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# Micro- and macro-observations of liquefaction of saturated sand around buried structures in centrifuge shaking table tests

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ABSTRACT

A novel experimental method was designed to study the micro-behavior of saturated sand around a buried structure in centrifuge shaking table tests under strong simulated earthquake loading, in addition to the traditional macro-measurements. One free field test was first carried out as a reference, followed by one test with a deep buried structure and one with a shallowly buried structure. During the tests with the buried structure, high quality pictures of moving sand around the structure were recorded by a newly developed image acquisition system. By analyzing the interesting pictures at reasonable intervals using an image analysis software, the evolutions of microstructural features were obtained such as the orientations of the long axes of particles, the orientations of contact normals between particles and the average contact number of the interesting group of particles. The results showed that the evolutions of the micro-features were consistent with those of the macro-measurements such as excess pore pressures and accelerations, which help illuminate the mechanism of sand liquefaction.



## 1. Introduction

A significant cause of damage in earthquakes is soil liquefaction, such as in the cases of the 1964 Niigata Earthquake [1], the 1964 Alaska Earthquake [2], the 1989 Loma Prieta Earthquake [3] and the 1995 Kobe Earthquake [4]. As a result, increased research attention has been paid to soil liquefaction. Among the available physical modeling techniques, geotechnical centrifuge testing has been one of the best methods for studies of soil liquefaction as it offers the ability to create relatively realistic full-scale stress–strain states and the evolutions of important physical quantities are relatively measurable [5].

Research on soil liquefaction by centrifuge modeling started as early as the 1980s [6–11]. The most influential and extensive research on soil liquefaction may have been the Project VELACS (VErification of Liquefaction Analysis by Centrifuge Studies) involving eight universities [12]. The project results helped to define a general mechanism of liquefaction and showed that similar results could be obtained when testing standard models at different centrifuge facilities. Kagawa et al. [13] further validated the similitude relations and modeling techniques that are commonly used in dynamic centrifuge tests, by comparing centrifuge tests with large-scale shaking table tests on some soil–pile–structure systems involving soil liquefaction.

Traditionally physical measurements in centrifuge model tests could only be collected at points where sensors were buried. Recently, researchers such as Gonzalez et al. [14] and Zeghal et al. [15] developed an identification technique to visualize the stress, strain and displacement fields with time using the measurements provided by sparsely distributed sensors in centrifuge models. Integrations of acceleration and interpolations of physical quantities were required. This may have been a great achievement for understanding the process of liquefaction from the macroscopic point of view. However, the macro-mechanical behavior of sand is always due to the evolution of microstructural behavior of sand under external loading. In addition, macro-mechanics which is defined on a finite volume of continuous media, may not explain highly localized phenomena such as piping that may occur during and after liquefaction. Microstructural observation thus may be more meaningful and helpful to reveal the mechanism of liquefaction [16]. Therefore, studies on the mechanism of liquefaction by characterizing the microstructural response of sand are greatly needed.

In this study, an image acquisition system was designed to record the process of sand liquefaction with high quality pictures. The interesting pictures at reasonable intervals were analyzed by an image analysis software GeoDip [17], which was specifically developed for the measurements of microstructural quantities for granular soils based on the digital image processing technique [18]. The evolutions of microstructural quantities for sand around the observed area were analyzed such as the orientations of the long axes of particles, the orientations of contact normals between

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particles and the average contact number of the interesting group of particles. Finally the micro–macro relationships for the sand behavior during liquefaction were discussed.

## 2. Centrifuge experiments

### 2.1. Test facilities

The centrifuge at Tongji University was used to carry out the tests. It has a maximum design acceleration of 200*g* and an effective radius of 3 m from the center of rotation to the base of the soil container. In order to simulate the free field boundary conditions, a laminar container [19,8,10,20] was used. It was made by Research and Development Center, Nippon Koei Co., Ltd., Japan. The inner dimensions of the laminar container were 500 mm (Length) × 400 mm (Width) × 560 mm (Height). It had 22 movable laminas, and the relative maximum displacement between two neighboring laminas was 5 mm. A strong and durable membrane with a thickness of 1 mm was attached to the base and walls of the laminar container so that some seismic waves could be absorbed by the walls and the container would be water-tight.

A model of a metro station was used as the underground structure. It also provided internal space for a high speed camera to take pictures during the tests. As the focus of the current research was sand liquefaction instead of structural deformation, the scaling laws for the stiffness of the metro station model did not need to be satisfied. It was important to keep the deformation of the metro station model to be extremely small so that the inside high speed camera would be able to work reliably under strong earthquake loading, therefore, an intact piece of high strength aviation aluminum was used to make the metro station model. A circular transparent window with a diameter of 60 mm was made of thick tempered glass. The high speed camera and LED lights were installed inside the structure, as shown in Fig. 1(a). Finally an aluminum plate with a thickness of 12 mm was fixed firmly on the top, as shown in Fig. 1(b). The final size of the metro station model was 214 mm × 214 mm × 214 mm. The total weight of the metro station model including everything inside was 16.1 kg. This resulted in an apparent unit weight of 16.1 kN/m$^3$ for the metro station model.

### 2.2. Image acquisition system

The image acquisition system included a high speed camera, an industrial control computer, a wireless router and a computer. The high speed camera (Model JAI CM-030GE-RA) can output 90 full frames per second in a continuous mode, with 640 (Horizontal) × 480 (Vertical) active pixel resolution. The industrial control computer was fixed on the platform near the centrifuge center, and was connected to the high speed camera through a network line. It was also connected to the computer in the main operating room through a wireless local area network. During the centrifuge tests, the researcher in the main operating room used the remote desk control program to operate the industrial control computer, which further controlled the high speed camera. The camera could take pictures of sand through the transparent glass window of the metro station model and store the pictures on the hard disk of the industrial control computer. After several trial experiments with great efforts, the image acquisition system was able to capture high quality pictures of moving sand during a simulated earthquake.

### 2.3. Soils employed

The sand used in the study was Fujian Standard Sand, a poorly graded medium sand with a mass–median–diameter of 0.35 mm, a coefficient of uniformity of 1.9 and a coefficient of curvature of 1.10.

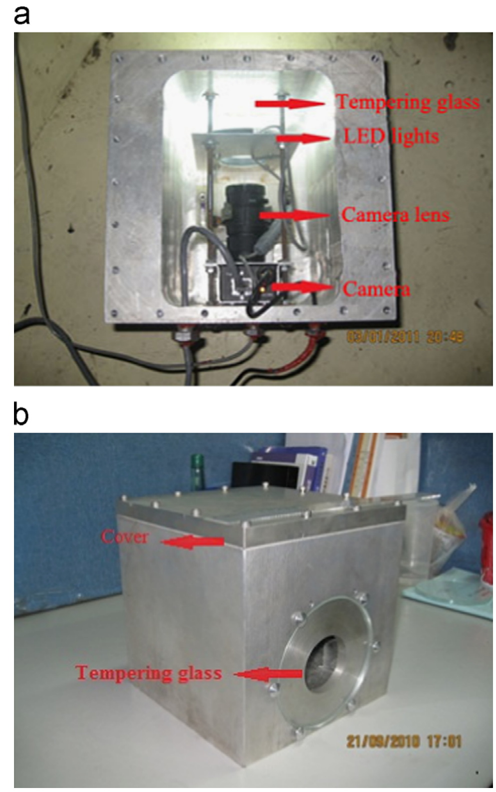


**Fig. 1.** Metro station model: (a) Inside; (b) Outside.

Its other engineering properties are: specific gravity = 2.643 g/cm$^3$; angle of internal friction = 32.8°; the maximum and minimum densities of dry sand were 1.74 g/cm$^3$ and 1.43 g/cm$^3$, respectively; and the maximum and minimum void ratios were 0.848 and 0.519, respectively.

### 2.4. Test design

A centrifugal acceleration of 50*g* was used in the tests. In centrifuge modeling of soil liquefaction, it is known that there is a conflict in the time scaling between the dynamic and consolidation events [21]. To overcome this problem, the permeability of sand is usually reduced by using a fluid that has a high viscosity, such as silicone oil or a water-soluble cellulose derivative [22,10]. In the current study, however, there is no specific prototype modeled and a specific viscosity is not a scaling requirement. With this consideration, water was used instead of highly viscous fluid.

Three centrifuge tests were carried out on sand under horizontal seismic loading. Test 1 simulated a free field condition, while Test 2 and Test 3 were for deep and shallowly buried structures, respectively. The layouts of the instrumentation are shown in Fig. 2. Note that the pictures for the microstructural evolution of sand were only available in Test 2 and Test 3 as the metro station with camera was only buried in these two tests.

### 2.5. Model construction

A wet pluviation process was used to create a uniform horizontal deposit of fully saturated sand with de-aired water at a relative density of 40%. Trial experiments were initially performed to ensure the sand uniformity and desired relative density. After the construction of the sand layer, a thin clay layer with extremely low permeability was placed on the sand layer to simulate a common site where liquefaction may occur.