Soil Dynamics and Earthquake Engineering 97 (2017) 25–36

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Effect of initial relative density on the post-liquefaction behaviour of sand

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ARTICLE INFO

Keywords:
Liquefaction
Multi-stage soil element test
Post-liquefaction behaviour
Saturated sand

ABSTRACT

Understanding the behaviour of soils under cyclic/dynamic loading has been one of the challenging topics in geotechnical engineering. The response of liquefiable soils has been well studied however, the post liquefaction behaviour of sands needs better understanding. In this paper, the post liquefaction behaviour of sands is investigated through several series of multi-stage soil element tests using a cyclic triaxial apparatus. Four types of sand were used where the sands were first liquefied and then monotonically sheared to obtain stress-strain curves. Results of the tests indicate that the stress-strain behaviour of sand in post liquefaction phase can be modelled as a bi-linear curve using three parameters: the initial shear modulus (G_1), critical state shear modulus (G_2), and post-dilation shear strain ($\gamma_{post-dilation}$) which is the shear strain at the onset of dilation. It was found that the three parameters are dependent on the initial relative density of sands. Furthermore, it was observed that with the increase in the relative density both G_1 and G_2 increase and $\gamma_{post-dilation}$ decreases. The practical application of the results is to generate p-y curves for liquefied soil.

1. Introduction

Liquefaction is one of the most dramatic phenomena which occur in saturated loose sands during an earthquake. Consequently, structures built on top or within the liquefied ground may fail due to either: increased lateral soil pressure, loss of bearing capacity, ground settlement due to post-liquefaction reconsolidation and other associated ground deformations. These consequences depend on a number of various factors, such as site conditions, earthquake characteristics, and the nature of the structure on the site.

The impact of liquefaction to the built environment was introduced to the geotechnical engineering community after the two main earthquakes in 1964 (i.e. Niigata earthquake, Japan and Alaska earthquake, United States). Since then, much research has been carried out to investigate the liquefaction phenomenon using laboratory experiments, model testing and analytical/numerical methods. Most of this research has focused on understanding the mechanism of pore water pressure development and undrained behaviour of sands leading to liquefaction triggering [10,16,4,24,6,9,26]; however, there is a little research done to date in terms of understanding the post-liquefaction response of sand. Yasuda et al. [31] carried out a series of multi-stage soil element tests on Toyoura sand at different relative densities. Vaid and Thomas [27] carried out a similar test procedure on Fraser River sand with different relative densities and effective confining stress. In these works, the soil samples were made to liquefy first by applying cyclic loading followed by monotonic shearing under a certain constant strain rate. The results indicated that the liquefied sand showed nearly zero stiffness up to a particular level of strain; after which the soil resistance increased dramatically with strain. Focusing on the effect of axial strain, relative density and effective confining stress on the post-liquefaction behaviour of sands, Sitharam et al. [23] carried out cyclic triaxial tests on Ahmadabad sand (India). Shamoto et al. [22], Hyodo et al. [7], and Kokusho et al. [11] also carried out similar studies on post-liquefaction behaviour. The main conclusion is that the undrained stress-strain response of post-liquefaction sand is dependent on relative density of soil. Furthermore, initial confining pressure of the sample has an insignificant influence on the post-liquefaction undrained stress strain response of sands.

After an earthquake, the behaviour of the liquefied soil which is underneath the weight of soil from the upper layer or superstructure would be dilative [25,27]. As a result, the hardening response observed at large strains can be explained in terms of the dilative response of soil under undrained monotonic shearing. According to Thomas [25], the stress-strain behaviour of sand at post-liquefaction stage can be divided into three stages as shown in Fig. 1: the first region would start immediately after liquefaction (i.e. zero effective stress) and consequently, would indicate zero shear stiffness. Due to the undrained monotonic load, the shear stiffness is gradually increased with the increase in strain, representing the second region. In the third region, the stress-strain curve becomes linear, which represents constant shear

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http://dx.doi.org/10.1016/j.soildyn.2017.02.007
Received 8 September 2016; Received in revised form 7 December 2016; Accepted 25 February 2017
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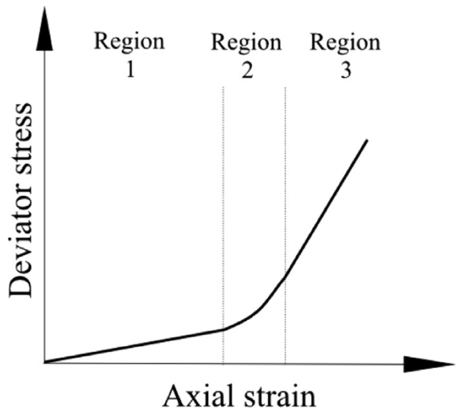

Fig. 1. Post liquefaction stress strain curve proposed by Thomas [25].

stiffness.

The trends of the post-liquefaction stress-strain behaviour were investigated by different researchers. The bi-linear behaviour of the stress-strain curve at post-liquefaction was proposed by Yasuda et al. [29]. Recently, Dash [5], Lombardi and Bhattacharya [14], Lombardi et al. [15] proposed a simple post-liquefaction stress-strain curve defined by four key parameters: the take-off shear strain, initial shear modulus, critical state shear modulus, and maximum shear stress.

In this paper, several series of multi-stage soil element tests were conducted on four different types of sand where the specimens were subjected to undrained monotonic shearing after full liquefaction has been achieved. The sands considered were reconstituted at different relative densities, consolidated under various effective confining stresses, and were made to liquefy under different levels of cyclic shear stress ratio (CSR). The obtained post-liquefaction stress-strain curve was modelled in terms of the initial shear modulus (G_1), critical state shear modulus (G_2) and a parameter called post-dilation shear strain ($\gamma_{post-dilation}$), which is related to the dissipation of excess pore water pressure during the monotonic shearing of the liquefied sand. Based on the tests reported in this study of Sitharam et al. [23] and Lombardi et al. [13] it appears that post-liquefaction stress-strain curve of sand, are mainly affected by the initial relative density while the effect of initial effective confining stress was negligible (at least within the range considered in the tests). Thus, the parameters to model the post-liquefaction behaviour can be expressed in terms of the initial relative density of the sand. Such a simplified way of estimating the stress-strain curve of liquefied sand has many applications, such as in investigating lateral spreading of liquefied soil, studying foundation settlements and estimating p-y curves for the analysis of soil-structure interaction.

2. Materials and experimental method

Four types of sand were used to carry out the experimental investigation; two commercially available sands, Redhill-110 sand (UK) and silica sand No. 8 (Japan), which are typically used in laboratory studies; and two natural sands from India, Assam sand and Ganga sand. Fig. 2 shows the microscopic photos of the sands while their index properties based on ASTM standards (D4253, 2006; D4254, 2006; and D854, 2010)[1–3] are listed in Table 1. The grain size distribution curves of the sands are shown in Fig. 2, where it is observed that all sands have uniform grain size distribution and low fines content. Also indicated in Fig. 3 the range of grain size distributions of sands which are deemed to have a high potential for liquefaction as well as the potential for liquefaction. This graph is based on past historical earthquakes in Japan and stipulated in the design code for port and harbour facilities [18].

Several series of advanced soil testing (i.e. multi-stage soil element test) using cyclic triaxial apparatus were carried out at the SAGE (Surrey Advanced Geotechnical Engineering) Laboratory at the University of Surrey. In these experiments, the samples were prepared using the dry pluviation method. Silicon grease was applied around the pedestal in order to decrease the friction between the membrane and the pedestal. The sample size was 100 mm in diameter and 200 mm in height. After preparing the specimen, small negative pressure of −10 kPa was applied in order to remove the mould from the sample.

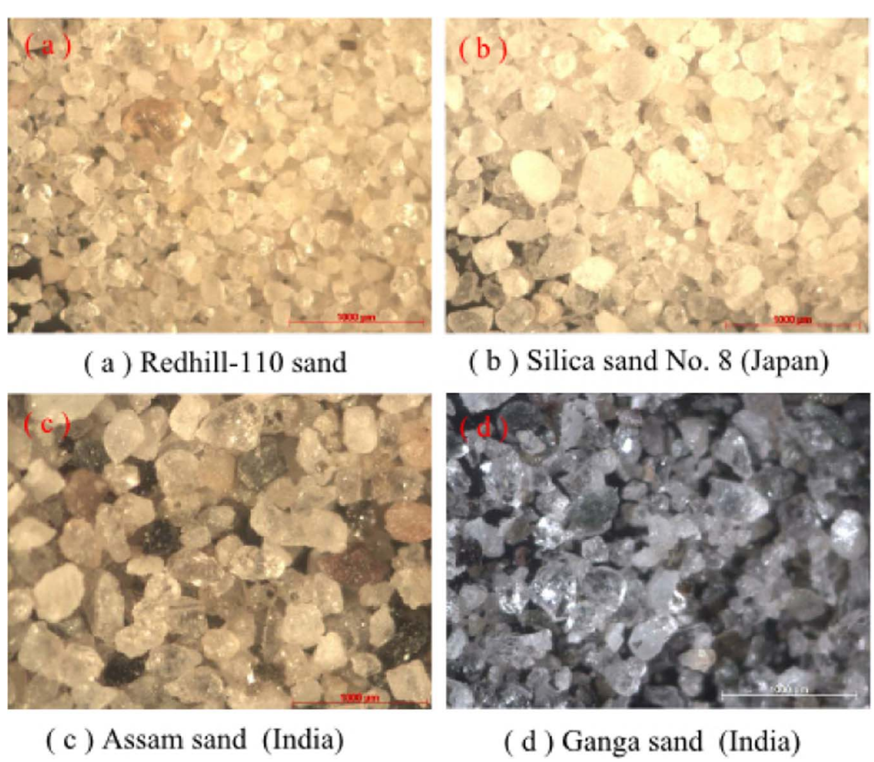

Fig. 2. Microscopic photo of sands used in the tests: (a) Redhill-110 sand; (b) Silica sand No. 8 (Japan); (c) Assam sand (India); and (d) Ganga sand (India).