

A Different Approach to Substructure Method for Calculation of Internal Forces in Piles

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1 Introduction

Pile foundations are widely used to transfer the foundation loads to deeper and stiffer strata, increasing the overall load carrying capacity and reducing settlements. The most realistic approach for soil-structure interaction is complete modelling of the system including super- and substructures (building and pile foundation) together with the soil medium for both static and dynamic loading conditions. However, since analyzing such a holistic model requires more time, combined structural and geotechnical knowledge and more computer processing power, a variety of approximations are also applied in professional engineering practice.

In this study, earthquake analyses of buildings with pile foundations and varying number of stories are conducted using both direct and substructure analysis methods. Two different site conditions -loose sand and soft clay overlying rock- are included in the analyses (see Tab. 1). Additionally, the methods are applied with different implementation procedures, including a newly introduced way to combine kinematic and inertial interaction analysis results in this study. The results are compared by the internal force and moment distributions in piles.

Tab. 1: Analysis cases

Site Profile	Loose Sand	Soft Clay + Rock
Soil Thickness	60 m	17 m clay + 8 m rock
Number of stories (building height)	4-story (14 m)	8-story (28 m)
	8-story (28 m)	12-story (42 m)
	12-story (42 m)	16-story (56 m)

2 Methodology

Direct analysis method is applied by modelling of all system components in Plaxis 2D, using HSsmall material model for soils and activating base earthquake motion. Substructure analysis method consists of kinematic interaction analysis in Plaxis 2D and inertial interaction analysis in SAP2000 software.

In the kinematic interaction analysis, the massless raft and piles are modelled in the soil medium and earthquake motion is applied. In inertial interaction analysis, only superstructure is modelled, where foundation system is represented by vertical and horizontal nonlinear interaction springs whose behavior is determined by incremental static loading of the kinematic interaction analysis model. Also, ground motion at foundation level is taken from kinematic interaction analysis and applied to inertial interaction model. To obtain the internal forces in piles due to inertial interaction analysis, the SAP2000 analysis results in interaction springs are applied to kinematic interaction model. Envelope force and displacement results are taken and grouped into two: pushing the building pseudo-statically to the Right and Left.

After this point, two different approaches are adopted for the rest of procedure: Unmodified and Modified. Unmodified approach represents the current engineering practice and Modified approach is the suggested procedure in the scope of this study.

2.1 Unmodified Approach

Force and displacement envelopes are assigned as static loads and displacements in the Plaxis 2D model separately (Right and Left). The results from the loading condition providing the absolute maximum internal force values in piles are selected as inertial interaction analysis results. Kinematic and inertial interaction analysis results are combined by simple summation of absolute maximum values.

2.2 Modified Approach

The envelope results taken from interaction springs are assigned to the Plaxis 2D model as staged loading, not in separate cases, i.e., Right and Left forces or displacements are applied in sequence without resetting the stresses and forces.

Kinematic and inertial interaction analysis results are combined by considering the compatibility of results. Instead of a simple summation of the absolute maximum results, the positive and negative directional results were summed separately, and the larger of these total values was taken as the final result.

3 Results and Discussion

The results from direct and substructure analyses are compared by internal force and moment diagrams of the piles. Since there are various approaches adopted in substructure analyses, the results are given with the approach names, e.g., if envelope force results are taken from SAP2000 and Unmodified approach is implemented, the results are named “Unmodified Force”. As an example, the moment and shear force results of the outermost pile in 8-story building on loose sand case is given in Fig. 1.

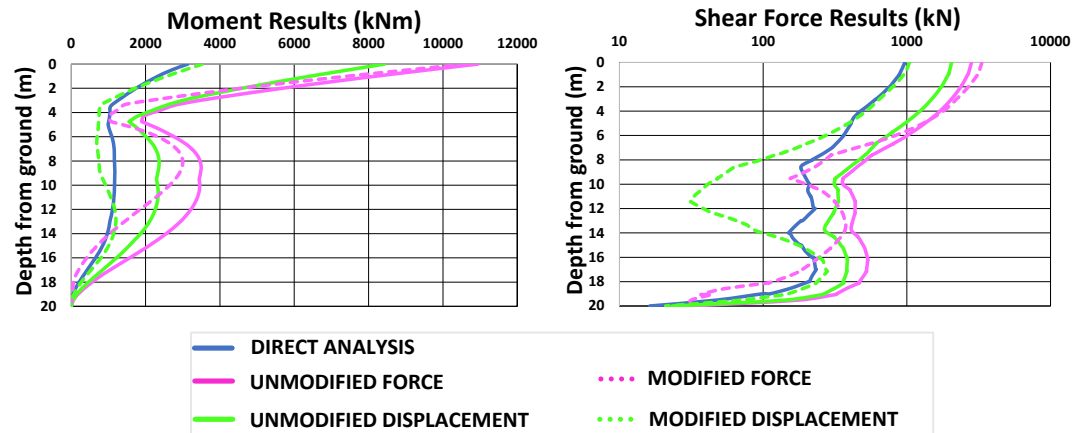


Fig. 1: Moment and shear force distribution results in outermost pile

Since the direct analysis model includes all the system components in a single model, it is assumed to have the most realistic and correct results. Therefore, error margins of substructure analysis approaches are calculated with respect to direct analysis results by Normalized Root Mean Square Error (NRMSE) method. For each case, the average error values (calculated for each pile row and then averaged) are presented for each internal force type in Tab. 2.

Modified Displacement approach has the best estimations for moment and shear force distributions in both site profiles. The highest errors for moment and shear are obtained from Unmodified Displacement approach in soft clay profile, where it varies in loose sand. For 8- and 12-story buildings, the worst estimations in moment diagrams are made by Unmodified Force approach, where those in shear force diagrams are made by Modified Force approach. In the shortest building case, Unmodified Displacement approach has the highest error values for all internal force types.

For the axial force results, Unmodified Displacement and Modified Force approaches provide the least errors in soft clay profile. On the other hand, the most accurate approach varies in the loose sand profile, where Unmodified Displacement has better outputs for 8- and 12-story buildings. The closest estimation is obtained in Modified Displacement approach for 4-story building.

Tab. 2: NRMS-Error values of analysis approaches for each internal force type

Analysis Cases	Substructure Analysis Approach	Axial Force	Shear Force	Moment
4-story on Loose Sand	Unmodified Force	0.164	0.867	0.992
	Unmodified Displacement	0.206	1.000	1.145
	Modified Force	0.169	0.628	0.660
	Modified Displacement	0.122	0.525	0.279
8-story on Loose Sand	Unmodified Force	0.375	1.800	1.804
	Unmodified Displacement	0.084	1.234	1.324
	Modified Force	0.436	1.896	1.370
	Modified Displacement	0.344	0.367	0.298
12-story on Loose Sand	Unmodified Force	0.370	0.891	0.744
	Unmodified Displacement	0.082	0.465	0.443
	Modified Force	0.250	1.054	0.500
	Modified Displacement	0.387	0.478	0.383
8-story on Soft Clay	Unmodified Force	0.319	0.649	0.829
	Unmodified Displacement	0.126	0.664	0.849
	Modified Force	0.120	0.563	0.661
	Modified Displacement	0.617	0.179	0.237
12-story on Soft Clay	Unmodified Force	0.318	0.722	1.102
	Unmodified Displacement	0.129	0.732	1.116
	Modified Force	0.151	0.663	0.973
	Modified Displacement	0.524	0.168	0.244
16-story on Soft Clay	Unmodified Force	0.294	0.487	0.785
	Unmodified Displacement	0.140	0.490	0.788
	Modified Force	0.163	0.433	0.735
	Modified Displacement	0.504	0.218	0.191

4 Conclusion

In this study, earthquake analysis of buildings with pile foundation and different heights are conducted using direct and various substructure analysis approaches. Two different site profiles are created: loose sand and soft clay overlying bedrock. A new implementation procedure (Modified approach) for substructure analysis method is also presented. Assuming that the full model provides the correct outputs, internal force and moment diagrams obtained from each substructure analysis approach are compared to full model results.

No single approach performed well for all cases or all internal forces. Modified Displacement approach improved moment and shear force estimations in both site profiles significantly and it provided the closest estimations to full model results. However, in axial force behavior, Unmodified Displacement and Modified Force approaches gave the best results in soft clay profile. On the other hand, the accuracy of approaches varies for the building in loose sand.