Long/Short-term Research Visit

2023LS-05

Disaster Prevention Research Institute
Kyoto University

Reliquefaction mechanism of sand specimen subjected to repeated shaking events using centrifuge modelling experiments

July 3 to September 29, 2023

Coordinator Gowtham Padmanabhan

[Project Report]

Date: 07. 22, 2024

* Check one of the boxes below.

☐ **General Collaborative Research**

☐ **International Collaborative Research**

☑ **Long/Short-term Research Visit**

☐ **New Exploratory Research**

(Project No. 2023LS-05)

To: Director of the Disaster Prevention Research Institute, Kyoto University,

[Principal Investigator]

Name : Gowtham Padmanabhan

Position : PhD Research Scholar

Affiliation : Indian Institute of Technology Roorkee

The results of the project are reported as follows.

Project Title : Reliquefaction mechanism of sand specimen subjected to repeated shaking events using centrifuge modelling experiments

Principal Investigator : Gowtham Padmanabhan

Affiliation : Indian Institute of Technology Roorkee

Name of the DPRI Contact Person : Prof. Ryosuke Uzuoka and Prof. Kyohei Ueda

Research Period / Duration of Stay : 07. 03, 2023 – 09. 29, 2023

Research Location / Location of Stay : Disaster Prevention Research Institute, Kyoto University

Number of the Participants in the Project : 04 (DPRI: 02 / non-DPRI: 02)

Anticipated Impact on Research and Education

Previous studies have significantly improved the knowledge on reliquefaction behavior and mechanism using physical modelling, whereas majority of these studies are limited to incremental or identical shaking pattern. Studies with the combination of foreshocks and aftershocks with mainshocks to investigate reliquefaction mechanism are not available. Moreover, these studies were conducted using 1g shaking table tests. Moreover, only limited studies are available to examine the behavior of pile group subjected to repeated shaking events. Studies on pile group subjected to repeated shaking events need to be performed to examine the performance of pile group subjected to soil reliquefaction. Considering these limitations, the present research aims to investigate the (1) reliquefaction behavior of free field model ground subjected to foreshocks-mainshock-aftershock-mainshock seismic sequence and compare it with an independent mainshock. (2) behavior of pile group in reliquefiable ground subjected to repeated shakings and its influence on excess pore pressure (EPP) compared to free field. A series of centrifuge model experiments were performed on free field and 2×2 pile group model grounds in Toyoura sand.

Research Report

(1) Purpose

This project aims to simulate different combinations of foreshock/aftershock with mainshock events to examine the reliquefaction mechanism. Dynamic centrifuge modelling is to be performed to simulate seismic motion in the prepared loose saturated sand specimen. The severity and extent of reliquefaction will be examined by continuous monitoring of generated excess pore pressure (EPP) and obtained maximum pore pressure ratio. The reliquefaction resistance obtained from sand densification and preshaking effect will be investigated for different shaking patterns.

(2) Summary of Research Progress

A series of centrifuge model experiments were performed in this study on levelled and mildly inclined sloping ground to investigate the sand reliquefaction behavior in free field and pile group models subjected to repeated shakings. Toyoura sand was used to prepare the model ground with 50% relative density and experimented at 50g centrifugal acceleration. Fig. 1 shows the centrifuge model container used in the study. A 2 × 2 pile group model was used to examine the response of piles and its effect on sand reliquefaction during repeated shakings. The seismic sequence represents the combinations of foreshocks and aftershocks associated with mainshock events. Tapered sinusoidal waveform was experimented at a constant 1 Hz shaking frequency, whereas the acceleration amplitude and shaking duration were twice for mainshocks than that of foreshocks and aftershocks. Acceleration time response, EPP, ground subsidence, bending moment and lateral displacement of the pile group were measured.

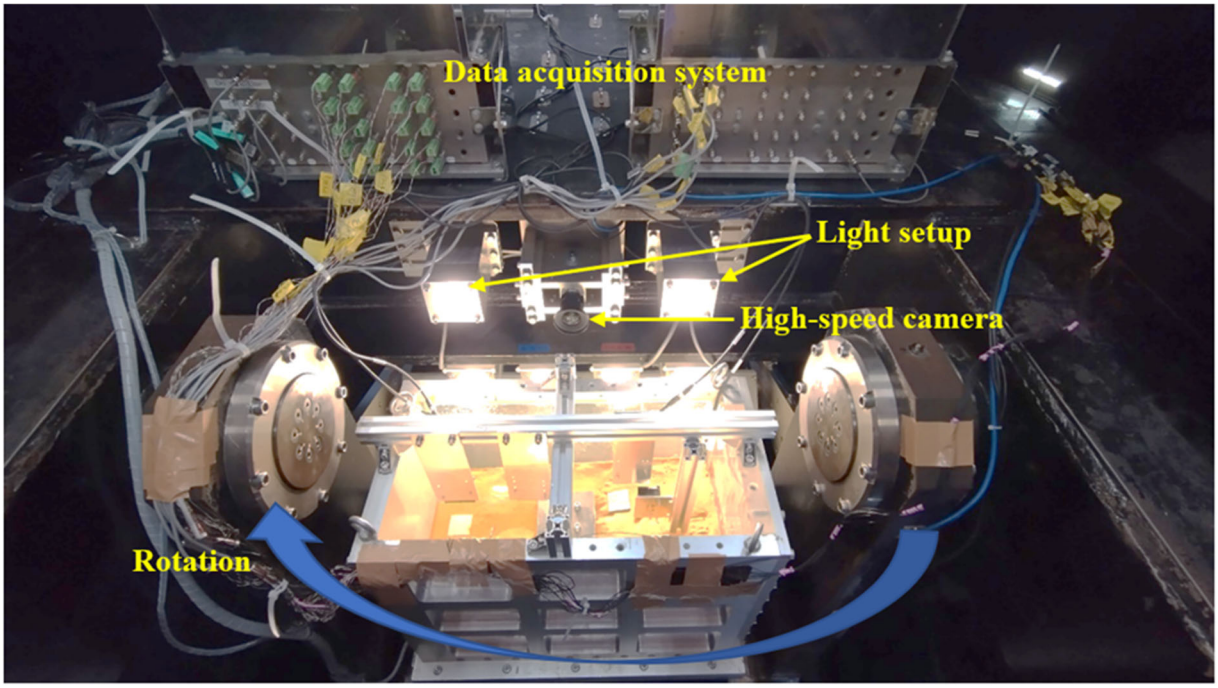

Fig. 1 Centrifuge model used in this study

(3) Summary of Research Findings

1. Application of foreshocks did not disturb the geometry of the sloping ground, whereas the mainshock disturbed the slope and transformed it as level ground. This was primarily due to significant generation of EPP, and lateral spreading triggered at the shallow depths. GeoPIV analysis has indicated that sand particles at shallow depths flow from upslope to downslope and apparently collapse the sloping ground model during the first mainshock.
2. Significant de-amplification was recorded in the sand deposit in both the free field and pile group model grounds. Unsymmetrical acceleration and the presence of shear-induced dilatancy spikes were also observed during mainshocks. These effects are primarily because of soil material damping and a greater amount of softening achieved during mainshocks due to liquefaction and subsequent reliquefaction.
3. Pile group model showed higher resistance to EPP generation and cumulative soil subsidence compared to free field model ground. For instance, peak EPP values were reduced by 15% and 25% at shallow depth during first and second mainshocks, respectively. In addition, presence of pile group model also delayed the time taken to achieve liquefaction and subsequent reliquefaction.
4. Complete liquefaction and reliquefaction during mainshocks (MS1 and MS2) has resulted in greater amount of soil softening and erased the beneficial effects of seismic preshaking achieved from prior foreshocks and aftershocks. This was recognized from the presence of unsymmetrical shear induced dilatancy spikes and complete reduction of recorded acceleration response, particularly at shallow depth (@2.5 m) and top surface.
5. First mainshock has contributed to the majority of the soil subsidence and apparently resulted in significant amount of sand densification in both the shaking sequences. However, the achieved sand densification and reduction in void ratio values did not contribute to liquefaction and reliquefaction resistance. This was associated with the increased magnitude of anisotropy due to repeated generation and dissipation of EPP. Apparent void ratio estimated using the advanced DIP technology were in good agreement with the real void ratio values estimated from the experiment. This technique offers the advantage of estimating void ratio values of soils where the physical means of void ratio estimation is not possible.

(4) Publications of Research Findings

1) Padmanabhan, G., Ueda, K., Maheshwari, B. K., and Uzuoka, R. (2024a). Reliquefaction behavior of sand and response of pile group subjected to repeated shaking sequence using centrifuge model experiments. *Soil Dynamics and Earthquake Engineering*, 182, 108741. https://doi.org/10.1016/j.soildyn.2024.108741

2) Padmanabhan, G., Ueda, K., Maheshwari, B. K., and Uzuoka, R. (2024b). Influence of Sloping Ground and Pile Group on Sand Reliquefaction Behavior using Centrifuge Modelling. *Canadian Geotechnical Journal*, (under review).

3) Padmanabhan, G., Ueda, K., Uzuoka, R., and Maheshwari, B. K. (2024c). Influence of Foreshock and Aftershock Events on Reliquefaction Potential of Saturated Sand Specimen using Centrifuge Modelling Experiments. *Japanese Geotechnical Society Special Publication*, 10(37), 1401-1406. https://doi.org/10.3208/jgssp.v10.OS-26-02

4) Padmanabhan, G., Maheshwari, B. K., Ueda, K., and Uzuoka, R. (2024d) Mesoscopic Mechanism Behind the Inherent Reliquefaction Resistance subjected to Repeated Earthquakes using Centrifuge Modelling and Advanced Digital Image Processing. *Soil and Foundations* (In pipeline).