EFFECTS OF IRREGULAR LOADING ON SAND RESPONSES BEFORE AND AFTER LIQUEFACTION INITIATION

W.S. Kwan\textsuperscript{1} and J. Huaz\textsuperscript{2}

ABSTRACT

Earthquake ground motions are often simplified to a series of harmonic loading cycle with a uniform amplitude in liquefaction evaluation, which essentially represents an earthquake loading by one point and surpasses the time domain characteristic of ground motions. This study utilizes a series of irregular loadings to study the effects of stress cycle order and loading frequency in timing of liquefaction initiation, final induced shear strain, and post-liquefaction monotonic response. The results show the order of stress is very important, but the effect of loading frequency is insignificant.

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Earthquake ground motions are often simplified to a series of harmonic loading cycle with a uniform amplitude in liquefaction evaluation, which essentially represents an earthquake loading by one point and surpasses the time domain characteristic of ground motions. This study utilizes a series of irregular loadings to study the effects of stress cycle order and loading frequency in timing of liquefaction initiation, final induced shear strain, and post-liquefaction monotonic response. The results show the order of stress is very important, but the effect of loading frequency is insignificant.

Introduction
Sand Liquefaction is a major urban risk for seismic prone cities like Los Angeles. Liquefaction assessment typically involves comparisons of earthquake loading and sand resistance, and estimations of consequence such as settlement and lateral spreading. While the past research efforts have been focused on the characterization of soil resistance to liquefaction, relatively less attention has been given to the characterization of earthquake loading and stress-strain behavior of liquefied sand. Earthquake loading is typically modeled as a harmonic motion, but it is important to gain insight into sand responses before and after liquefaction initiation under realistic ground motions. Before physically modeling the complex transient ground motion loadings and learning its corresponding effects, it is essential to start with relatively simple wave forms to isolate the effects of time-domain characteristics of ground motions. Under a Cyclic Simple Shear (CSS) setup, this study adopts a series of cyclic loadings, which include nine uniform loading cycles at 0.1 Hz, and a double-amplitude loading cycle at various locations (2nd, 4th, 6th, 8th, and 10th) with two different frequencies (0.1 and 0.01 Hz) on reconstituted Siri sand specimens at a medium density (Dr = 45 to 57%). In accordance with the most popular liquefaction evaluation procedure [1], the earthquake loading is the same for the ten irregular loadings described above since all of them have the same maximum amplitude of loading.

Liquefaction induced lateral spreading involves understanding in post-liquefaction stress strain responses that typically start with a flat and low stiffness then begin to dilate until reaching ultimate strength. The low stiffness region ranges from a few to several tens of percent of strain [2]. The change from the no-strength phase to dilative phase is due to particle rearrangement from cyclic loading, especially loading after liquefaction-initiation. When the cyclic loading is continued after liquefaction initiation (rₐ = 1), the shear strain will keep on growing while the

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excess pore pressure is very close to the initial vertical effective stress. With an increasing amplitude of shear strain following the liquefaction initiation, each cycle of loading is likely to increase disturbance and destroy the fabric of sand created at the time of specimen preparation, and therefore weaken the post-liquefaction monotonic response [3]. This study investigates the effects of post-liquefaction loading on the monotonic responses.

Many studies have investigated the effects of loading frequency in liquefaction potential of reconstituted sand specimens in triaxial setups, but reached contradictory conclusions. [4] performed tests on gravelly soil at frequency range of 1 to 20 Hz and [5] performed cyclic triaxial tests on Monterey No. 0 Sand at frequency range of 2 to 25 Hz, and both conclude that the effect of loading frequency is negligible. [6] performed tests on Monterey No. 0 Sand at frequency ranges of 0.001 to 1 Hz; [7] investigated the effect of loading frequency with Ahmedabad sand with range of 0.1 to 0.5 Hz; [8] performed tests with irregular loading on sand specimens at a frequency range of 0.05 to 6 Hz. The three studies [6, 7, 8] all conclude that the effect of loading frequency is significant, and liquefaction resistance decreases with an increase in loading frequency. This study investigates the effect of frequency in a simple shear setup with a range from 0.01 to 0.1 Hz.

For this experimental study, sand responses were investigated through two consecutive stages: 1) Irregular cyclic loading; 2) Monotonic loading phase on liquefied sand if liquefaction had initialized. This paper shows the results that focus on the effects of peaking cycle location and frequency on sand responses before and after the end of the first stage cyclic loading: 1) Generation of excess pore pressure and induced cyclic shear strain from the nine plus one cycles; 2) The effects of loading frequency at the dominant pulses and 3) Post-liquefaction stress-strain behavior followed the end of Irregular loading. Results show that frequency has insignificant effect, and the location of peaking cycle affects the timing of liquefaction initiation (the earlier the peaking cycle, sooner liquefaction occurrence) and post-liquefaction responses (the earlier the peaking cycle occurs, the longer the low stiffness phase is).

Testing Program

Ten CSS tests are presented in this paper. The Siri sand specimens were reconstituted using moist tamping method, and soil properties of Siri sand are shown in Fig. 1 [9]. The tests were performed using a Global Digital Systems (GDS) made EMDCSS apparatus that can accept use-defined loading so the irregular loadings were applied without interruption. NGI-type wired-reinforced membranes (C=1.5) were used for the specimen’s horizontal confinement. Soil specimens were consolidated to 196 kPa, and then loaded with irregular loadings at constant volume. If a soil specimen was liquefied, a monotonic loading stage was followed under undrained condition (except Test#8).

Testing Results

Fig. 2 shows the ten input shear stress histories (a and g), and the test results including the cyclic loading stage and post-liquefaction monotonic shearing stage. Since Test#5 and Test#10 (10th cycle double peak loading) have not reached liquefaction initiation, so there is no monotonic stage following the cyclic loading stage. Figs. 2b and 2h show very consistent results in pore pressure
Figure 2. Test results of ten irregular loading tests. a-f: 0.1 Hz double amplitude peaking tests (Test#1-5). g-l: 0.01 Hz double amplitude peaking tests (Test#6-10). Eight tests, #1-4 and #6-9, have reached liquefaction initiation; two tests, #5 and #10, have not reached liquefaction initiation.
generation, which implies consistency of the soil specimens. Figs. 2b, 2h, 2c, and 2i show that the timing of liquefaction initiation and overall induced shear strain are strongly dependent on the location of peaking cycle. The earlier the peaking location (2\textsuperscript{nd}) occurs, the sooner liquefaction is initiated, and the higher the amount of shear strain is induced at the end of loadings. Figs. 2f and 2l show the post-liquefaction stress-strain responses are also dependent on the location of the peaking cycle. The earlier the peaking location occurs, the sooner liquefaction initiation is, and the weaker the post-liquefaction response is (i.e., longer duration in the no strength phase).

Fig 3. compares the 0.1 Hz versus 0.01 Hz double amplitude peaking cycles in terms of generated peak-to-peak pore pressure and shear strain. The results show that 0.01 Hz cycles generally generate more excess pore pressure and shear strain than those from 0.1 Hz, but the differences are insignificant.

**Conclusions**

The irregularly loaded CSS tests presented in this paper show that the loading frequency has insignificant effect on liquefaction potential, and the order of stress cycle is important to liquefaction initiation timing, and post-liquefaction stress-strain response even though the current stress-based liquefaction evaluation procedure does not consider the order of stress cycle.

**Acknowledgement**

This soil testing program was conducted at the laboratory of Norwegian Geotechnical Institute (NGI) during the first author’s Postdoctoral study. The supports from NGI are greatly appreciated.

**References**