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Soil-Structure Interaction Modelling for Piles in Performance-Based Seismic Design

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ABSTRACT

The importance of performance based design approaches and soil structure interaction in seismic design of structures are internationally recognized. Seismic Soil-Structure Interaction (SSI) is a key factor that has to be considered in design, particularly for retaining structures and structures with deep foundations, such as jetties. However, seismic design standards hardly provide any straight forward tools for engineers to account for SSI in design. This study therefore was initiated, aiming at the development of efficient performance-based design approaches that can be applied by engineers. Currently available design methods are investigated and the performance of simple and more advanced methods are assessed by means of a comparative study. Based on a case study a promising and efficient uncoupled approach is proposed in which dynamic analysis of site and structure are decoupled. With this approach one is able to efficiently assess the structure dynamic response, even for more complex structure geometries.

Introduction

Traditionally the structural engineering community has relied on pseudo-static response spectrum or linear dynamic modal techniques for seismic design. Accuracy assessment of these techniques has been considering predominantly multi storey buildings with a fixed base. The site characterization then is accounted for in the response spectrum selection rather than including SSI in the analysis. Jetty structures are, like many other port and offshore structures, at the interface of structural and geotechnical engineering and the performance of the traditional response spectrum method is less clear. Past post-earthquake surveys show typical failure modes for these type of structure often strongly dominated by differential and permanent deformations in soils and effects of SSI. Especially for sites with strongly varying stiffness of adjacent soil layers it is important to consider kinematic SSI of pile foundations.

Modern performance-based seismic design codes and guidelines (e.g. PIANC, 2001) do specify requirements with respect to the analysis type as a function of importance. Typically for important / high risk structures dynamic analysis is required towards final design, this is reasonable because it provides significantly more insight in the actual seismic response of a structure. Such requirements however are often neglected by designers. Reasons can be found in practical computational modelling limitations and strict engineering budgets. To overcome this

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cap an efficient uncoupled nonlinear dynamic analysis approach is proposed in this paper. In addition the additional possibilities by the appealing new Plaxis 2D embedded pile row feature are discussed.

Investigated New Method

In this study an efficient uncoupled nonlinear dynamic analysis approach is proposed. With this new uncoupled approach time consuming and complex 3D coupled nonlinear dynamic analysis would not necessarily be part of a jetty or wharf seismic design. The following sequence of sub steps is followed:

1. The near field pile-soil interaction of the pile group represented by Winkler p-y foundation is verified and adapted by comparing pushover characteristics with results of 3D coupled soil-structure Finite Element Analysis (FEA).
2. The site response is calculated by means of conventional equivalent linear frequency domain analysis or nonlinear finite element analysis.
3. The site response is applied as an imposed motion on the support nodes of the selected Winkler p-y springs (step 1), connected to the piles in a structural finite element model. With this structural model the dynamic response of the structure is calculated.

In this study also a fourth step with 3D coupled nonlinear dynamic analysis has been performed in order to develop and assess the uncoupled dynamic method.

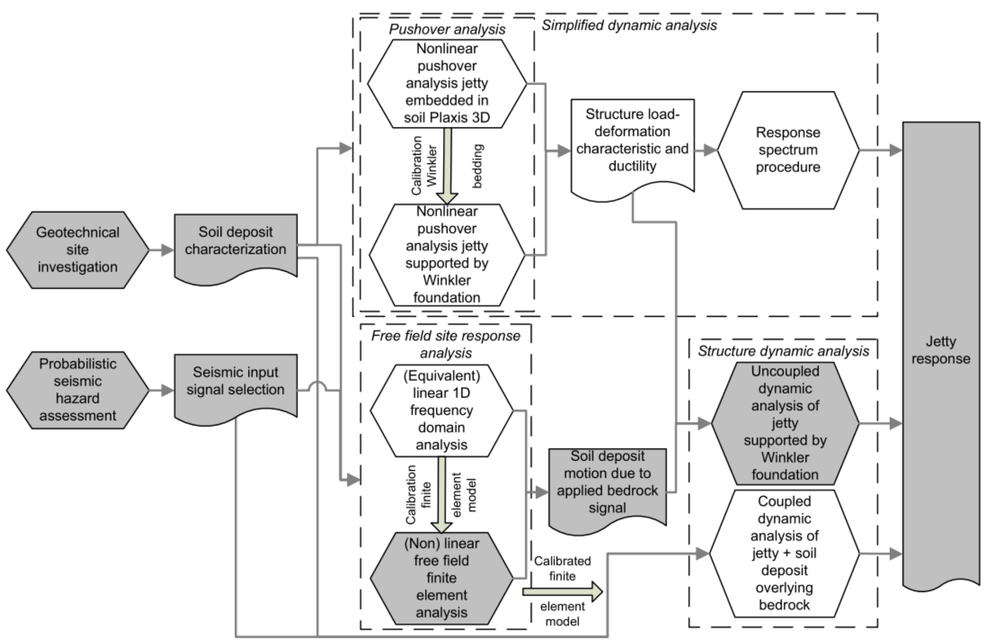

Figure 1: Performance-based seismic design methods (uncoupled method in grey shading).

In parallel nonlinear response spectrum analysis is performed based on the in step 1 obtained pushover curves. The N2-method variant (Fajfar, 1999) is applied. By comparing results of nonlinear dynamic analysis to response spectrum analysis results, the conservatism of the nonlinear response spectrum results is assessed. The proposed design method in relation to other performance-based design methods is presented in Figure 1.

A jetty project in the Marmara Sea area (Turkey) was selected as a reference case. The case project covers the typical situation of a high seismicity area with a jetty founded on large diameter end bearing steel piles embedded in soft (clay) alluvial soil deposits. This setting is relevant for many seismically active near shore marine delta areas.

Local soil conditions include a 10 m top soft clay layer (s_u = 4 - 21 kPa), a 10 m second medium stiff clay layer (s_u = 30 - 5 kPa) and underlying layers of dense sand and a hard clay seismic base layer. The local water depth ranges from zero at the shoreline to maximum 18 m.

Pushover analysis: Calibration of p-y Springs by Comparison to 3D Finite Eement Pile-Soil Models

Pushover analysis was performed on both jetty models with Winkler foundation and on single pile and jetty (pile group) models in Plaxis 3D. 3D modeling of pile-soil interaction in Plaxis 3D is used as a tool to verify and fit the traditional p-y Winkler representation of SSI for the specific situation.

The Hardening Soil (HS) constitutive model with and without small strain overlay model (HSsmall) are applied. Consistency of soil input parameters has been of main importance in this comparative study since Winkler and HS(small) soil characterization are typically based on different input parameters . An extensive set of correlations is used to determine consistent parameters of the different clay layers.

Standard ISO p-y curves based on the available soil data initially were applied. It was concluded that the p-y expressions for soft clay (Matlock, 1970) have an initial stiffness and ultimate capacity both being conservative. Winkler p-y curves for soft to medium stiff clays developed by Jeanjean (Jeanjean, 2009) showed a very good fit of pile-soil interaction obtained from Plaxis 3D. An almost perfect fit was obtained on both global and local level as is shown in Figure 2 that presents the pile bending moments over the pile height for two load levels.

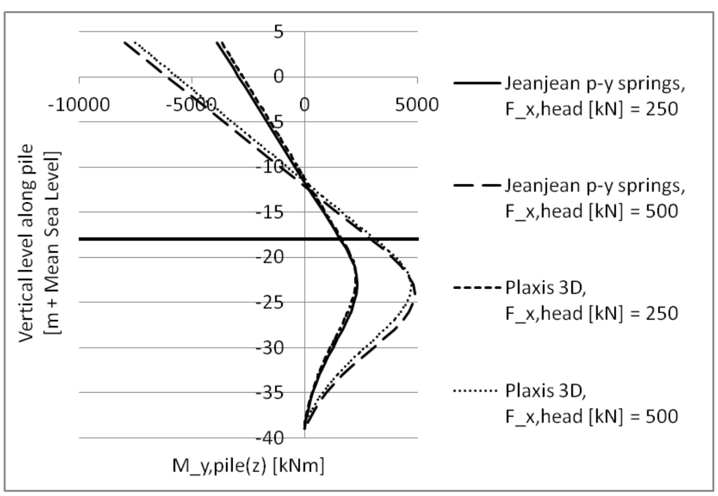

Figure 2: Comparison of pile bending moment at two load levels.

Verifying p-y curves by Plaxis 3D modeling has the following important advantages:

- HS(small) advanced soil models conceptually better represent real soil behavior;
- HS(small) input parameters are often better correlated to field and lab experiments and therefore a more reliable input parameter;
- Pile-soil interaction depends on a number of pile, soil and soil layering characteristics, which are not all accounted for in simple p-y expressions;
- Pile group efficiency can accurately and case-specifically be determined from Plaxis 3D analysis, where p-multipliers from codes are generalized expressions.

Pushover analysis with advanced 3D soil-structure models is a useful tool to provide accurate input for nonlinear response spectrum analysis. Within the new proposed approach it however forms an important model verification towards uncoupled nonlinear dynamic analysis on Winkler soil-structure models as well.

Dynamic Site Response Analysis

As was shown in Figure 1, in this study two jetty dynamic analysis approaches were studied and compared: uncoupled and coupled dynamic analysis. For both methods seismic site response analysis is a mandatory preliminary step. The dynamic response of the site is calculated along two methods: conventional equivalent linear analysis and nonlinear FEA.

Input signals recorded near the case study site (Kocaeli 1999, Düzce 1999) were selected, filtered and scaled. In a series of dynamic site response analyses the model was calibrated with respect to element size, dynamic time stepping the time integration scheme and boundary effects. The soil deposit response by numerical 2D Plaxis model should converge to the frequency domain solution for 1D shear wave propagation problem through layered soil. This verification covers mesh dependency and boundary disturbance effects. A damped Newmark time integration scheme (α=0.1) was found to be essential for a stable solution where it has a limited effect on the calculated response amplitude, as was also concluded by Sigaran Loria and Jaspers-Focks (Sigaran Loria and Jaspers Focks, 2011). Boundary effects in 2D and 3D models were assessed by means of comparison with the 1D equivalent linear frequency domain analysis solution.

Frequency domain analysis of shear waves propagating vertically through equivalent linear layered soil was coded in Matlab, based on the theory of 1D wave propagation. Various expressions for modulus reduction and damping curves as a function of cyclic shear strain available in literature have been compared after which Hardin and Drnevich (1972) is selected.

After calibration of the plane strain FE model for mesh dependency and boundary disturbances the focus was shifted towards the performance of the various soil constitutive models when applied in dynamics. The focus was on the performance of the Hardening Soil model with Small strain stiffness (HSsmall). The HSsmall includes hysteretic damping as a function of strain amplitude and hence is suggested to be conceptually suitable to be applied in dynamic problems (Brinkgreve et al, 2007). The present study however revealed poor performance of the HSsmall model in dynamics of shallow soft soil layers. The reset of the HSsmall stiffness at deviatoric principal strain rate reversals may for these conditions result in unrealistic development of accelerations as is shown in figure 3.

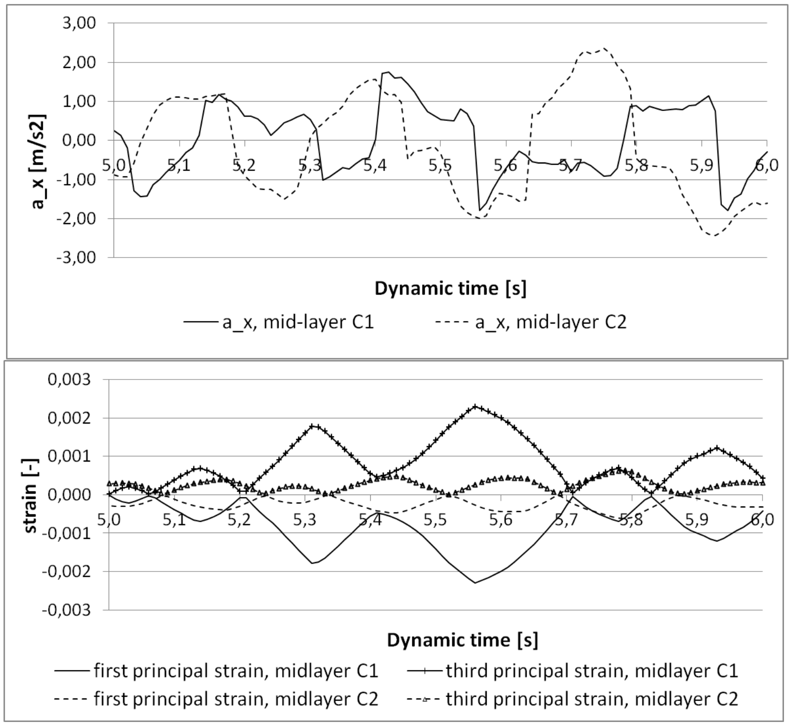

Figure 3: Development of accelerations and the corresponding strains (C1 = soft clay, C2 = medium stiff clay).

High G_o/G_{ur} ratios, as typically apply to soft to medium stiff clays, are found to further deteriorate the HSsmall performance for these type of soils. Removing the stress dependency of shallow layers and assigning a constant stiffness to shallow layers was found to be the most effective measure to improve the dynamic HSsmall performance.

Uncoupled and Coupled Dynamic Time History Analysis of Site and Structure

Modelling aspects

In the new uncoupled approach, the structure response was calculated with Seismostruct, which is a structural finite element code specifically suitable for structural seismic design. A structural pile-deck model supported by Winkler springs was built. The complex Winkler spring characteristics were obtained by combining springs calibrated by static pushover analysis with parallel dashpots according to Gazetas & Dobry (Gazetas and Dobry, 1984a, 1984b). The dynamic response of the structure is calculated for excitation of the Winkler support nodes. These input motions are derived from site response analysis by either nonlinear Plaxis 2D site response analysis or equivalent linear frequency domain analysis.

Coupled dynamic analysis of soil deposit and structure was performed with a Plaxis 3D finite element model including both the soil deposit overlying bedrock and the jetty structure cross-section (Figure 4). Details regarding the modeling procedure can be found on the Plaxis website (http://www.plaxis.nl/publication/seismic-jetty-design). Both the modelling of soil and structure in this model are verified extensively in previous steps which is a key aspect when processing such advanced models.

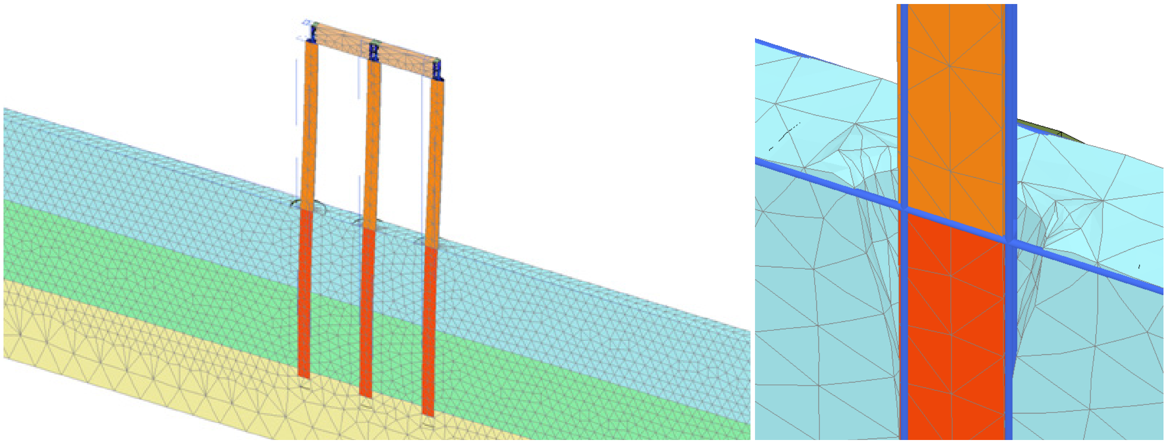

Figure 4: 3D Coupled soil structure Plaxis 3D model.

Results

By comparison of nonlinear static, uncoupled and coupled dynamic jetty response results, the accuracy of the uncoupled approach was investigated. Peak seismic structure demands calculated from nonlinear dynamic and nonlinear response spectrum analysis were found to be similar. During preliminary design stages the use of simplified dynamic response spectrum analysis is therefore acceptable for jetty structures. It was found that internal forces and displacement responses obtained from nonlinear coupled and the proposed nonlinear uncoupled dynamic analysis are signal dependent, but generally very similar. The complex Winkler foundation captures the near field pile-soil interaction. Minor deviations between results develop at the onset of global soil failure at extreme acceleration levels. This can be explained by the piles that in the coupled approach interact with the surrounding soil, where this full coupling is not accounted for when an uncoupled calculation is performed.

Figure 5 shows the jetty drift development in time when subjected to a Düzce (1999) East-West recorded signal. In terms of displacements structure responses calculated based on input from equivalent linear site response analysis (e.g. Shake, for this study coded in Matlab) were found to deviate significantly from responses calculated from nonlinear uncoupled and coupled analysis. This is a result of zero soil permanent displacements that by definition result from equivalent linear site response analysis and extreme acceleration level variations of the soil along the pile, not being limited by soil plasticity. Nonlinear time domain analysis results show high sensitivity to the seismic input signal (duration, intensity, frequency content, etc.). It is advisable to use significantly more input signals than typically required as a minimum by design codes.

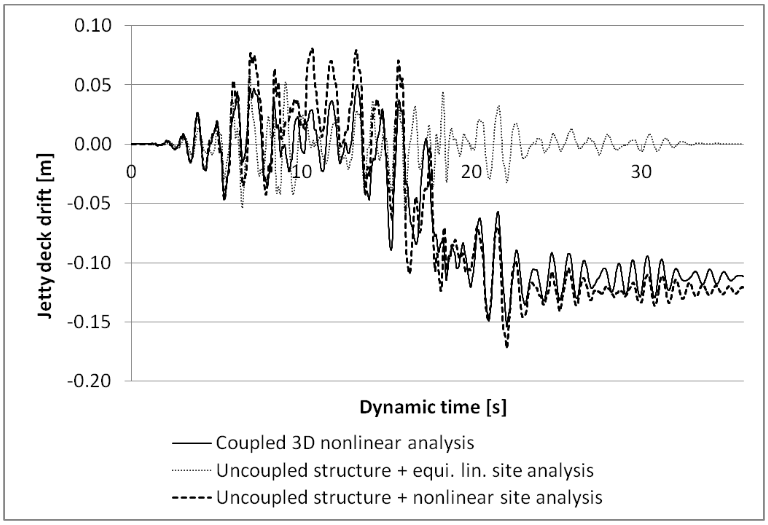

Figure 5: Development of jetty drift over time in dynamic analysis.

From the analyses results it is concluded that uncoupled nonlinear site response and structure dynamic analysis as proposed in this study is a useful tool in performance based seismic design. Including nonlinear site response analysis in the uncoupled approach enables evaluation of effects of kinematic pile loading and permanent soil displacements. This assessment of residual displacements is typically is required by modern performance based seismic codes. It is advised to not calculate residual displacements with uncoupled analysis in which the site response is calculated with an equivalent linear method. The fully nonlinear uncoupled method provides the opportunity to assess with the structural dynamic model the 3D seismic response of complex 3D jetty geometries. This is not possible with coupled nonlinear models because computational modeling limitations constrain the analysis in terms of geometric complexity.

Pile-Soil Interaction Modeling in 2D Plane Strain Models with the Plaxis 2D embedded Pile-Row Feature

Along the proposed uncoupled method the structural dynamic calculation is performed by a structural finite element model in which the soil is represented by nonlinear springs. This seems to result acceptable performance for structures in level ground. However, for soil retaining quay walls or structures with piles constructed in slopes the structure has a preferred direction of displacement under seismic loading. SSI herewith has a different characteristic. This is important to note in relation to the proposed method, because this aspect limits its applicability.

This limitation can be overcome for quay wall type of structures with the new embedded pile row feature available in Plaxis 2D. With this feature it becomes possible to perform coupled pushover and coupled dynamic analysis for a 2D cross section of a quay wall, without exceeding computational limitations. Pile-soil interaction is taking into account by the embedded pile row feature as a function of pile spacing and soil stiffness. For further details one is referred to Sluis et al., 2014. No lateral ultimate capacity slider was included up to date, but a work-around is found as proposed by Sluis et al., 2014. In the new Plaxis 2D 2015 version a lateral slider is available, but its performance was not assessed by the authors before handing in this paper. With this approach it is possible to perform coupled dynamic analysis of soil and piles for soil retaining port structures including piles and relieve decks. This was done for the new quay walls for Baku New International Sea Port, for which the model layout is shown by figure 5. Limited Plaxis capabilities for modeling structural nonlinear behavior form an important disadvantage in using this tool for performance-based seismic design, in contrary to the proposed uncoupled method. It should be decided per specific case which approach (uncoupled 3D or coupled 2D) suits best to the requirements.

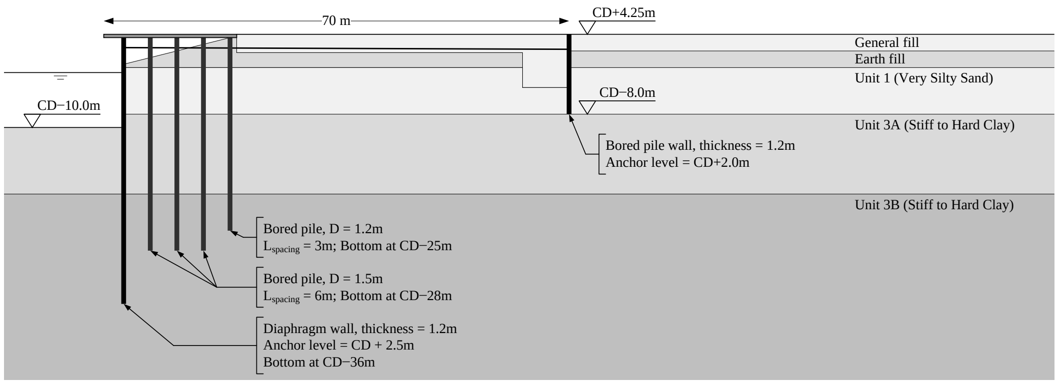

Figure 6: Schematic cross section of the New Baku International Sea Port quay wall.

Concluding Remarks

An uncoupled nonlinear dynamic method for performance-based seismic design of piled structures is proposed in this paper. The performance of this method was evaluated based on comparison to fully coupled nonlinear FEA of soil and a structure. Analysis results for an oil jetty case study project imply promising performance of the proposed method. SSI of piled structures, even with a complex geometry, can be better assessed with the proposed method. This follows the trends in modern performance based design codes. The method can be applied for many types of piled structures, except cases where the soil loading on the piles is clearly asymmetric, such as a quay wall structure with a relieve deck on embedded piles. For these types of structures the Plaxis 2D embedded pile row feature forms a useful tool for design.

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