（ 続紙 1 ）

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論文題目	Kinematic and inertial loading-based seismic assessment of pile foundations in liquefiable soil （液状化地盤における杭基礎の地盤変位・慣性力に基づく地震時挙動の評価）		

（論文内容の要旨）

The thesis presents various aspects of the performance of pile foundations in liquefied soils. An effort has been made to improve the current understanding of the pile foundations under large non-linear behavior. The thesis presents the major research finding in terms of results obtained from FEM analysis (2-D and 3-D) and total of 16 dynamic centrifuge tests developed. The centrifuge tests were carried out considering varying sloping inclination angles of the ground surface as well as for the cases involving plain ground conditions. The tests were developed considering the uniform and multi-layer soil deposit. The centrifuge experiments were carried out under harmonic excitations and transient waveforms having different earthquake characteristics in order to assess the performance of pile foundations under different conditions. There are eight chapters in total in the thesis.

Chapter 1 presents the introduction, background and fundamentals regarding the performance of pile foundation in liquefied soils.

Chapter 2 presents the studies available in the literature considering the analytical, numerical and experimental research. The performance of piled-foundations during the previous earthquakes is also reported in terms of case-studies. Chapter 2 also outlines the critical appraisal of the literature and limitations associated with the established research in the literature. At the same time, the detailed objectives and motivations associated with the present research are outlined. The methodology adopted to conduct the present research work is presented in terms of 2-D plane strain FEM analysis, Centrifuge model testing and 3-D FEM analysis.

Chapter 3 presents the brief introduction about the strain space multiple mechanism model, which is used further to assess the soil-pile-structural interactions. This chapter shows the applicability of the model by validating the responses involving lateral spreading using LEAP centrifuge database. The strain space multiple mechanism model is found replicate the desired dynamic stress-strain responses obtained during the centrifuge model testing involving lateral spreading events. The dilative response of the soil post-liquefaction was found to be very well captured during the earthquake loading. The degradation in initial stiffness of soil during an earthquake loading due to significant amount of excess pore pressure generation was appropriately simulated. Hence, it can be said that the modeling of soil elements using a strain space multiple mechanism model is effective in capturing the detailed soil response in a correct way during liquefaction. The model can further be used to assess the soil-structure interactions during liquefaction.

Chapter 4 presents the 2-D FEM to study the soil-pile kinematic interactions. Initially, the applicability of the strain space multiple mechanism model towards the prediction involving the liquefied soil is shown validating with the centrifuge test results considering soil-pile kinematic interactions. A frequency based assessment was carried out to study the soil-pile

kinematic interactions depending on the varying excitation frequencies associated with an earthquake for two earthquakes having significantly different arias intensity. For the cases involving lesser values of excitation frequency, soil did undergo excessive liquefaction resulting in pile to receive very little lateral displacement as compared to the free field displacement. However, with the increase in excitation frequency, pile undergo increased lateral displacement. The comparison of the obtained results with the BDWF analytical methodology highlighted shortcomings of the analytical solution to consider the non-linear soil-pile kinematic interaction involving the phenomenon of liquefaction. However, the kinematic interaction factor represented by rotation was found to be in a good agreement.

Chapter 5 presents the centrifuge model tests to study the influence of the sloping inclinations of the ground surface, which may lead to considerably different kinematic interactions with the piles. The chapter also shows the varying kinematic loads from larger monotonic to a small magnitude of monotonic moment over the course of multi-shaking events. This chapter also presents the influences of a multi-layer soil deposits involving the lateral spreading of soil. The centrifuge tests were carried out for a single and a 2X2 pile group and it is shown that the pile nearest to the upslope side was subjected to the least bending moments during the lateral spreading.

Chapter 6 presents the centrifuge test analysis, where the results obtained from 12 centrifuge tests are discussed. The tests were carried out considering a plain deposit, an inclined deposit taking into account the homogeneity and heterogeneity of the soil model. The centrifuge tests were carried out for only a soil-pile model, soil-pile-footing model and a soil-pile-footing superstructure model aiming to show the performance of pile foundations under different loading conditions. The tests were carried out for realistic earthquakes possible in real life scenario having different earthquake characteristics which might induce different level of damages on the soil-pile-structure system depending on their intensity. These tests were developed in order to assess the potential failure locations in pile consider various uncertainties associated with the problem. The tests indicated the pile response to significantly differ based on its location in a group

Chapter 7 presents the coupling mechanism of kinematic and inertial loading using a 3-D FEM program. The 3-D FEM code was used to analyze the soil-pile kinematic interactions and soil-pile-structural interactions on a plain ground. The results obtained were validated with the centrifuge experiments which showed reasonable agreement of the developed 3-D FEM meshing. From the analysis, moment was found to increase significantly with the increase in number of stories, with much prominent effects of coupled inertial-kinematic interactions being observed for a building having more no. of floors.

Chapter 8 enlists the conclusions and major research finding achieved from the present study. The future scope is also presented.

（続紙 ２ ）

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（論文審査の結果の要旨）

本論文は、液状化地盤における杭基礎の地盤変位・慣性力に基づく地震時挙動の評価を目的としたものである。液状化地盤における杭基礎の地震時挙動は複雑であり、これまでも様々な研究がなされているが、例えば、側方流動が生じる傾斜地盤における杭基礎の地震時挙動など不明な点も残されている。本研究では遠心模型実験や数値解析を用いて、傾斜地盤も含む液状化地盤における杭基礎の地盤変位・慣性力に基づく地震時挙動を評価した。

(1) 土・水連成の多孔質体理論とひずみ空間多重せん断モデルを用いた二次元および三次元有限要素解析を用いて液状化地盤中の杭基礎挙動を再現した。はじめに、水平地盤中の杭基礎の遠心模型実験に基づき、液状化地盤と杭を接続する相互作用バネのモデル化を含む数値解析の妥当性を確認した。その後、液状化地盤における杭の入力損失係数の周波数特性について、相互作用バネを導入した有限要素法と梁・バネモデルによる解析解を用いて評価し、梁・バネモデルの限界を示した。

(2) 飽和傾斜地盤のおける杭基礎の遠心模型実験では、液状化による側方流動地盤と杭基礎の相互作用の評価において地表面の傾斜を考慮することの重要性を明らかにした。側方流動の上流側に位置する杭では地盤変位による曲げモーメントの影響は小さくなるのに対して、側方流動の下流側に位置する杭では地盤変位による曲げモーメントの影響が大きくなることを明らかにした。側方流動地盤の運動エネルギーがこのような現象の原因と思われる。

(3) 一様地盤および多層地盤、水平地盤および傾斜地盤など多様な地盤条件における上部構造物を含む杭基礎の遠心模型実験を実施した。一様地盤と多層地盤では杭基礎の破壊モードが異なることを示した。また、杭基礎の破壊メカニズムは、地盤変位による運動学的相互作用と上部構造物の慣性力による相互作用に依存しており、その影響はフーチング内の杭の位置や深さ方向で異なることを示した。

以上のように、一様地盤や多層地盤、水平地盤や傾斜地盤、上部構造物の有無など多様な条件下で、液状化地盤中の杭基礎の地震時挙動を実験的・解析的に評価したものであり、今後の杭基礎の耐震設計において有益な知見を与えるものと評価でき、学術上、実際上寄与するところが少なくない。よって、本論文は博士（工学）の学位論文として価値あるものと認める。また、令和３年８月１１日、論文内容とそれに関連した事項について試問を行って、申請者が博士後期課程学位取得基準を満たしていることを確認し、合格と認めた。

なお、本論文は、京都大学学位規程第１４条第２項に該当するものと判断し、公表に際しては、当該論文の全文に代えてその内容を要約したものとすることを認める。