



## PLAXIS as a Tool for Soil-Structure Interaction Modelling in Performance-Based Seismic Jetty Design

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The importance of soil structure interaction in seismic design of structures is recognized by the seismic design community, which is very much moving towards performance based design principles. Particularly for structures with deep foundations in soft soil conditions, soil-structure interaction is a key factor that has to be considered in design. Jetty structures can be such structures. However, seismic design standards do hardly provide any straight forward tools for engineers to account for soil-structure interaction in design. It is clear that a challenge exists, which has initiated this study. This paper addresses how Plaxis can efficiently be applied as a tool in seismic soil-structure interaction problems, which has been an important part of the entire MSc thesis study (TU Delft), that has covered a wider range of related aspects.

**➤ Jetty structures are, like many other port and offshore structures, at the interface of structural and geotechnical engineering.** 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 regular multi storey buildings with a fixed base. For geotechnical structures (i.e. jetties, quay walls, however these techniques are less common and their performance is less clear. Past post-earthquake surveys show typical failure modes that are often strongly dominated by differential and permanent deformations in soils. Since these effects are vital for post-earthquake performance and possibly induce global failure, they should in a way be accounted for in performance-based design.

### Problem definition

The study has concentrated at performance-based seismic design of jetty structures and aspects related to numerical soil-structure interaction modelling. A Witteveen+Bos case of a jetty design project located in a high seismicity area in Turkey was taken as a starting point. The following study however has considered soil-structure interaction for piles in general, in order to be able to extend the results into a wider range of future seismic design projects and other projects relating to the dynamics of foundations.

It is noted that in this study seismicity is assumed

to be represented by vertically propagating shear waves, which is a common simplification adopted in the seismic engineering community. It is realized that this assumption is not generally justified, in particular for very near-fault projects.

### Proposed Method

In the first stage of the study a comprehensive literature study was performed, aiming at the

definition of possible performance based design strategies for jetty type of structures. Based on this literature study [references can be found in the thesis report] a flowchart has been constructed [Figure 1], that describes proposed steps to be taken by engineers to efficiently account for soil-structure interaction in design and obeying performance based code requirement in final design stages. According to literature jetty type

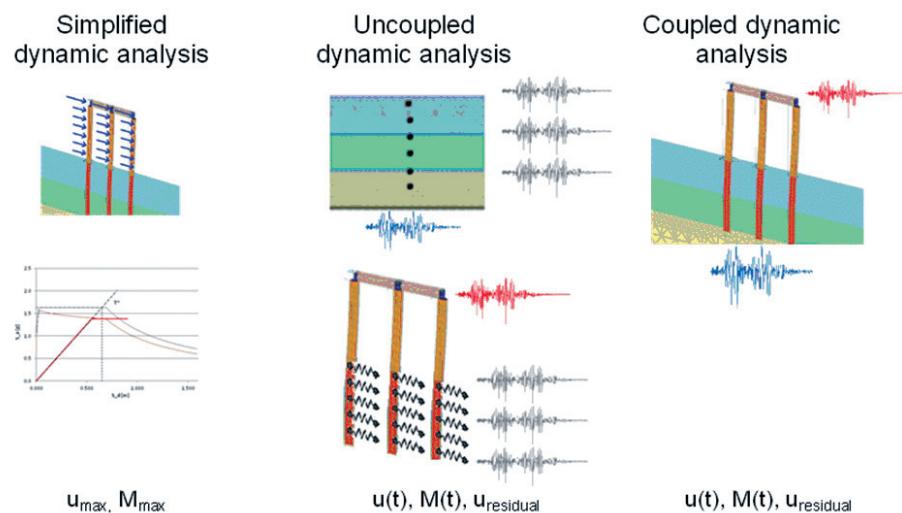


Figure 1: Flowchart of proposed seismic design analysis methods for jetty structures



of structures may be analyzed by means of the following procedures:

- Simplified dynamic analysis (pushover + response spectrum method)
- Uncoupled dynamic analysis of site and structure
- Coupled dynamic analysis of site and structure

For all three methodologies pushover analysis of the jetty is an important sub step that determines the nonlinear lateral load-deformation characteristics and capacity of the structure.

Towards uncoupled or coupled dynamic analysis of site and structure, site response analysis is an important preliminary step, for which both equivalent linear and nonlinear methods were addressed and compared in this study. The different steps as outlined above will subsequently be discussed in this paper.

#### Pushover Analysis

According to literature and seismic design standards, pushover analysis combined with response spectrum procedures is the most common approach for seismic design of regular structures (often referred to as simplified dynamic analysis). Since this approach relies on pre-assumed failure modes it requires caution when applied to irregular structures or other structures for which the dominant dynamic modes cannot easily be identified. Structural engineering community often accounts for soil in their models by simplified Winkler p-y springs. The characteristics of these springs are commonly based on decades old codes, which are based on limited experimental data. In this study the common code-based p-y expression were verified by PLAXIS 3D numerical analysis of single piles embedded in layered soil.

In pushover-analysis the hardening soil (HS) constitutive model was adopted in order to account for hardening plasticity and stress dependent stiffness characteristics, as are observed for real soils. In order to identify the most likely HS input

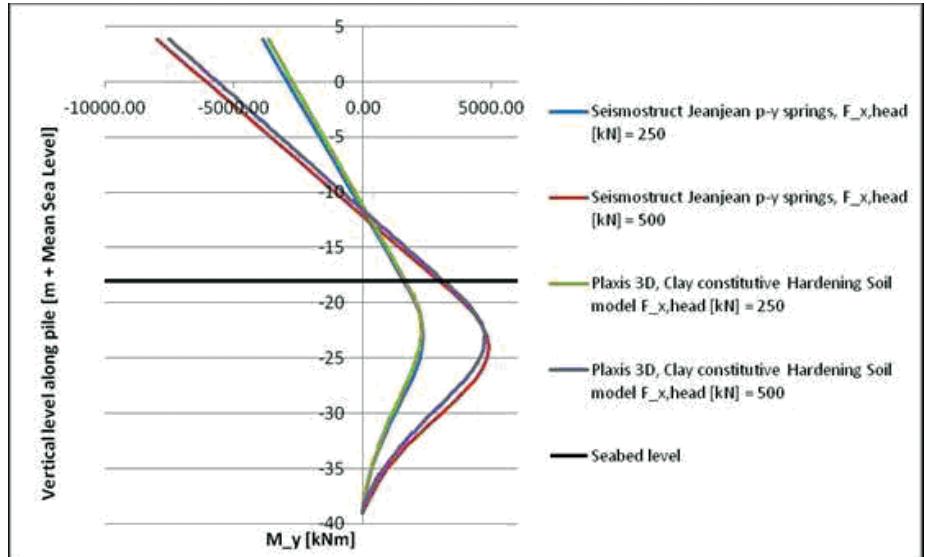


Figure 2: Bending moment distribution along the piles for both Winkler and HS continuum models

parameters based on limited soil survey, a large number of correlations from literature where included in parameter selection for both sand and clay materials. The pile was modelled by means of a combined plate and solid in order to be able to easily identify pile bending moments and also properly account for geometric aspects of the circular shaped pile interacting with the soil. Point of attention in the modelling of these circular shaped elements has been the locking of interfaces, which may result in overestimation of pile stiffness.

According to performance based design principles, most codes allow pile deck systems to develop limited plastic hinging at the fixed pile heads during high intensity earthquakes to dissipate energy and prevent global collapse. In the recent release of PLAXIS 3D however plasticity of plates is

not included. A workaround is found by an artificial plastic hinge by means of elastic-plastic anchors to include the important local nonlinear response at the pile connection to the deck.

Based on a large series of pushover analysis, including a parametric study of variations in HS input parameters, it was concluded that the commonly applied Matlock p-y expressions for soft clays have a too low initial stiffness and ultimate capacity. This conclusion corresponds to the conclusion drawn by Jeanjean [1], who recently has proposed alternative p-y expressions for soft clays. The Jeanjean p-y expression where compared to the results from PLAXIS 3D pushover analysis. An almost perfect fit on both global pile and local pile-soil level was obtained, as is indicated by figure 2 that shows the bending moment distributions along

the pile length. This perfect fit has provided good confidence in both the Jeanjean p-y expressions for soft clay and the accuracy of HS input parameters that can be obtained when one includes a large number of correlations in the selection of hardening soil parameters.

The verification of p-y springs by PLAXIS 3D analysis has been identified as an important and efficient calibrating sub step towards the application of these Winkler p-y springs in simplified soil-structure dynamic analysis. Additionally also group effects where studied. Group efficiency factors for both transversely spaced and shadowing piles proposed in literature were assessed by PLAXIS 3D pile group analysis. While group efficiency reductions proposed in literature were found to be strongly varying, Plaxis 3D pushover analysis was identified as a very efficient and useful tool to find case specific group efficiency reductions, taking into account various contributing factors like e.g. pile diameter, spacing and stiffness and soil types and layering.

#### Response Spectrum Analysis

The jetty transverse lateral load-deformation characteristics resulting from pushover analysis on both PLAXIS 3D and Winkler p-y jetty-soil models were included in a performance-based response spectrum procedure as proposed by Fajfar (N2-method) [2]. Although the Fajfar method is in itself purely analytical, the relation of pushover capacity and spectral demand is nicely represented in a graphical acceleration-displacement response spectral format, by utilizing the acceleration – displacement relationship:

$$u(t) = Ue^{i\omega t} \rightarrow ii(t) = -\omega_0^2 Ue^{i\omega t}$$

$$\rightarrow \left| \frac{S_{ii}}{S_u} \right| = \frac{1}{\omega_0^2} = \frac{T_0^2}{4\pi^2}$$

The response spectrum demand was based on ISO 19901-2 regulations, as a function of the bedrock

acceleration level, the upper 30 m soil deposit characteristics and the structure estimated fundamental period, as is common in most seismic design codes. It is noted here that the Fajfar N2-method relies on the equal-displacement rule for elastic response spectrum reduction beyond the elastic range. Alternatively, the equal-potential-energy criterion can be applied, as was also considered in this study. For the jetty structure (with fundamental period  $T_0=1.25$ s) no significant difference in results was obtained, as was to be expected based on the fundamental frequency according to Miranda & Bertero [3]

In the present study response spectrum analysis was included as a reference solution and it was decided to stick to a practical single-mode response spectrum procedure, where more advanced multi-mode (adaptive) methods are available.

#### Site Response Analysis

As was shown in figure 1, in this study finally two jetty dynamic analysis methods were studied and compared, being uncoupled and coupled dynamic analysis. For both methods preliminary site response analysis is an important sub step.

For the uncoupled variant the soil deposit dynamic responses to an applied bedrock signal are determined at different depths, which subsequently are applied to Winkler support nodes of the nonlinear p-y springs that account for near field pile-soil interaction in the structural dynamic model.

Towards coupled dynamic analysis of site and structure in PLAXIS 3D, the site response analysis forms an important calibration step of the finite element model.

Different recorded bedrock horizontal motion signals were selected, filtered and scaled before being applied to the bottom of the finite element

model. In a large series of dynamic site response analyses first the model was calibrated with respect to element size, dynamic time stepping the time integration scheme and boundary effects. To this extend initially a linear elastic soil constitutive model was applied, for which the soil deposit response obtained from the numerical 2D PILAXIS model should converge to the frequency domain solution for 1D shear wave propagation problem through layered soil, provided that similar dynamic characteristics are assigned to the soil.

Adopting a damped Newmark time integration scheme was found to be essential for a stable solution were it only has a very limited effect on the calculated response amplitude, as was also concluded by Sigaran de Loria and Jaspers-Focks [4]. Boundary effects were studied and compared with the 1D frequency domain analysis solution and a PLAXIS 2D model with tied boundaries. Also a comparison of responses obtained from a PLAXIS 2D plane strain model and a PLAXIS 3D soil slice model was made, in order to verify the PLAXIS 3D dynamics module performance.

Frequency domain analysis of shear waves propagating vertically through equivalent linear layered soil was coded in Matlab, based on the theory as outlined in Kramer (1996) [5]. In equivalent linear frequency domain analysis effective modulus reduction and equivalent damping are assumed to be constant over time, corresponding to a shear strain averaged over time. Various expressions for these modulus reduction and damping curves are available in literature, where in this study expressions according to Hardin & Drnevich were applied, after being verified in a comparative study including relationships proposed by Hardin & Drnevich [6], Vucetic & Dobry [7], Ishibashi & Zhang [8] and Santos & Correia [9].

After the PLAXIS 2D plane strain finite element model was calibrated with respect to the model

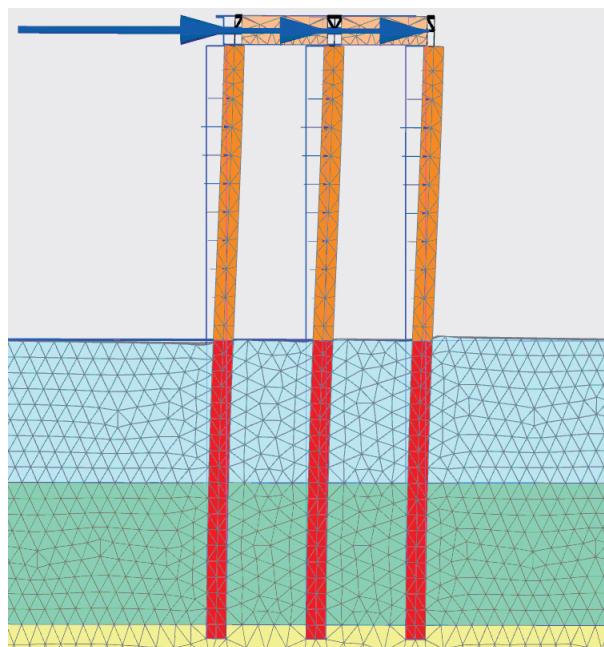


Figure 3: Jetty cross-section pushover

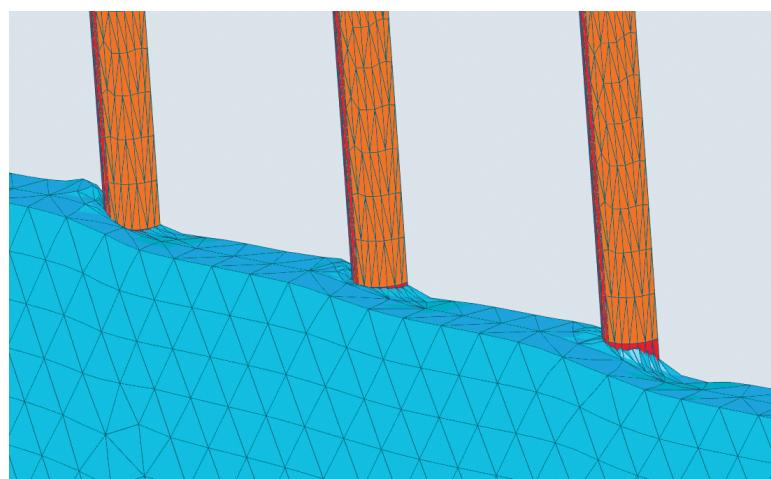


Figure 4: Pile-soil deformation for lateral pushover loading

basic issues mentioned before, the focus was shifted towards the performance of the various soil constitutive models available in Plaxis when applied in dynamics. Herein the focus was on the performance of the Hardening Soil model with Small strain stiffness (HSsmall) and soil modulus reduction curves and damping characteristics as a function of cyclic shear strain. The HSsmall includes hysteretic damping as a function of strain amplitude and hence is conceptually very attractive to be applied in dynamic problems. However, in this study the HSsmall model was found to have a poor performance in dynamics when applied to shallow soft soil layers having low stiffness due to low local stress levels. More specifically can be stated that 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 figures 6 and 7 for a specific dynamic time interval. The suddenly changing stiffness matrix in the equation of motion forces the acceleration vector to undergo sudden changes as well. In reality this behaviour will not be observed since a finite time interval is related to the stiffness development, where in the HSsmall numerical model it is not. Additionally the relatively high  $G_s/G_0$  ratio, as typically applies to soft to medium clays, was found to further deteriorate the HSsmall performance for these type of soils.

Remedial measures to improve the HSsmall performance were sought. Removing the stress dependency of shallow layers (by setting HSsmall

stress dependency parameter  $m = 0$ ) and assign a constant stiffness to shallow layers was found to be the most effective measure. Doing so allows engineers to benefit from the HSsmall hardening plasticity and hysteretic strain dependent damping features, while minimizing negative consequences of HSsmall performance for low stiffness soil layers.

Compared to the response calculated by equivalent linear frequency domain analysis, Plaxis nonlinear HSsmall site response analysis results in lower peak acceleration levels of the soil deposit at high intensity shaking, but higher response levels at low intensity shaking. This is explained by much higher damping levels at these high intensity motion intervals and effects of plasticity that limit peak acceleration responses. This behaviour may be considered more realistic for real soils that also show failure and permanent deformations during earthquakes.

#### Coupled and uncoupled site + structure dynamic analysis

During the last step of the study presented in this paper the dynamic response of a jetty transverse cross-section was calculated. As explained before, both uncoupled and coupled analysis of site and structure were performed.

In the uncoupled approach, the structure response was calculated with Seismostruct, which is a structural finite element code specifically suitable for structural seismic design purposes. 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 [10, 11]. The dynamic response of the structure then was calculated for imposed Winkler support node excitations that were derived from separate site response analysis by either nonlinear PLAXIS 2D site response analysis or equivalent linear frequency domain analysis.

For coupled dynamic analysis of soil deposit and structure, a single PLAXIS 3D finite element model was built including both the soil deposit overlying bedrock and the jetty structure cross-section. With this model the coupled dynamic response was calculated. The geometry of the coupled system is presented in figure 8.

Although the number of elements was minimized as far as possible, accuracy and stability requirements resulted in a finite element mesh consisting of approximately 60000 elements and a maximum allowable time stepping of 0.003 s for a 30 s seismic input signal. On a modern pc a single run of these type of coupled dynamic analysis takes about 3 days and the required model calibration takes weeks. Hence it may be concluded that for general seismic design projects the full coupled analysis computational effort still is a factor limiting its applicability. Additionally it is noted that a strong signal-dependence of response levels was obtained, based on which a larger number of input signal time histories than proposed in seismic design codes is to be recommended, further increasing engineering effort.

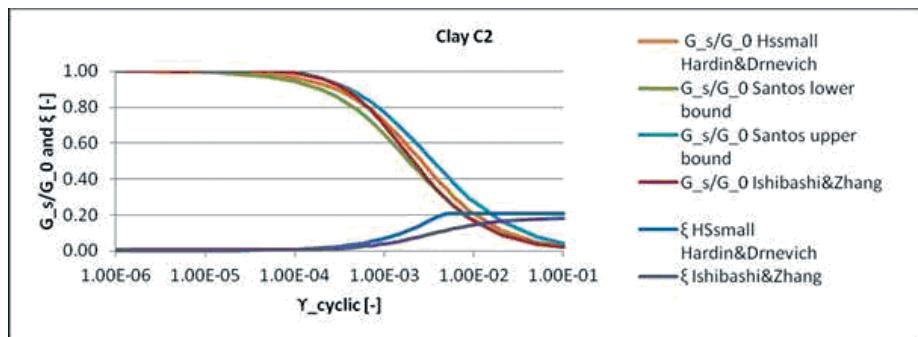


Figure 5: Comparison of modulus reduction and damping curves for one of the clay materials considered

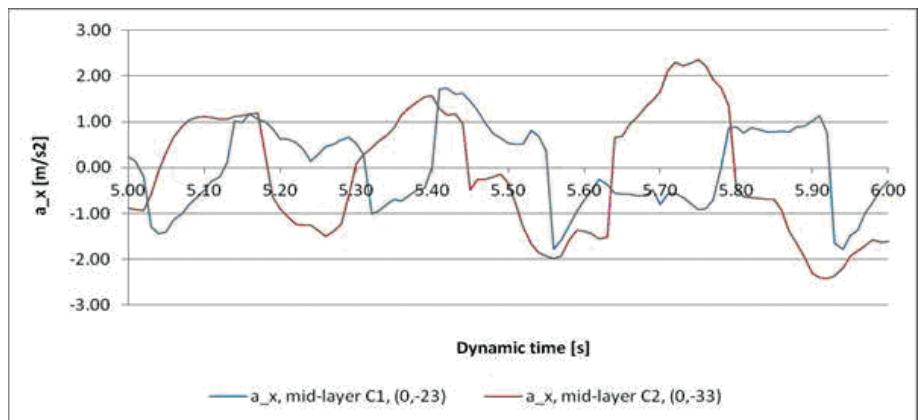


Figure 6

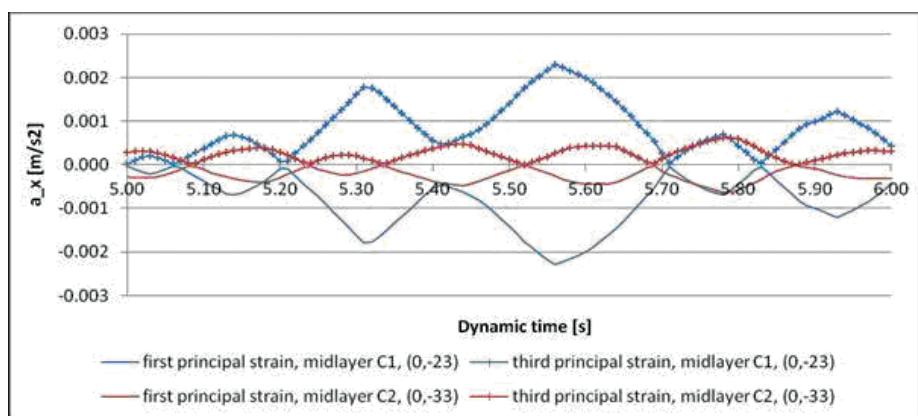


Figure 7

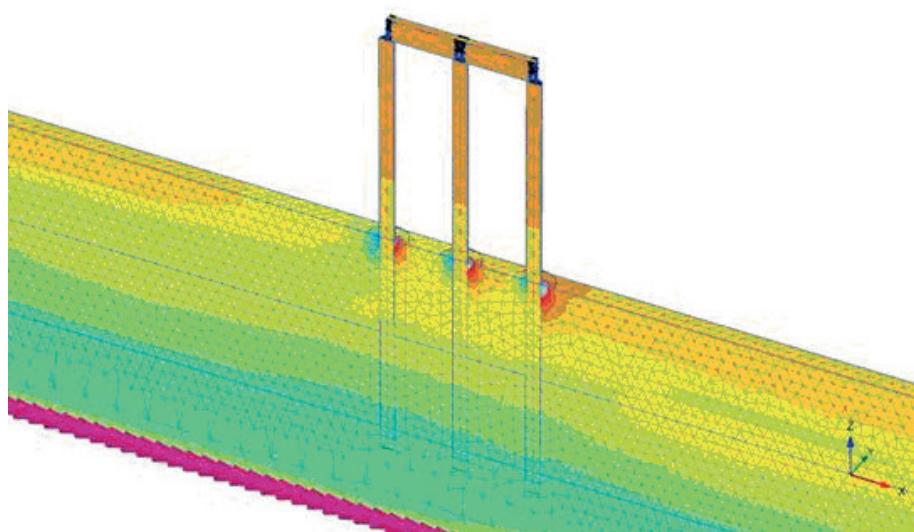


Figure 8

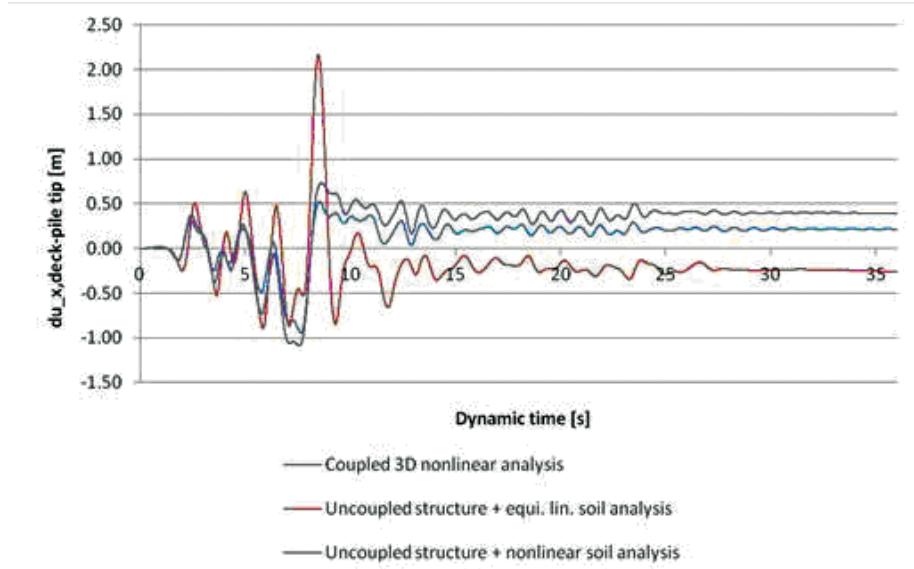


Figure 9

By comparison of the uncoupled and coupled calculated dynamic jetty response, the accuracy of the computationally much more attractive uncoupled analysis was investigated. Figure 9 shows the pile drift development in time when subjected to the Kocaeli (1999) East-West recorded signal.

It was found that responses obtained from nonlinear coupled and nonlinear uncoupled analysis are generally reasonably similar. The complex Winkler springs (provided that they are calibrated in preliminary steps) capture the near field pile-soil interaction quite well. Deviations between both methods develop at the onset of global soil failure of the deposit at extreme acceleration levels. This can be explained by the piles that in the coupled approach interact and support the surrounding soil, where this full coupling is not accounted for when an uncoupled calculation is performed.

Uncoupled structure responses obtained based on equivalent linear site analysis however were found to deviate significantly from responses calculated from coupled analysis. This may be explained by development of extreme acceleration level variations of the soil along the pile, not being limited by global or local soil failure. Besides, permanent deformations calculated from this uncoupled approach differ significantly from the full nonlinear analysis results, at least for the high acceleration levels considered in the present study.

From the results of the dynamic analyses it was concluded that the uncoupled type of dynamic analysis as proposed in this study may be a reasonably accurate and relatively efficient tool in performance based seismic design, especially for irregular pile-deck type of jetty and wharf structures where torsional effects may be dominant for response.

Comparison of peak responses from dynamic analysis and simplified dynamic analysis Peak displacement demands calculated by simplified dynamic response spectrum analysis were found to be similar to the peak displacement demands calculated by coupled and uncoupled nonlinear dynamic analysis. Therefore it was concluded that simplified dynamic response spectrum analysis for jetty type of structures is the tool to be used in preliminary design stages. It is however noted that additional uncoupled dynamic analysis definitely is to be preferred in final design stages in order to be able to identify unexpected failure modes and estimate permanent displacements, the latter of which is limited by modern performance based seismic code requirements.

#### Conclusions and Recommendations

The study presented in this paper considers a seismic design problem at the interface of structural engineering and geotechnical engineering, for which straight forward design procedures are very limited. Along modern performance-based design principles a design strategy was defined for jetty type of structures.

Finite element modelling with PLAXIS 2D and 3D and the dynamics modules has been a key aspect in; calibration steps, preliminary static analysis, and dynamic analysis in final design stages. As is often the case for seismic design projects, no verification of models by measured responses during earthquakes was available. Hence it was a key issue in the present study to verify all sub steps in order to prevent black-box finite element analysis. During this study it was obtained that PLAXIS 2D and 3D are very useful tools in different stages of seismic jetty design, but engineers should still be aware of their limitations and the need for verification of results.

PLAXIS 3D was found to be a powerful tool for static verification of equivalent Winkler foundations for pile groups towards dynamic analysis. However, for high intensity earthquake design utilizing nonlinear structural behaviour of plates should preferably be included in new releases of PLAXIS 3D. PLAXIS 2D may be applied to perform nonlinear site response analysis in the proposed uncoupled dynamic analysis approach. PLAXIS 3D coupled dynamic analysis of site and structure resulted in excessive computational demands which still is a limiting factor for general application.

The proposed approach supplies engineers with a design strategy better fitting to modern code requirements compared to traditional methods. When applying nonlinear time domain analysis, one should be aware of the high sensitivity to the selected seismic input signal, and its intensity. Based in the present study the authors recommend to calculate dynamic responses for a higher number of input signals than the relatively limited number ranging from 3 to 7 as typically required by international seismic design codes.

As a last remark it is noted that the focus of this study has been on jetty structures, but the typical dynamics of large end-bearing shafts in soft soils are relevant for different types of onshore and offshore structures as well. Further development of knowledge, concepts and methodologies is being planned by Witteveen+Bos for the near future.

More information, the thesis report, questions or request for corporations with Witteveen+Bos, please contact: f.besseling@witteveenbos.nl or h.lengkeek@witteveenbos.nl

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