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PILE-SOIL-PILE INTERACTION IN DESIGNING THE FOUNDATION OF RC STRUCTURES

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ABSTRACT

The paper analyzes the effects of pile-soil-pile interaction on the transverse bridge frame on specific example of building. It considers a small group of piles arranged in a single row. The columns are continuously set on piles over the RC blocks (raft beams). The typical pile-soil conditions were varied. Some phases of construction, typical of this type of calculation, have been included. The interaction was analyzed for homogeneous and linear elastic soil (semi-space), with some other models of analyzing pile-soil interaction were also indicated. The paper also presents redistribution of forces depending on the stiffness of the raft beams or superstructure. The calculation parameters were introduced in mathematical model using a simplified method.

KEY WORDS: pile-soil interaction, bridge frame, specific building, soil parameters, homogeneous soil, comparative analysis.

INTERAKCIJE ŠIP-TLO-ŠIP PRI TEMELJENJU AB OBJEKATA

APSTRAKT

U radu je analiziran uticaj interakcije šip-tlo-šip na poprečni okvir/ram mosta i primer jedan specifičan primer zgrade.. Razmatra se mala grupa šipova raspoređenoj u 1 vrsti. Stubovi se kontinualno nastavljaju na šipove preko AB blokova (naglavica). Varirani su karakteristični uslovi šip-tlo. Obuhvaćeni su neke faze građenja, karakteristične za ovu vrstu proračuna. Interakcija je urađena za homogeno i linearno elastično tlo (poluprostor), a naznačeni su i drugi modeli za analizu interakcije šip-tlo. Prikazana je preraspodela sila u zavisnosti od krutosti naglavne grede ili gornje konstrukcije. Korišćena je pojednostavljena metoda uvođenja proračunskih parametara u matematički model.

KLJUČNE REČI: interakcija šip - tlo, ram mosta, specifična zgrada, parametri tla, homogeno tlo, uporedna analiza

INTRODUCTION

This paper analyzes the effects of pile-soil-pile interaction on the redistribution of settlement and forces between piles in a group. The piles are embedded in homogeneous soil with a constant modulus along the depth. Two pile arrangements were considered: one on the raft beam (4x1) and another on the raft slab (3x3).

The first arrangement consists of a small group of piles arranged in a single row. The columns are continuously set on piles over the box shape RC blocks (raft beams), where the ribbed reinforcement continues.

The paper discusses several typical pile-soil conditions, with the pile length and diameter, as well as the soil modulus, being varied. Some construction phases, typical of this type of calculation, were also considered, and redistribution of forces depending on the stiffness of raft beam (cap) or superstructure was presented. Individual parameters in calculation model and their potential influence towards the state of fracture and number of piles have been introduced using a simplified method.

EXPLANATION OF THE FLOWCHART AND NOTATIONS USED

Entering pile and soil properties:

- Pile properties:
- Pile length: L (m)
- Pile diameter: D = 1.50m
- Pile modulus: Ep = 25000 MPa

Soil properties:

- Soil modulus: Es = 10 MPa
- Poisson number: ν = 0.50

Here, piles are arranged and spaced in rows and columns in rectangular layout, where the boundary case is the square arrangement or arrangement on the beam as a single or column (circular schedule would be preferred as it often occurs in the bridge and reservoirs piers, drawn with dash line in the flowchart):

- Number of columns (in the y direction) $n_x = 4$ (integer)
- Column spacing expressed through pile diameter (s_x=4.15 m, $s_x/D=4.15/1.5=2.77$).
- Number of rows (in the x direction): $n_y = 1$ (integer)
- Row spacing is expressed through pile diameter: sDy = 1.
- The soil type is expressed through ratio of the soil modulus on the half and the entire pile length: ro = (EsL/2) / (EsL) = 1

In general case, soil properties are assumed with 4 models:

1. Constant soil modulus with the depth of ro = 1
2. Linear soil modulus change with the depth of ro = 0.5
3. Parabolic soil modulus change with the depth of ro = 0.707
4. Surging change, double-layer soil, whereby the pile base is only a few pile diameter in the bottom layer, making it a standing pile.

The fourth case is a specific case of general multi-layer soil model, which also includes trapezoidal soil modulus change with a surge of modulus at a depth L.

Force resultant or force arrangement were entered for the group of piles as Vsi (kN) (i = 1, ... n) or SumV. Three groups of forces were also designed to be entered for the corner, edge and interior of the raft beam.

Based on the entered values, the program calculates:

- Pile length to diameter ratio: L/D = 20/1.5 = 13.33
- Individual pile stiffness: Kv = 155.9911 [kN / mm]
- Resultant of the initial force vector SumV, or the distributed force vector Vsi (kN), (i = 1, ... n).
- There is a possibility of recording the vector of external forces.
- Coefficients of interaction (the influence of settlement of the loaded pile caused by loading the neighbouring piles: αij, (i = 1, ... n; j = 1, ... n; i = j, αii = 1)

Calculation of iterations in order to calculate redistribution of the vector of external forces on a *very rigid beam*. This calculation is based on iterations of all piles in the group. Namely, given the symmetric nature of the problem, determinant of the system deflection is zero, which disables the vector of redistributed external forces to be directly obtained as the inverse of deflection matrix because in this case singularity occurs. Thus, there are two alternative ways to come to the solution: either forming a 'condensed' matrix-vector where conditions of symmetry are condensed or eliminated, or calculating redistribution iteratively:

- Calculating the settlement of each individual pile on a very flexible, evenly loaded, raft beam: wi (mm), (i = 1, ... n)
- Calculating the mean value of deflection of the pile group, wsr = sumwi/n (mm)
- Calculating the vector of settlement difference for each individual pile correction vector of external forces.

Table 1, 2 and 3 shown deflections for evenly loaded group of piles on a very flexible beam, and the redistribution of these force on a very rigid raft beam. Force redistribution is calculated due to the interaction of piles for a group of 4 piles of D = 1.50 m diameter, which is embedded in soil with a constant modulus along the depth (no change). Soil modulus Es is a variable factor, so that in Table 1 it is 10 MPa, in Table 2 it is 20 MPa, with 25 Mpa being in Table 3. Due to changes in the soil modulus, the stiffness of individual piles Kv, based on which the interaction is calculated, also changes, so that for Tables 1, 2 and 3, it is: 155.99, 302.94 and 373.49 [kN/mm]. Other model parameters in the tables remain unchanged, so that the distance between the pile axes is s = 4.15 m, while the length to diameter ratio is L/D = 20 / 1.5 = 13.33. The distance between the axes of end piles is 12.45 m.

The intensity of calculated forces due to the load induced by the own weight of an actual object deviates by less than 5% from those shown in Tables 1-3. The calculated differential settlement between two adjacent piles in Table 1 is 2.5 mm, in Table 2 it is 1.3 mm, while in Table 3 the differential settlement is 1.1 mm (the amounts of differential settlements are rounded to one decimal).

Table 4 shows a similar problem as in previous tables; virtually, it is Table 3, with two exceptions: the pile diameter is slightly smaller and it is D = 1.20 m, with the length being slightly larger and it is L = 32 m. This has also changed the stiffness of individual piles, which is then Kv = 439.39 [kN/mm]. The calculated differential settlement between two adjacent piles in Table 4 is 0.7 mm.

Table 1: Settlement of the pile group and redistribution of forces for a very stiff raft beam: pile length 20 m, pile diameter D = 1.50m, constant soil modulus Es = 10 MPa, Kv = 155.9911 [kN/mm], axis distance s = 4.15 m, s/D = 2.77, L/D = 20/1.5 = 13.33

Табела 1: Слегање групе шипова и прерасподела сила за веома круту наглавицу
Дужина шипа 20 m, Пречник D=1.50m, Es=10 MPa, Kv=155.9911 [kN/mm], међусобни размак s=4.15 m, s/D=2.77, L/D=20/1.5=13.33,

	Pile	No. 1	No. 2	No. 3	No. 4	Σ	srw* (mm)
x-coordinate	[m]	0.000	4.155	8.310	12.465		
Initial forces	[kN]	2500	2500	2500	2500	10000	
Initial deflection	[mm]	26.675	29.201	29.201	26.675		27.938
Forces after redistribution	[kN]	2777.95	2222.05	2222.05	2777.95	10000	
Deflection after redistribution	[mm]	27.797	27.798	27.798	27.797		27.797
Change in force	[-]	1.1112	0.8888	0.8888	1.1112	1.1112	
*srw – mean pile group deflection							

During the completion, the ends of prefabricated supports (MN) rely on the formwork buttresses. These supports are made monolith using an RC beam cast in situ above the piers of the middle frame. Dimensions of the cross-beam frame (in fact the monolithic part of the slab) are ((2x4m) x15.36m) x 1.15 m.

Table 2: Settlement of pile group and redistribution of forces for very stiff raft beam: length 20m, D=1.50m, Es=20 MPa, Kv=302.93 [kN/mm], s/D=2.77, L/D=13.33

Табела 2: Слегање групе шипова и прерасподела сила за веома круту наглавицу
Дужина шипа 20 m, Пречник D=1.50m, Es=20 MPa, Kv=302.9367 [kN/mm], s/D=2.77, /D=13.33,

	Pile	No. 1	No. 2	No. 3	No. 4	Σ	srw
x-coordinate	[m]	0.000	4.155	8.310	12.465		
Initial forces	[kN]	2500	2500	2500	2500	10000	
Initial deflection	[mm]	13.735	15.036	15.036	13.735		14.386
Forces after redistribute	[kN]	2777.95	2222.04	2222.04	2777.95	10000	
Deflection after redistribute	[mm]	14.313	14.314	14.314	14.313		14.313
Change in force	[-]	1.1112	0.8888	0.8888	1.1112		

For D=1.50 m and L=20 m, the initial load comes only from the pile-soil difference and the pile's own weight. Thus, for Beška, the differential load (pile weight relative to soil weight, which is virtually an additional load) amounts: g=(1.50/2)^2*3.14*(25-19.2)=10.24 kN/m'; G=10.24 kN/m'* 20 m=204.88 kN, which is approximately 10% of the service load. According to this calculation, this causes an initial deflection of about 2.5 to 3 mm.

Table 3: Settlement of the pile group and redistribution of forces for a very stiff raft beam: length 20 m, D = 1.50m, Es = 25MPa, Kv = 373.4915 [kN/mm], s/D = 2.77, L/D = 13.33
Табела 3: Слегање групе шипова и прерасподела сила за веома круту наглавицу
Дужина шипа 20 m, Пречник D=1.50m, Es=25MPa, Kv=373.4915 [kN/mm], s/D=2.77, L/D=13.33,

	Pile	No. 1	No. 2	No. 3	No. 4	Σ	srw
x-coordinate	[m]	0.000	4.155	8.310	12.465		
Initial forces	[kN]	2500	2500	2500	2500	10000	
Initial deflection	[mm]	11.141	12.196	12.196	11.141		11.669
Forces after redistribute	[kN]	2777.95	2222.04	2222.04	2777.95	10000	
Deflection after redistribute	[mm]	11.6098	11.610	11.610	11.6098		11.6099
Change in force	[-]	1.1112	0.8888	0.8888	1.1112		

Table 4: Settlement of the pile group and redistribution of forces for a very stiff raft beam: length 32 m, D = 1.2m, Es = 25 MPa, Kv = 439.3875 [kN/mm], s/D = 3.46, L/D == 26.67
Табела 4: Слегање групе шипова и прерасподела сила за веома круту наглавицу
Дужина шипа 32 m, Пречник D=1.2m, Es=25 MPa, Kv=439.3875 [kN/mm], s/D=3.46, L/D==26.67

	Pile	No. 1	No. 2	No. 3	No. 4	Σ	srw
x-coordinate	[m]	0.000	4.155	8.310	12.465		
Initial forces	[kN]	2500	2500	2500	2500	10000	
Initial deflection	[mm]	10.116	10.83	10.83	10.116		10.474
Forces after redistribute	[kN]	2729.39	2270.61	2270.61	2729.39	10000	
Deflection after redistribute	[mm]	10.4415	10.4417	10.4417	10.4415		10.4416
Change in force	[-]	1.0917	0.9082	0.9082	1.0917		

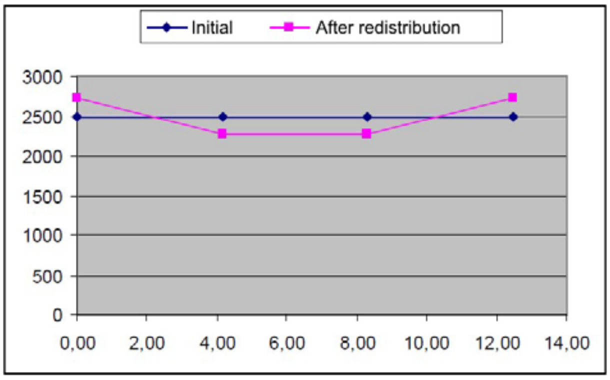

Figure 1: Redistribution of forces (Table 4) - force/x-coordinate. Change in force is about 11%.
Slika 1: Прерасподела сила на основу табеле 4. Сила/координата шипа. Промена силе око 11%

The change in mean deflection during iterations is the result of interaction and adopted differential precision in deflection of individual piles and the mean deflection. The adopted accuracy in difference is 10^{-4}. In the iteration, the law of conservation of sum of vertical forces applies.

REDISTRIBUTION OF FORCES IN A GROUP OF 9 PILES

Here, the redistribution of forces is presented for a group of 9 piles in 3x3 arrangements. The redistribution is made according to methods outlined in the work of Pender and Fleming. The moment in the middle of the slab has also been calculated using the differential method for 1m thick slab made of MB30 class concrete. The total force acting on the slab is 1.000 kN. Table 5 shows the state before the iterations for a very flexible raft slab under steady load, Vi = 111.11 kN/pile. The table also shows deviation from the mean deflection of each individual pile. At the end of each table, the bending moment for the 3x3 arrangement is calculated in the centre of the slab span (raft) using the differential method, with slab thickness being 1 m, and Poisson number 0.20.

Table 5: Settlement of the pile group and redistribution of forces for the flexible raft: pile length 20 m, pile diameter D = 0.75 m, constant soil modulus Es = 25 MPa, axis distance S/D = 3.0
Табела 5. Слегање групе шипова и прерасподела сила за флексибилну наглавицу
Дужина шипа 20 m, Пречник D=0.75 m, Es=25 MPa, међусобни размак s/D=3.0

I	N=9 wi (mm)	w sr – wi	*Δ* wi ^2	*Δ* wi (%)	V i	*Δ* Vi (%)	1iter Vi
1	1,292721	0,041100	0,001689	3,0814	111,111	3,423784	114,5349
2	1,352901	-0,019080	0,000364	-1,4304	111,111	-1,589381	109,5217
3	1,292721	0,041100	0,001689	3,0814	111,111	3,423784	114,5349
4	1,352901	-0,019080	0,000364	-1,4304	111,111	-1,589381	109,5217
5	1,421905	-0,088084	0,007759	-6,6038	111,111	-7,33761	103,7735
6	1,352901	-0,019080	0,000364	-1,4304	111,111	-1,589381	109,5217
7	1,292721	0,041100	0,001689	3,0814	111,111	3,423784	114,5349
8	1,352901	-0,019080	0,000364	-1,4304	111,111	-1,589381	109,5217
9	1,292721	0,041100	0,001689	3,0814	111,111	3,423784	114,5349
Σ	12,004393		0,015972	-8,3E-14			
sr	1,3338214		0,042127				
M	70,99	(kNm)	vb=0.2				

Situation after redistribution for the very rigid raft.

Table 6: Settlement of the pile group and redistribution of forces for the very stiff raft: pile length 20 m, pile diameter D = 0.75 m, constant soil modulus Es = 25 MPa, axis distance S/D = 3.0
Табела 6: Слегање групе шипова и прерасподела сила за веома круту наглавицу
Дужина шипа 20 m, Пречник D=0.75 m, Es=25 MPa, међусобни размак s/D=3.0

I	n=9	w sr – wi	*D* wi ^2	*D* wi (%)	V i	*D* Vi (%)	1iter Vi
1	1.327603	0.000012	0.000000	0.0009	127.174	0.001171	127.1751
2	1.327622	-0.000007	0.000000	-0.0005	103.514	-0.000528	103.5135
3	1.327603	0.000012	0.000000	0.0009	127.174	0.001171	127.1751
4	1.327622	-0.000007	0.000000	-0.0005	103.514	-0.000528	103.5135
5	1.327637	-0.000022	0.000000	-0.0016	77.2467	-0.001267	77.24546
6	1.327622	-0.000007	0.000000	-0.0005	103.514	-0.000528	103.5135
7	1.327603	0.000012	0.000000	0.0009	127.174	0.001171	127.1751
8	1.327622	-0.000007	0.000000	-0.0005	103.514	-0.000528	103.5135
9	1.327603	0.000012	0.000000	0.0009	127.174	0.001171	127.1751
Σ	11.948537		0.000000	-8.4E-14	999.998	-8.36E-13	999.9996
sr	1.3276152		0.000012				
M	0.015	(kNm)	vb=0.2				42 iterations

Table 7: Distribution of forces on piles for a very stiff raft, according to Table 5
Табела 7: Расподела сила на шипове за веома круту наглавицу, према табели 5

1.000	0.814	1.000
0.814	0.607	0.814
1.000	0.814	1.000

REDISTRIBUTION OF INFLUENCES IN RELATION TO THE CENTER OF STIFFNESS OF SKELETAL BUILDING

In dimensioning a skeletal building (without RC walls) founded on groups of 5, 4 and 3 piles based on ESO according to EC8, when accounting for torsion in both directions separately in soils of low rigidity, which can be adequately replaced by elastic springs (as secant rigidity) of k = 6.000 kN/m', there is an increasing need for reinforcement. This occurs only in the four end piles which are located on the building's corners and are the most remote from the centre of stiffness. In each corner of the building there is a group of 3 piles, with 4 of them being along the edges and 5 in the interior. The building has a relatively large base span (24x24 m), and consists of 3x3 fields and 8 floors. With the reduction of the number of floors or the span, this effect disappears, so that even distribution can be applied to each individual group of piles. This effect also disappears when the secant stiffness of soil is doubled. The piles diameter is 60 cm. The dimensioning is done in the SAP software, with the participation of another seismic direction of 30%, according to EC8.

CONCLUSION

Table 6 of this paper shows the coefficient of utilization of a group of 9 piles (3x3 arrangement), which in this case is 7.863/9 = 0.87. This shows that short rafts can lead to significant force redistribution on piles in the group. Therefore, for the state of fracture, it is necessary to check the change in condition and position of plastic joints also in relation to the change of normal forces and thus the normalized normal forces. With fully utilized force, for the absolutely rigid beam, the maximum permissible load of the central pile is 61%, which is less than the coefficient of utilization of the pile group. Also, when the raft beam is loaded by earthquake induced bending moment, normal forces in the edge piles are increasing (decomposed to the coupling).

A specific effect of redistribution can occur in special cases of funding of large buildings on soft soil, as well as in individual piles furthest from the centre of the object's stiffness. This phenomenon depends on the object's span and stiffness ratio, the piles and the soil.

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APPENDIX – FLOWCHART: calculating pile interaction in the group