

ANALYSIS OF PILES IN LIQUEFYING SOILS

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Abstract: Two methods for analysis of piles in liquefying soils are discussed and comparatively examined in this paper: an advanced method for dynamic analysis based on the effective stress principle and a simplified analysis based on the pseudo-static approach. The former method aims at an accurate simulation of the complex liquefaction process and soil-pile interaction while the latter is a design-oriented approach aiming at an optimum trade-off between the accuracy and simplicity required in the preliminary assessment and design of piles. Typical models, analysis procedures and characteristic features of both methods are discussed in order to illustrate their advantages and shortcomings and hence provide guidance for their application to the evaluation of seismic performance and design of piles.

1. INTRODUCTION

Soil liquefaction during strong earthquakes significantly affects the performance of pile foundations leading to damage and even collapse of piles. In the 1995 Kobe earthquake, for example, massive liquefaction of reclaimed fills caused damage to numerous pile foundations of buildings, storage tanks and bridge piers. The unprecedented level of damage to foundations of modern structures instigated a great number of research studies in an effort to better understand soil-pile interaction in liquefied soils and to improve the seismic performance of pile foundations. In the initial stage of these studies, detailed field investigations on the damage to piles, in-situ soil conditions and features of permanent ground displacements were conducted. The field investigations were then followed by experimental studies aiming to clarify the mechanism of the damage by means of seismic centrifuge tests, 1-g shake table tests and benchmark experiments on full-size piles. Based on these studies, analysis concepts and procedures have been proposed and examined in an effort to explore design methodologies for piles in liquefied soils. This paper discusses two analysis methods that received particular attention either because of their high potential in modelling the complex soil-pile interaction in liquefying soils or due to the capacity to model the salient features of pile behaviour by a simple approach that is practical for engineering applications.

2. SOIL-PILE INTERACTION IN LIQUEFYING SOILS

Soil-pile interaction in liquefying soils is a very intense dynamic process that involves significant changes in the soil characteristics and interaction loads over a relatively short period of time during and immediately after the ground shaking. In what follows, we will illustrate some typical features of the ground response and loads on piles in liquefying soils through the use of Figure 1.

During the intense ground shaking in loose saturated sandy deposits, the excess pore water pressure rapidly builds up until it eventually reaches the effective overburden stress σ_v' , as shown in

Figure 1a. At this stage, the effective stress practically drops to zero and the soil liquefies. In the example shown in Figure 1a from the 1995 Kobe earthquake, the excess pore pressure reached its maximum in just 6-7 seconds, and this was practically the time over which the soil stiffness reduced from its initial value to nearly zero. This intense reduction in stiffness and strength of the soil was accompanied with equally rapid increase in the ground deformation as illustrated with the solid line in Figure 1b where horizontal ground displacements within the liquefied layer are shown. Note that these displacements are cyclic in nature and representative for a free field level ground response. The peak displacements of about 40 cm occurred just before or at the time of development of complete liquefaction and were accompanied with relatively high ground accelerations of about 0.4g. During this phase of intense ground shaking and development of liquefaction, the piles are subjected to both kinematic loads due to ground movement and inertial loads from the vibrations of the superstructure. Both these loads are oscillatory in nature with magnitudes and spatial distributions dependent on a number of factors including ground motion characteristics, soil density, presence of non-liquefied crust layer, and predominant periods of the ground and superstructure, among others.

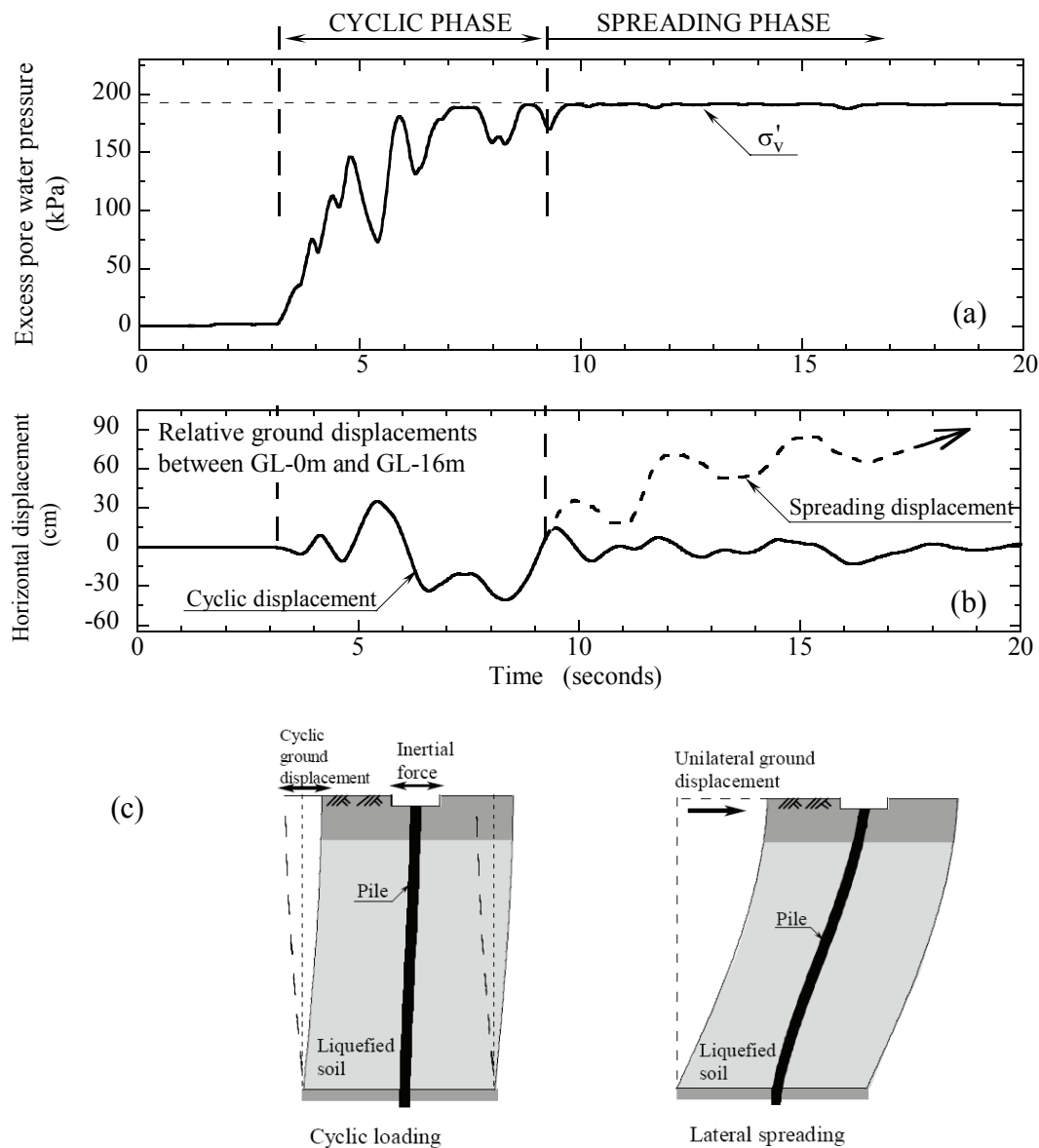


Figure 1. Illustration of ground response in liquefied soils and effects on piles: (a) excess pore water pressure; (b) lateral ground displacements; (c) loads on piles during cyclic loading and lateral spreading

In the subsequent phase of the response following the liquefaction, the stiffness and strength of the liquefied soil remain very low, and hence large unilateral ground displacements may develop due to lateral spreading, as indicated with the dashed line in Figure 1b. Lateral spreads typically develop in sloping ground or in loose backfills behind waterfront structures and often result in excessive permanent displacements of up to several meters in the down-slope or seaward direction. The spreading may be initiated either during the intense pore pressure build up, at the initiation or well after the development of complete liquefaction and hence there are no general rules for combining the kinematic and inertial loads on piles during the spreading phase. In general, however, the ground displacements are approximately one order bigger and the inertial loads are relatively small as compared to those in the cyclic phase of the response, as illustrated schematically in Figure 1c. Thus, when analyzing the behaviour of piles in liquefying soils, it is often useful to distinguish between the cyclic phase and lateral spreading phase of the pile response because the soil characteristics and loads on the pile are quite different between these two phases.

3. METHODS OF ANALYSIS

There are several methods available for analysis of piles in liquefying soils including sophisticated finite element analysis based on the effective stress principle and simplified design-oriented methods based on the pseudo-static approach. The effective stress analysis permits evaluation of seismic soil-pile interaction while considering the complex effects of excess pore water pressure and highly nonlinear stress-strain behaviour of soils in a rigorous dynamic analysis. This method basically aims at very detailed modelling of the complex liquefaction process through the use of advanced numerical procedures. The pseudo-static analysis of piles, on the other hand, is a practical engineering approach for assessment of piles based on routine computations and use of relatively simple models.

3.1 Dynamic Effective Stress Analysis

The dynamic analysis based on the effective stress principle has been established as one of the principal tools for analysis of liquefaction problems. Over the past two decades, the application of the effective stress analysis gradually has expanded from the 1-D analysis of a free-field ground to more complex 2-D analyses involving earth structures and soil-structure interaction systems. Recently, attempts have been made to apply this method to a three-dimensional analysis of large-deformation problems. In what follows, the requirements and advantages of such analysis are illustrated on the example of a 2-D SSI analysis for the analytical model shown in Figure 2.

3.1.1 SSI Model

Figure 2 shows an FEM model of a storage tank on pile foundation embedded in liquefiable soils. Solid elements are used for modelling the soil while beam elements are used for modelling the piles, foundation mat and the tank. Note that the finite element mesh extends throughout the whole model, but was removed from the central part in the figure in order to clarify the foundation soils and geometry. Several important features are apparent in this model. Clearly, the discretization of the soil into finite elements allows a complex geometry and variable soil properties to be modelled. Hence, multiple liquefiable layers with different liquefaction resistance including ground improvement by sand-compaction piles along the perimeter of the pile foundation are incorporated in the model. The model is subjected to an earthquake excitation specified by an acceleration time history at the base of the model.

An elastic-plastic constitutive law is used for modelling the highly nonlinear stress-strain behaviour of the soil including practically all aspects of cyclic undrained behaviour of liquefiable soils. It allows for dilatancy effects, stiffness degradation including the extreme strain-softening and precise simulation of the cyclic strength or liquefaction resistance observed in laboratory tests. Hence the

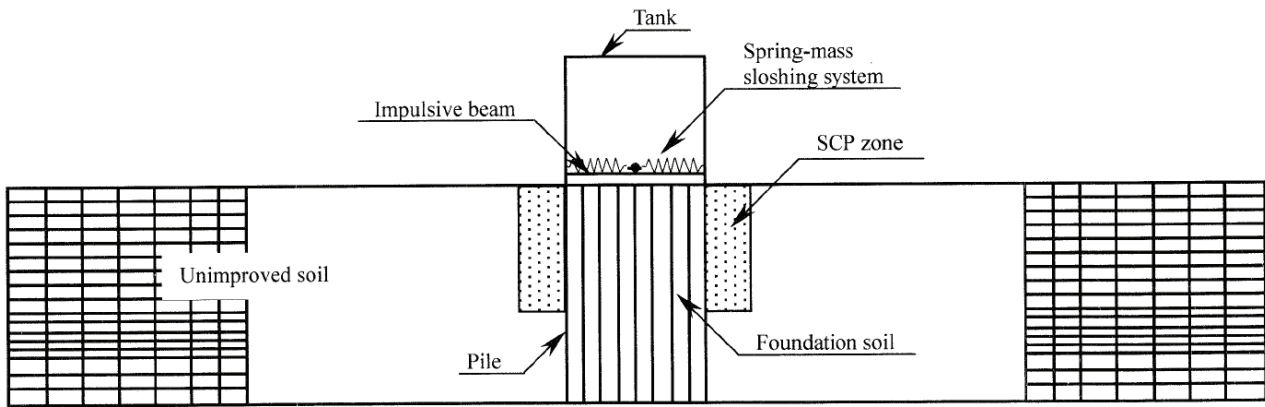


Figure 2. Finite element model for seismic effective stress analysis of a soil-pile-tank system

model shown in Figure 2 permits to analyze the soil-pile-structure-fluid system under dynamic excitation in a step-by-step procedure by considering the key features of liquefaction including development of excess pore pressure and its effects on the variation of stiffness and strength of soils.

3.1.2 Implementation

Whereas the predictive capacity of the effective stress analysis has been verified in many studies (e.g. Ishihara and Cubrinovski, 2005; Cubrinovski et al., 2005), its application in engineering practice is constrained by two key requirements of this analysis, namely, the required high-quality data on in-situ conditions, physical properties and deformational behaviour of soils, and quite high demands on the user regarding the knowledge and understanding of the phenomena considered and the particular features of the adopted numerical procedure.

By and large, an effective stress analysis involves the following steps:

1. *Determination of parameters of the constitutive model*
2. *Definition of the numerical model*
3. *Dynamic analysis and interpretation of results*

Figure 3 summarizes these steps including the details described below.

In the first step, parameters of the constitutive model are determined using results from laboratory tests on soil samples and data from in-situ investigations. The types of laboratory tests are usually model-specific and usually include tests for determination of stress-strain relationships of soils and liquefaction tests. Whereas most of the constitutive model parameters can be directly evaluated from the laboratory tests and in-situ data, some parameters are determined through a calibration process in which best-fit values for the parameters are identified in simulations of laboratory tests (element test simulations).

Following the selection of appropriate element types, mesh size and geometry, key issues in the definition of the numerical model are the determination of the initial stress state and selection of appropriate boundary conditions for the dynamic analysis including treatment of discontinuities. Stress-strain behaviour and liquefaction resistance of soils are strongly affected by the initial stress state, and therefore, an initial stress analysis is required to determine the static normal and shear stresses in all elements of the model. Selection of appropriate boundary conditions along end-boundaries and soil-pile-footing interfaces are equally important for an unconstrained response and development of relevant deformation modes.

Considering the geometry of the problem and anticipated behaviour, numerical parameters such as computational time increment and numerical damping are eventually adopted, and the dynamic effective stress analysis is then executed. The analysis is quite demanding on the user in all these steps including the final stages of post-processing and interpretation of results since it requires a good

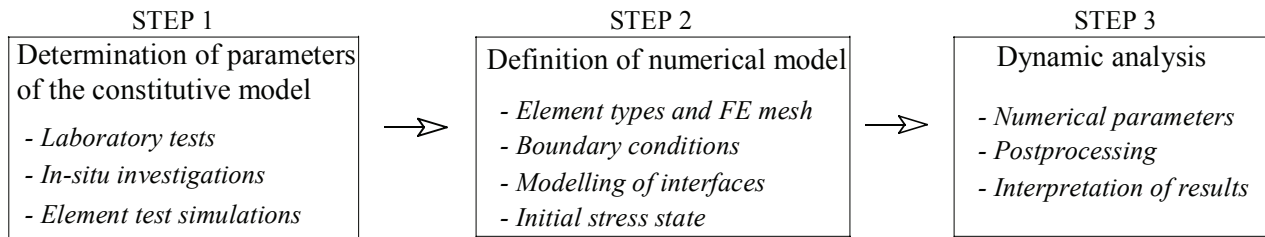


Figure 3. Principal steps in the implementation of effective stress analysis

command of the numerical tools and understanding of the problem and stress-strain behaviour of soils and piles.

3.2 Pseudo-Static Analysis

For preliminary assessment and design of piles, a simplified analysis may be more appropriate provided that such analysis: (i) captures the mechanism associated with liquefaction and lateral spreading; (ii) permits estimation of the inelastic response and damage to piles, and (iii) addresses the uncertainties associated with liquefaction and lateral spreading. The pseudo-static analysis of piles in liquefying soils introduced below was developed based on these premises.

Unlike the effective stress analysis which aims at simulating the very complex process in detail as it develops through time, the pseudo-static analysis aims at estimating the maximum pile response by using the salient mechanism of deformation and a relatively simple model. The key issue in such analysis is thus the selection of appropriate values for the deformational properties and loads on the pile that represent the soil and loading conditions at the time when the maximum response of the pile develops. As discussed in Section 2, the liquefaction characteristics and lateral loads on piles vary significantly in the course of ground shaking and are therefore quite different between the cyclic phase and subsequent lateral spreading phase of the pile response. For this reason, the cyclic phase and lateral spreading phase are treated separately in the pseudo-static analysis.

3.2.1 Soil-pile model

The most frequently encountered soil profile for piles in liquefied deposits consists of three distinct layers, as shown in Figure 4 where the liquefied layer is sandwiched between a non-liquefied crust layer at the ground surface and non-liquefied base layer. It is commonly assumed that during the

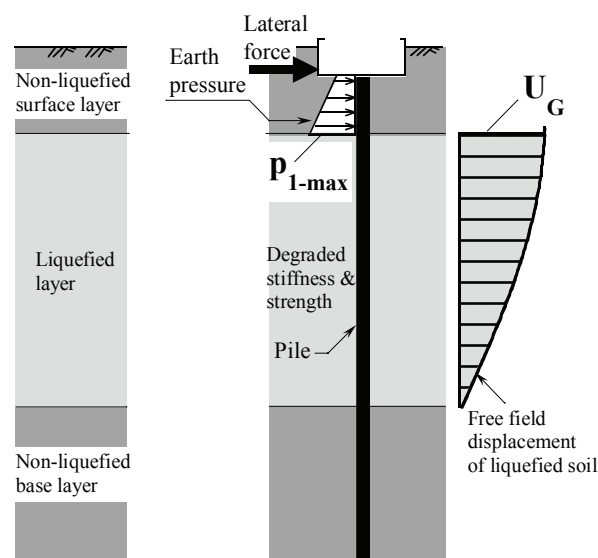


Figure 4. Simplified kinematic mechanism for piles in liquefiable soils

lateral ground movement in the course of shaking and spreading, the non-liquefied layer at the ground surface is carried along with the underlying spreading soil, and when driven against embedded piles, the crust layer is envisioned to exert large lateral loads on the piles, as indicated with the earth pressure in Figure 4. Thus, key features that need to be considered in the simplified pseudo-static analysis are the significant stiffness and strength reduction in the liquefied layer, excessive lateral movement of the liquefied soil, large lateral loads from the crust layer, and lateral load at the pile head due to inertial effects.

Based on these assumptions, both conventional discrete beam-spring models (Figure 5) and closed-form solutions based on simplified three-layer models (Cubrinovski and Ishihara, 2004) have been developed for the pseudo-static analysis of piles. The former approach permits more rigorous analysis because it allows variation of soil (spring) properties and irregular distribution of ground displacement throughout the depth; the latter approach, on the other hand, is appealing to the engineering practice because of its simplicity both in the preparation of input data and interpretation of results.

3.2.2 Key parameters and uncertainties

Input parameters for the three-layer model and adopted simple characterization of nonlinear behaviour of the soil and pile are shown in Figure 6. As indicated in Figures 5 and 6, the lateral ground displacement (kinematic load) and force at the pile head (load transferred through the upper foundation including inertial effects) are the only external loads applied to the soil-pile model. It is very difficult to reliably predict this loads, however, in particular the magnitude and spatial distribution of spreading displacements, and the combination of lateral ground displacement and inertial load relevant for the cyclic phase of the response.

The bilinear p - δ relationships for the soil shown in Figure 6 are defined by the initial stiffness through the conventional subgrade reaction approach and by the ultimate lateral soil pressure, p_{max} . The subgrade reaction coefficients k can be evaluated using empirical correlations based on the elastic property of the soil or SPT blow count while the ultimate lateral pressure for the non-liquefied layers can be estimated based on the Rankine passive pressure, as described in Cubrinovski and Ishihara (2004).

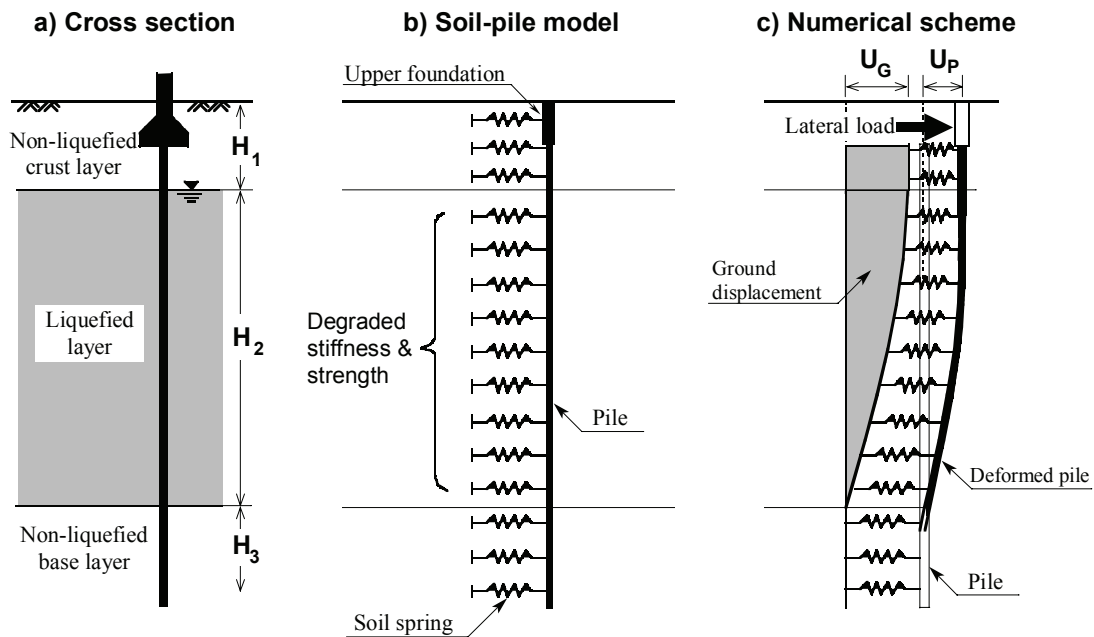


Figure 5. Typical FEM beam-spring model for pseudo-static analysis of piles

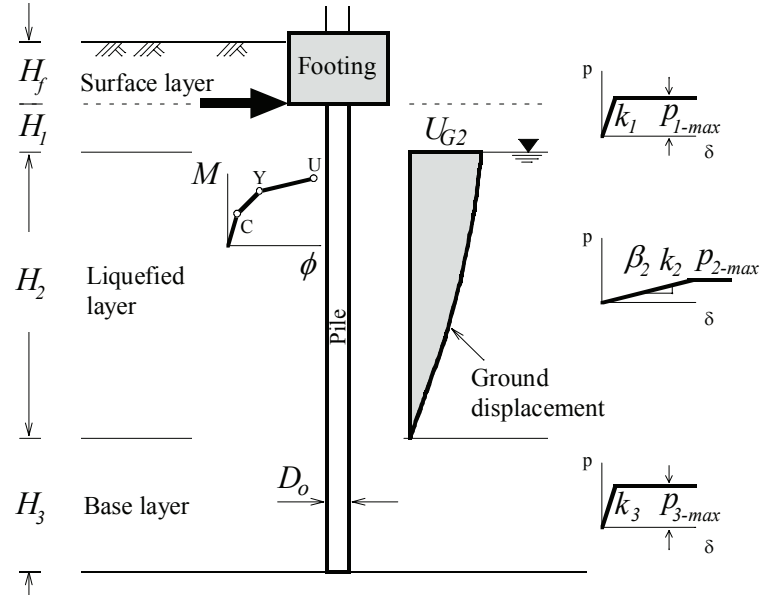


Figure 6. Characterization of nonlinear behaviour and input parameters for pseudo-static analysis

Here, particularly influencing for the pile response is the ultimate pressure from the crust layer, p_{1-max} because of the unfavourable point of application of this load and its large magnitude; for single piles under passive loading, this pressure was found to be 4.5 times the Rankine passive pressure (Cubrinovski et al., 2006).

The largest uncertainty is associated with the level of degradation in stiffness and strength of the liquefied soils. In the model, this degradation is accounted through the stiffness degradation factor β_2 and use of the residual strength of liquefiable soils for determining the ultimate pressure p_{2-max} . Experiments on piles and back-calculations from case histories indicate a large variation in these parameters. Typically, β_2 takes values in the range between 1/50 and 1/10 for cyclic liquefaction and between 1/1000 and 1/50 for lateral spreading (Tokimatsu and Asaka, 1998; Cubrinovski et al., 2006). The residual strength can be evaluated using the empirical correlation between the undrained strength and SPT blow count proposed by Seed and Harder (1991), but the scatter of the data is quite large and hence the value of the residual strength may vary significantly for a given SPT blow count, e.g. $S_u = 5$ to 27 for $(N_1)_{60} = 10$.

Because of the uncertainties in the values of key parameters of the model, it is critically important to conduct parametric studies and evaluate the pile response by considering a relatively wide range of relevant values for U_{G2} , β_2 and p_{2-max} in particular. In addition, pile group effects have to be considered since the pseudo-static analysis is commonly conducted by using a single pile model. Provided that variations in the applied loads and key parameters as above are properly considered, the pseudo-static analysis permits to estimate the range of pile response and expected level of damage to pile for the adopted ground and loading conditions. More details on the pseudo-static analysis of piles in liquefying soils can be found in Cubrinovski et al., 2007.

4. CONCLUDING REMARKS

The key characteristics of the dynamic effective stress analysis and pseudo-static analysis of piles in liquefying soils are summarized in Figure 7.

The effective stress analysis aims at detailed modelling of the complex soil-pile interaction in liquefied soils, and hence, this analysis procedure is quite complex and burdened by the large number

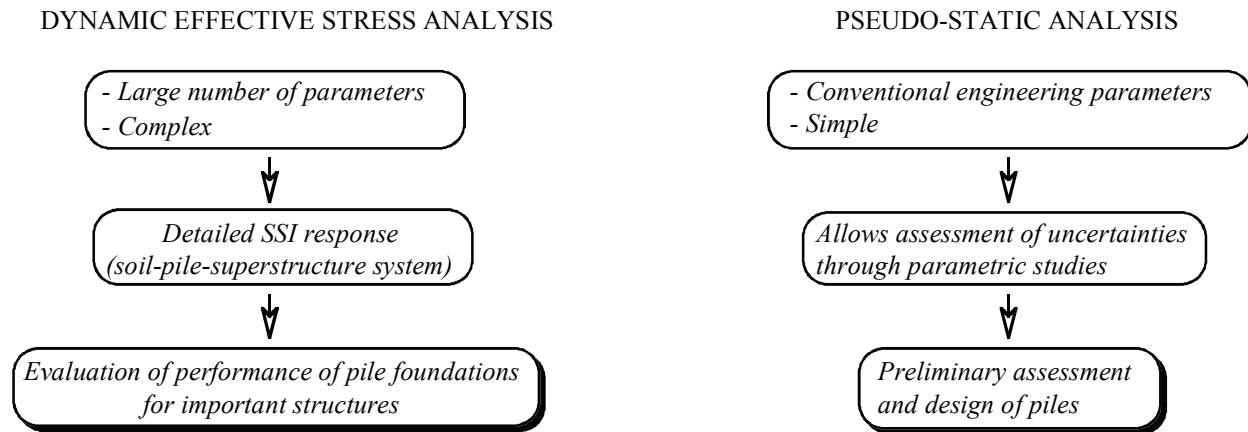


Figure 7. Features of effective stress analysis and pseudo-static analysis of piles in liquefying soils

of parameters and expertise needed for its execution. This analysis, however, permits detailed modelling of the stress-strain behaviour of soils and effects of excess pore pressures throughout the intense ground shaking and subsequent lateral spreading, and hence, allows accurate simulation of the soil-pile interaction including effects from the superstructure. For these reasons, the effective stress analysis is very suitable for a rigorous evaluation of the seismic performance of pile foundations of important structures.

The pseudo-static analysis is a simple design-oriented approach that uses conventional engineering parameters and modelling. For these reasons, it is suitable for preliminary assessment and design of piles. Because of the gross simplification of the problem and significant uncertainties associated with liquefaction and lateral spreading, however, the key parameters in the analysis are not uniquely defined, but rather they may vary over a wide range of values. Thus, when analysing piles with the simplified pseudo-static approach, parametric studies need to be conducted and in order to evaluate the possible range of responses and damage level to the pile. The cyclic phase and lateral spreading phase of the pile response should be treated separately in the pseudo static analysis.

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