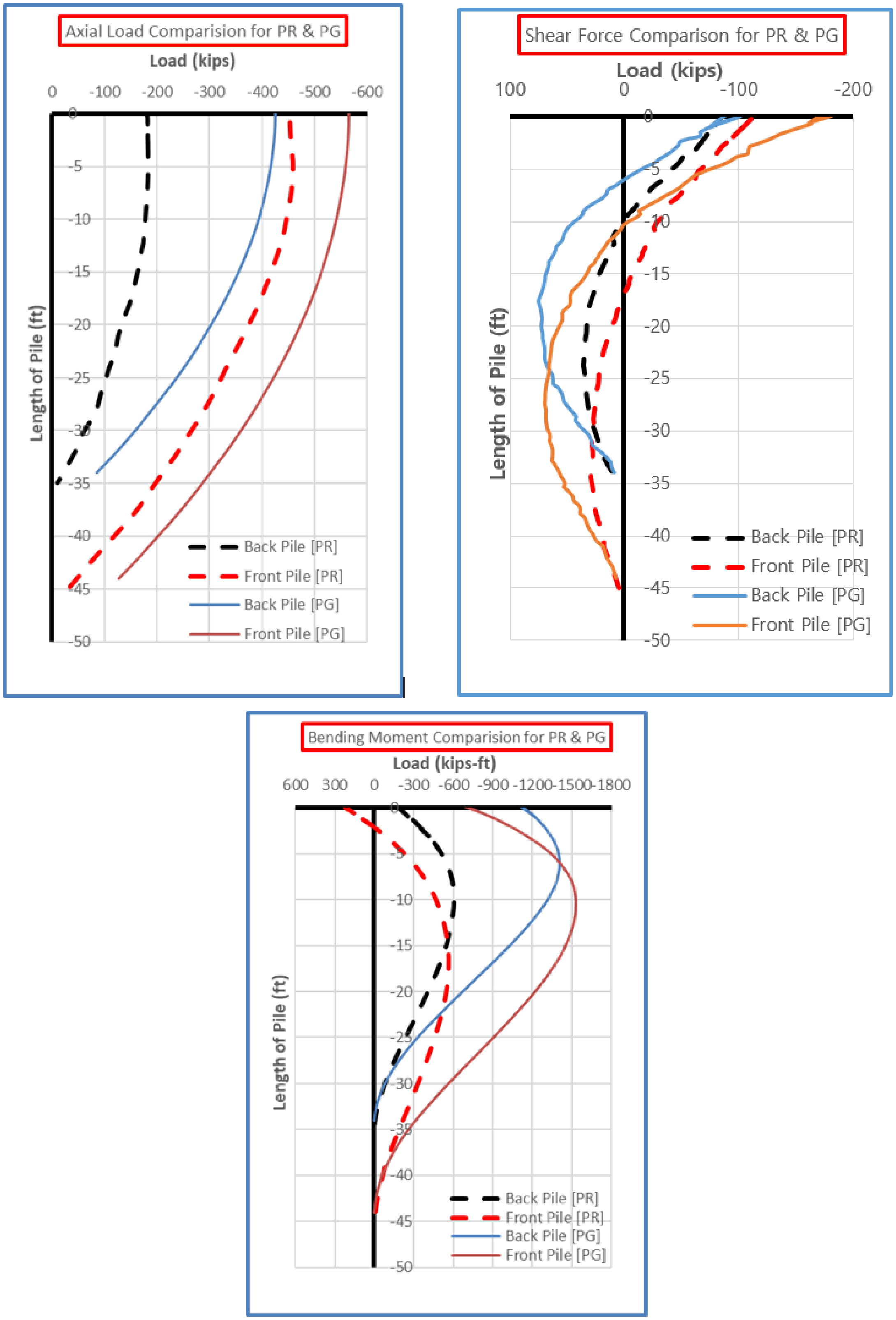

FIGURE 11
COMPARISON FOR PILED RAFT AND PILE GROUP

TABLE 10
LATERAL ANALYSIS OF PILE UNDER SERVICE AND FACTORED LOAD

Service Load Condition	Factored Load Condition
Max. Moment = 341 kip-ft	Max. Moment = 650 kip-ft
Max. Shear = 54 kip	Max. Shear = 109 kip
Lateral Deflection = 0.08 in	Lateral Deflection = 0.12 in

TABLE 11
LATERAL ANALYSIS OF PILED RAFT

Load cases	Lateral load (kips)	Load resisted (kips)	
		Back Pile	Front pile
Service-I	286	72	116
Strength-1(a)	394	105	144
Strength-1(b)	430	119	159
Extreme Event-1	410	113	145

CONFLICT OF INTEREST

The authors state no conflict of interest

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