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Energy-based evaluation of liquefaction potential under non-uniform cyclic loading

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ABSTRACT

Uniform cyclic loading is commonly used in laboratory tests to evaluate soil resistance to earthquake-induced liquefaction, even if the cyclic stresses induced by earthquakes in the field are highly irregular. This paper discusses the use of stress and energy-based approaches to evaluate the liquefaction resistance of sand under irregular loading. Results of undrained cyclic triaxial tests including a large-amplitude singular peak loading cycle are presented and compared to those obtained using uniform loading. Although samples are subjected to loading patterns which would have been deemed equivalent by conventional stress-based methods, the number of cycles required to trigger liquefaction strongly depends on the amplitude and location of the peak within the loading history. Conversely, a unique relationship exists between the accumulation of dissipated energy per unit volume, computed using stress and strain measurements, and the observed residual pore water pressure build-up for all tests, throughout the entire cyclic loading application. This demonstrates that conventional laboratory tests using uniform loading conditions can be employed to determine liquefaction resistance if their interpretation is carried out based on energy principles.

1. Introduction

Earthquake-induced soil liquefaction has been a subject of intensive research during the last decades. This phenomenon involves significant loss of the soil's strength and stiffness due to excess pore water pressure build-up, as well as a concurrent dissipation of energy mainly by frictional mechanisms [33]. Based on the assumption made by Nemat-Nasser and Shokooh [32] that pore water pressure generation can be uniquely related to the cumulative energy dissipated per unit volume of soil up to the onset of liquefaction, several energy-based procedures for the evaluation of liquefaction potential of sand have been developed (e.g. [12,9,28,16,14,26]). According to Liang et al. [30], when compared to alternative stress-based (e.g. [38,37,20]) and strain-based (e.g. [15]) approaches, energy-based methods have the strong advantage of accounting for both induced shear stress and strain, thus avoiding the need to decompose the irregular shear stress (or strain) time histories to find an equivalent uniform loading.

In order to verify the suitability of the energy concept for liquefaction evaluation, several laboratory testing programmes were designed to verify the uniqueness of the relationship between pore water pressure build-up and dissipated energy per unit volume. In particular, a series of undrained cyclic triaxial tests in which the energy content of the specimens was continuously monitored were performed by Simcock et al. [39]. A greater energy dissipation was observed as excess pore water pressure increased. Further evidence on the satisfactory relationship between these quantities was presented by Towhata and Ishihara [41]. Indeed, based on results of torsional shear tests using different loading patterns, the authors concluded that the relationship between excess pore water pressure generation and dissipated energy per unit volume is unique throughout the entire test, being independent of the shear stress path followed in each test. A similar conclusion was drawn by Baziar and Sharafi [8] and Kokusho [26] when analysing results of undrained hollow cylinder torsional tests and undrained cyclic triaxial tests, respectively.

The laboratory testing programme performed by Figueroa and his co-workers [16,30,14] is also noteworthy. These authors concluded that the energy required for the onset of liquefaction – known as capacity energy – was practically independent of the loading pattern used (uniform and non-uniform) and type of test performed (torsional cyclic shearing and centrifuge experiments). These results seem to be confirmed by the recent study of Polito et al. [35], where cyclic triaxial tests using three different uniform loading shapes (sinusoidal, trian-

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Nomenclature

a_{av}	average of the representative values of the acceleration time-history of a ground motion (analysis of real earthquake records)
a_{max}	maximum peak acceleration of a ground motion (analysis of real earthquake records)
C_u	uniformity coefficient
D_{50}	mean grain size
e	void ratio
e_0	void ratio before shearing
e_{min}, e_{max}	minimum and maximum void ratios, respectively
g	acceleration of gravity (≈9.81 m/s^2)
G_s	density of soil particles
k	total number of points in which a stress-strain loop is discretised
M_w	moment magnitude
N	number of loading cycles
N_{liq}	number of loading cycles required to the onset of liquefaction
N_p	number of the loading cycle at which the peak load was applied
N_{tot}	total number of representative cycles of the acceleration time-history of a ground motion (analysis of real earthquake records)
$N(a_{max})$	representative cycle at which the maximum acceleration occurred (analysis of real earthquake records)
p'	mean effective stress
p'_0, p'_p	mean effective stress after consolidation and at the moment the peak loading cycle was applied, respectively
q	deviatoric stress or deviatoric stress oscillation (two-way symmetrical stress reversal loading)
q_p, q_u	deviatoric stress oscillation of the peak loading cycle and of the remaining uniform loading, respectively
q_{max}	maximum deviatoric stress
r_u	excess pore water pressure ratio
$(r_u)_{res}$	residual excess pore water pressure ratio (i.e. corresponding to zero deviatoric stress)
α	azimuth of a ground motion, i.e. the angle from North to the orientation of the sensor component, in clockwise direction
δW	dissipated energy per unit volume per cycle
Δu	excess pore water pressure
$(\Delta u)_{res}$	excess pore water pressure corresponding to zero deviatoric stress
ΔW	accumulation of dissipated energy per unit volume
$\Delta W_{e;liq;max}$	accumulation of maximum stored elastic energy per unit volume until the onset of liquefaction
ε_a	axial strain
$\varepsilon_{a;\,max}$	maximum amplitude of axial strain
ε_{DA}	double amplitude axial strain
σ'_0	isotropic effective stress after consolidation

gular and rectangular), as well as two irregular patterns where performed.

In this paper, a laboratory testing programme was carried out using a non-uniform loading pattern absent from previous research, characterising shock-type earthquakes – i.e. ground motions where the maximum induced shear stress is clearly higher than the remaining shear stress history [22]. This experimental programme aimed at comprehensively investigating the applicability of stress- and energy-based approaches to the prediction of the effect of a singular large-amplitude peak load on the liquefaction resistance of sand. Indeed, the study of a large number of earthquake records has shown that the location and magnitude of the peak acceleration varies widely between seismic events. As a result, in this paper, undrained cyclic triaxial tests in which a singular peak loading cycle of larger amplitude was applied within an otherwise uniform loading pattern were performed. Both the location and magnitude of the peak loading cycle were systematically varied in each test, highlighting the influence of an earlier or later crossing of the phase transformation line [23] on the liquefaction resistance of sand. Moreover, conventional undrained cyclic triaxial tests using uniform loading were also carried out in order to assess whether stress-based methods can adequately deal with the irregularity of loading. The stress oscillations imposed in these conventional tests were chosen to be equivalent to those imposed in the non-uniform triaxial tests in accordance with the methodology proposed by Seed and Idriss [38] and Idriss and Boulanger [20]. Based on the obtained results, it is discussed whether or not conventional laboratory tests using uniform loading can be reliably used for the evaluation of liquefaction resistance. The complete set of experimental results are subsequently interpreted using an energy-based approach. The relationships between the excess pore water pressure generation, the observed double amplitude axial strain and the accumulation of dissipated energy per unit volume are examined throughout the entire test. Conclusions are drawn about the ability of energy-based methods to accommodate the loading irregularity observed in real earthquake

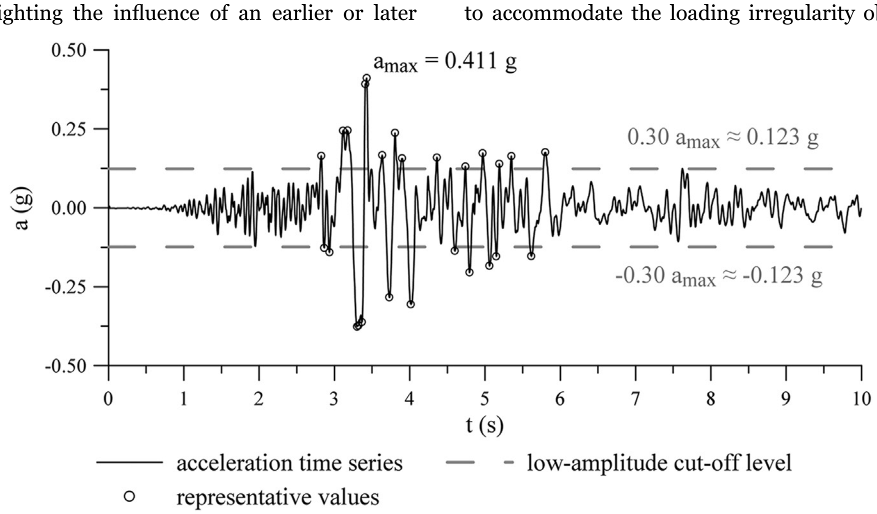

Fig. 1. Representative horizontal acceleration peak values for the 1989 Loma Prieta earthquake recorded at Gilroy Array Station 1 in the North-South direction.