Effect of pile cap flexural rigidity on the behaviour of bridge foundations

EFFECT OF PILE CAP FLEXURAL RIGIDITY ON THE BEHAVIOR OF BRIDGE FOUNDATIONS

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SUMMARY

In the design of reinforced concrete bridge foundations, most of the pile caps are assumed to be rigid; neglecting the effect of the pile caps' rigidities. Also, the piles are considered to be acting as rigid supports for the pile caps; without taking into account their axial stiffness.

The main objective of the present research work is to emphasize the effects of the pile cap flexural rigidity and the piles' axial stiffness on distributing the column loads on the piles; and consequently the global behavior of the bridge foundation.

A reinforced concrete pile cap designed as a typical pier foundation for a multi-span highway bridge is analysed by the finite element method considering the cracked modulus of elasticity of concrete. In this study, the thickness of the pile cap is changed in order to study the effect of its flexural stiffness on the behavior of the foundation. The pile cap is subjected to the different load cases specified in the AASHTO code {1}; including the seismic loads obtained from the dynamic analysis for seismic performance category "B". Also, the piles are modeled as elastic springs taking their axial stiffness into account.

The results of the present research work have been used to formulate some recommendations concerning the design of the pile caps and the distribution of the pile loads.

1 INTRODUCTION

In the common design of reinforced concrete bridge foundations, the pile caps are assumed to be rigid in the determination of the pile loads. Also, the piles are considered to act as rigid supports. This research work studies the effects of the pile cap rigidity and the axial stiffness of the piles on distributing the column loads on the piles; and consequently the design of the pile cap itself. These effects are more significant in the cases of pile caps which are subjected to high loads and moments, such as those of multi-span bridge foundations, especially in the seismic load cases.

A typical pier foundation for a multi-span highway bridge, about 400m long, has been chosen to study the effect of the pile cap flexural rigidity, and the axial stiffness of the piles on the overall behavior of the bridge foundation. The intermediate spans of the bridge are 35m, while the end spans are 25m. The width of the bridge is 17.0m, including four highway lanes.

The typical cross section of the bridge consists of a double vent prestressesd box girder, (Fig. 1). The bridge deck is supported on central piers. In the longitudinal direction of the bridge, the three intermediate piers are monolithic with the deck; while the rest of the piers have guided bearings to allow for the longitudinal deck movement due to temperature variation, creep and shrinkage. The piers have different heights varying between 5m and 12m.

A detailed finite element model was prepared for the bridge considering the highway moving loads according to the AASHTO specifications {1}, in addition to the prestressing loads, the temperature effects, and the seismic loads obtained from the dynamic analysis. Another finite element model was prepared for the typical pile cap of the monolithic piers; which resists the most critical loads from the temperature movements and the seismic forces, (Fig. 2).

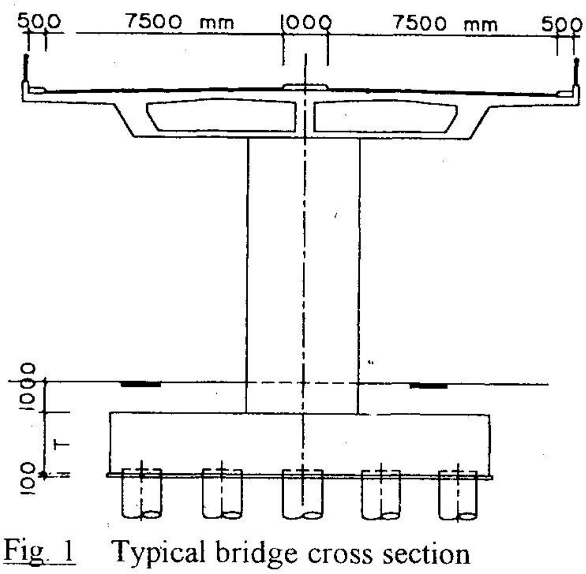

Fig. 1 Typical bridge cross section

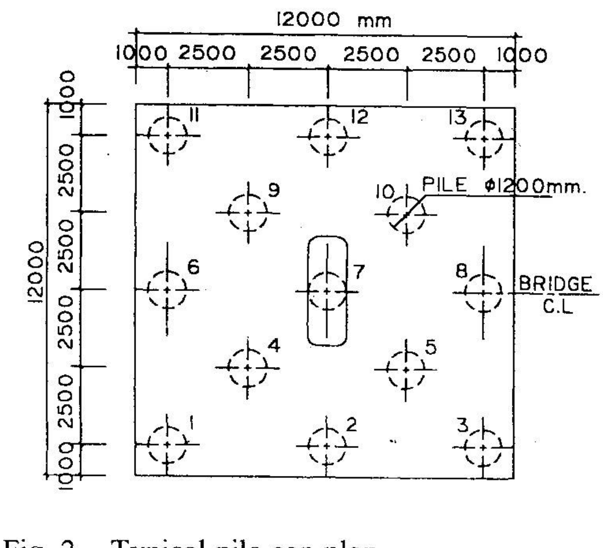

Fig. 2 Typical pile cap plan

2 DESCRIPTION OF THE PILE CAP AND THE ACTING LOADS

The studied pile cap size is 12 x 12m and is supported on thirteen piles. The length of each pile is 24m and its diameter is 1.2m with a vertical capacity of 3000 KN. This capacity can be increased by 33% in the seismic load cases. The box girder bridge is loaded as per AASHTO code {1}. The dead load carried by the typical pier is 12750 KN. The maximum reaction on the pier due to the live loads (4 lanes) is about 4000 KN; while that due to the eccentric live loads is about 2600 KN, in addition to a transverse moment of about 12000 KN.m.

The bridge was designed according to the AASHTO specifications for seismic design {2}, and was classified as seismic performance category "B". Thus, the acceleration coefficient was considered as 0.19g and the elastic moments due to the earthquake forces were determined independently along both the longitudinal and transverse directions of the bridge using the SAP2000 program {3}. The seismic moments for the critical pier were found to be 50000 KN.m and 60000 KN.m in the longitudinal and transverse directions, respectively. However, it was found that the moment obtained in the longitudinal direction exceeded the elastic moment capacity of the pier. Accordingly, the elastic moment in this direction was divided by the appropriate response modification factor for the footings; and a plastic hinge design was considered.

The critical case of loading for the studied pile cap was found to be the case of earthquake in the transverse direction. Thus, 100% of the obtained transverse moment was considered, in addition to 30% of the obtained modified moment in the longitudinal direction. This load combination was taken according to AASHTO load combinations to account for the directional uncertainty of earthquake motions and the simultaneous occurrences of earthquake in the two principal directions

3 FINITE ELEMENT MODELING AND PARAMETRIC STUDY

The pile cap was analysed using a three dimensional finite element model by the SAP90 program {4}. The model consisted of 625 nodes and 576 elements. In this analysis, the reinforced concrete pile cap was assumed to be a linearly-elastic material with a modulus of elasticity of 2.1E7 KN/m^2 and a Poisson's ratio of 0.2. To consider the effects of concrete cracks on the pile cap stiffness, the modulus of elasticity was reduced by 25%. Since the flexural stiffness of a pile cap is a function of its dimensions (depth to width ratio); the pile cap was analyzed using different depths (1.0, 1.5, 2.0, 2.5, 3.0 and 5.0 m). All of the thirteen piles were modeled as elastic spring supports considering their axial stiffness. The elastic spring constants were taken as 742200 KN/m for the compression piles, and 371000 KN/m for the tension piles. This reduced value for the tension piles was due to the fact that the pile displacement associated with tension was larger than that in compression under the same amount of axial load.

4 RESULTS OF THE PARAMETRIC STUDY

4.1 Pile Cap Deflections

A comparison is made between the deformed shapes of the studied pile cap under the applied loads for 1m and 3m thickness in (Fig. 3 and 4), respectively. It is clear that for the pile cap with 1m thickness, a flexible behavior is obtained with a maximum deflection value of about 1.0 cm. Thus, the assumption of a rigid footing becomes erratic for this thickness. On the other hand, the model with 3m pile cap thickness shows a rigid behavior; with a maximum deflection of about 0.43 cm. The same deflection value was obtained for the 5m thickness model. This considerable difference in the deformed modes and the obtained deflection values strongly affect the distribution of the applied loads on the supporting piles.

4.2 Moments Acting on Pile Caps

The values and patterns of the bending moments M_{11} and M_{22} of the studied pile cap in the two principal directions for 1m and 3m thickness are illustrated in (Fig. 5 to 8), respectively. From these figures, it can be concluded that:

- The negative moment variations between the 1m and 3m thickness pile caps can attain 28%; while positive moment variations can attain 19%.

- The maximum moments obtained from the model with 1m thickness are less than those obtained from the 3m thickness model. This proves that, the flexible pile cap reduces the loads on the edge and corner piles and consequently increases the loads on the interior ones. This may lead to critical cases for the loading capacities of the interior piles.
- The values of moments obtained from the computer models are much higher than those calculated by the rigid analysis. Also, in the computer models, the moments are concentrated near the column; while in the rigid analysis the moments are distributed along the width of the pile cap. This may cause a critical situation for the safety of the pile cap design, as obtained from models having small thickness between 1m and 2m.

4.3 Pile Reactions

The ratio of the pile loads obtained from the finite element analysis to those obtained from the analysis of the pile cap as a rigid footing ($P_{F.E}/P_{Rigid}$) versus the pile cap thickness; are shown in (Fig. 9 to 11) for the different locations of the piles: corner, edge, and interior piles, respectively. In these curves, the pile cap own weight and weight of fill have been excluded in order to emphasize the effect of the studied parameters on distributing the pier loads on the supporting piles. Table (1) shows the values of the pile loads both for a rigid footing analysis as well as for the results of the present finite element analysis. The negative load values indicate tension forces on the piles. From these figures and table, the following can be summarized:

- For corner piles, the ratio between the pile reaction obtained from the finite element analysis and that obtained from the rigid analysis can reach 9%, 72%, 90% and 98% for the models with 1m, 2m, 3m and 5m thickness, respectively. This large variation in the obtained reactions emphasizes the effect of the pile cap thickness and rigidity on distributing the applied loads.
- For edge piles, the ratio between the pile reaction obtained from the finite element analysis and that obtained from the rigid analysis can reach 1%, 85%, 95% and 99% for the models with 1m, 2m, 3m and 5m, respectively. For pile No. "2", the pile reaction obtained from the rigid analysis is (-734 KN), while that obtained from the model with 1m thickness is (-1730 KN). Upon the addition of the pile cap own weight and weight of fill, the aforementioned values reach (-257 KN) and (-980 KN), respectively. This tensile force (-980 KN) exceeds the own weight of the pile (680 KN) and represents a critical case for the pile.
- For interior piles, the ratio between the pile reaction obtained from the rigid analysis and that obtained from the finite element analysis can reach 11%, 58%, 90% and 99% for the models with 1m, 2m, 3m and 5m thickness, respectively. For pile No."10", the pile reaction obtained from the rigid analysis is (2052 KN); while that obtained from the model with 1m thickness is (4634 KN) and reaches (5158 KN) when taking into account the pile cap own weight and weight of fill. This value exceeds the pile capacity in seismic cases (4000 KN).

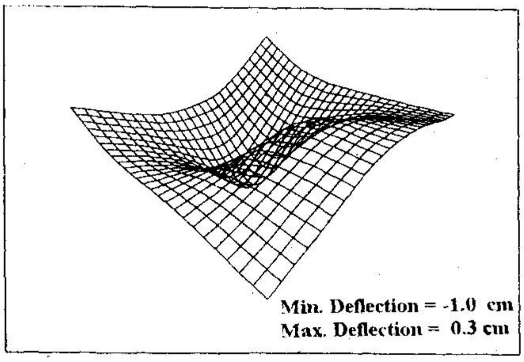

Fig. 3 Deformed shape of 1m thick. model

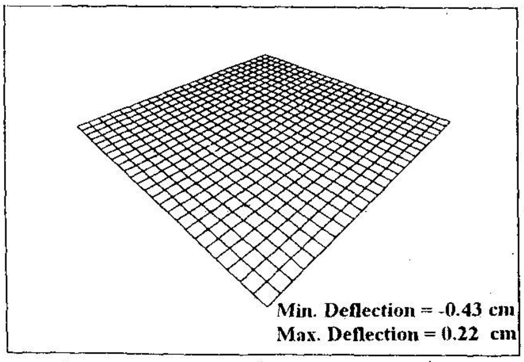

Fig. 4 Deformed shape of 3m thick. model

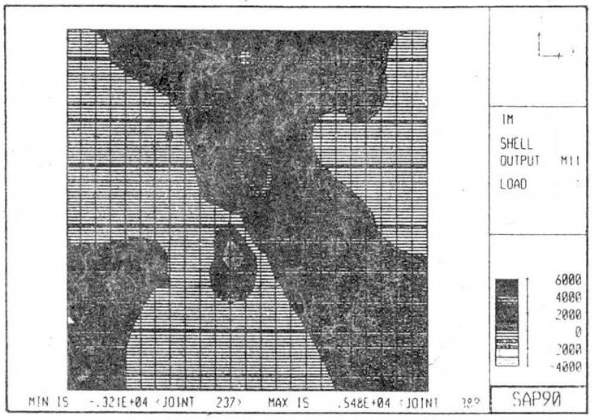

Fig. 5 M_{11} of 1m thickness model

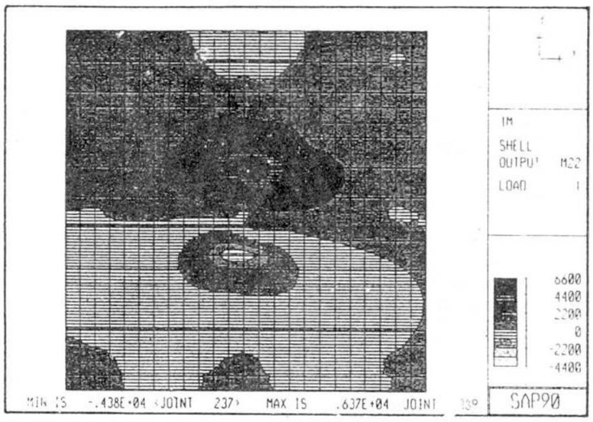

Fig. 6 M_{22} of 1m thickness model

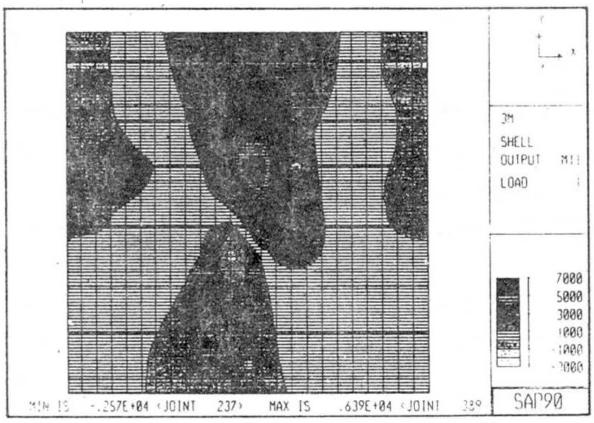

Fig. 7 M_{11} of 3m thickness model

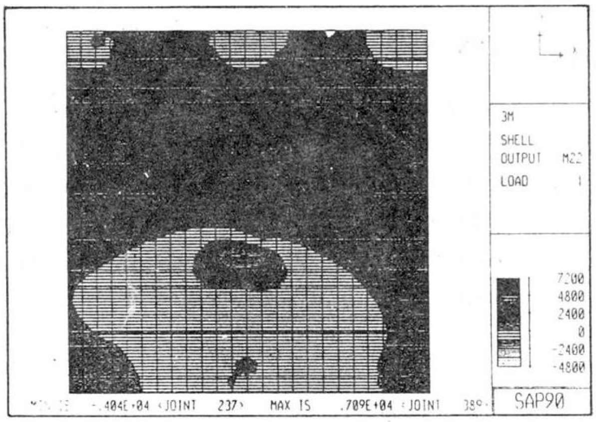

Fig. 8 M_{22} of 3m thickness model

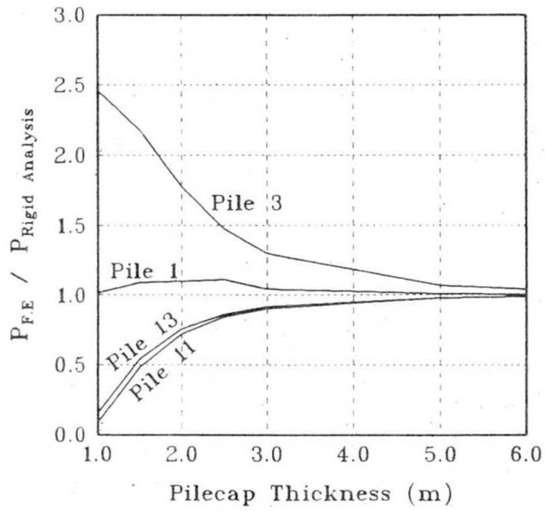

Fig. 9 ($P_{F.E}/P_{Rigid}$) ratio for corner piles

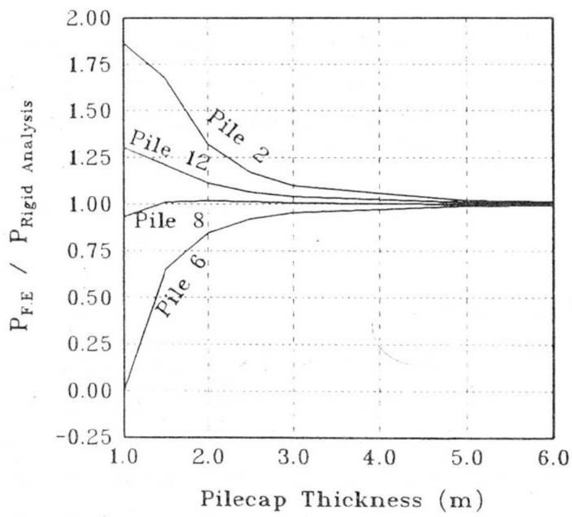

Fig. 10 ($P_{F.E}/P_{Rigid}$) ratio for edge piles

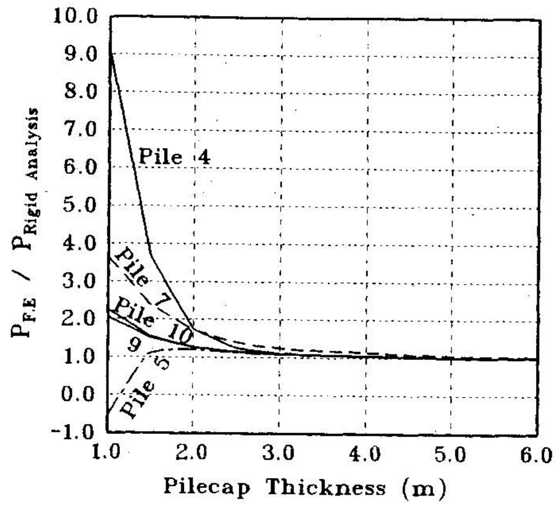

Fig. 11 ($P_{F.E}/P_{Rigid}$) ratio for interior piles

Pile No.	1m		2m		3m		5m		Rigid Analysis
	$P_{F.E}$	$P_{F.E^*}$	$P_{F.E}$	$P_{F.E^*}$	$P_{F.E}$	$P_{F.E^*}$	$P_{F.E}$	$P_{F.E^*}$	
1	-1180	-692	-1273	-562	-1213	-204	-1175	402	-1162
2	-1370	-982	-970	-208	-807	227	-750	837	-734
3	-750	-323	-540	170	-396	613	-327	1250	-305
4	-835	-482	-158	618	-101	940	-92	1496	-91
5	-186	418	410	1187	370	1412	346	1934	338
6	-4	523	468	1230	527	1561	547	2132	552
7	3579	4199	1690	2487	1223	2274	1035	2627	981
8	1315	1786	1435	2179	1420	2456	1412	2998	1410
9	3348	3890	2058	2834	1770	2811	1657	3245	1624
10	4634	5158	2626	3402	2240	3283	2094	3683	2052
11	200	579	1634	2345	2047	3057	2216	3793	2266
12	3514	4004	3002	3763	2800	3835	2719	4305	2695
13	483	862	2366	3077	2864	3874	3064	4641	3123

$P_{F.E^*}$ includes own weight of pile cap and weight of fill

Table 1 Pile Reactions for different pile cap thick.

5 CONCLUSIONS

- The design of the pile cap as a rigid footing is acceptable when the ratio (L/T) does not exceed (2.4); where (L) is the distance between the pier centerline and the center of the furthermost corner pile and (T) is the thickness of the pile cap.
- If the ratio (L/T) exceeds (2.4), a flexible behavior is expected and a detailed finite element analysis is required for the design of the pile cap.
- Flexible pile caps reduce the pile reactions on corner and edge piles and increase the loads on the interior ones. This may cause tensile forces on the outer piles; and may over-load the interior piles beyond their load carrying capacities.
- The flexural rigidity of the pile cap strongly affects the obtained deformed shapes of the footing and consequently affects the distribution of the pile loads.
- The rigidity of the pile cap considerably affects the obtained straining actions of the pile cap

6 NOTATIONS

L	:	The distance between the pier centerline and the center of the corner pile.
M_{11}, M_{22}	:	Pile cap moments in the longitudinal and transverse directions, respectively.
$P_{F.E}$	:	Pile load obtained from the finite element analysis.
P_{Rigid}	:	Pile load obtained from the analysis of the pile cap as a rigid foundation.
T	:	Pile cap thickness.

REFERENCES

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