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Full Length Article

Dynamic properties and liquefaction behaviour of cohesive soil in northeast India under staged cyclic loading

Shiv Shankar Kumar*, A. Murali Krishna, Arindam Dey

Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam, 781039, India

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A B S T R A C T

Estimation of strain-dependent dynamic soil properties, e.g. the shear modulus and damping ratio, along with the liquefaction potential parameters, is extremely important for the assessment and analysis of almost all geotechnical problems involving dynamic loading. This paper presents the dynamic properties and liquefaction behaviour of cohesive soil subjected to staged cyclic loading, which may be caused by main shocks of earthquakes preceded or followed by minor foreshocks or aftershocks, respectively. Cyclic triaxial tests were conducted on the specimens prepared at different dry densities (1.5 g/cm^3 and 1.75 g/cm^3) and different water contents ranging from 8% to 25%. The results indicated that the shear modulus reduction (G/G_{max}) and damping ratio of the specimen remain unaffected due to the changes in the initial dry density and water content. Damping ratio is significantly affected by confining pressure, whereas G/G_{max} is affected marginally. It was seen that the liquefaction criterion of cohesive soils based on single-amplitude shear strain (3.75% or the strain at which excess pore water pressure ratio becomes equal to 1, whichever is lower) depends on the initial state of soils and applied stresses. The dynamic model of the regional soil, obtained as an outcome of the cyclic triaxial tests, can be successfully used for ground response analysis of the region.

1. Introduction

Several studies and earthquake evidences indicated the occurrence of liquefaction in loose saturated sand deposits at shallower depths. Subjected to cyclic loading, the increase in pore water pressure (PWP) causes the reduction in shear strength due to the release of contacts between the particles. Apart from sandy soils, which are more commonly prone to liquefaction, natural soil deposits in the field comprises different types of soil and soil-mixtures such as silty-sand, silt, silty-clay, clay or any combinatorial soils. Among these soils, cohesive soil, owing to its small particle size and substantially low void ratio, is considered to be more resistant to liquefaction in comparison to the cohesionless soils in the event of an earthquake. However, severe damages of structures, such as large deformation of ground and collapse of fills, were observed due to failure of clay base layers during earthquakes (Hyodo et al., 1993). Therefore, before designing the aseismic structures on clay or silty-clay soil, geotechnical engineers should know the liquefaction susceptibility and the dynamic properties of such soils as well. Several studies reported the parameters influencing the dynamic properties of cohesive soil (Hardin and Drnevich, 1972a; Kokusho et al., 1982; Ishibashi and Zhang, 1993; Dutta and Saride, 2015; Sas et al., 2015; Gu et al., 2016), i.e. the effective confining pressure, shear strain, plasticity index, frequency of loading, number of loading cycles, void ratio, degree of saturation, overconsolidation ratio and particle size.

Researchers have also conducted cyclic tests (e.g. resonant column tests, cyclic triaxial tests and cyclic simple shear tests) to anticipate the liquefaction behaviour of silt, sand, clay, silty-clay and silty-sand soils (Kokusho et al., 1982; Vucetic and Dobry, 1991; Matsui et al., 1992; Ansal et al., 2001; Okur and Ansal, 2007; Dutta et al., 2017; Lei et al., 2017; Price et al., 2017; Thian and Lee, 2017; Xiao et al., 2018). It was concluded that the behaviour of soils, i.e. the degradation in stiffness or cyclic strength, is strongly influenced by the rise of PWP, governed by the soil plasticity and loading frequency. The increase in PWP in saturated cohesive soil is relatively less than that in the cohesionless soil, because of the cohesion between the soil particles offering higher resistance to particle separation during seismic shaking. Therefore, the cumulative pore pressure may not be the only suitable reason to

* Corresponding author.
E-mail addresses: shivshankar.mit@gmail.com, k.shiv@iitg.ernet.in (S.S. Kumar).
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define the cyclic failure criterion for clay or cohesive soils (Li et al., 2011). Bray and Sancio (2006) reported that the plasticity index (PI) is a better indicator of the liquefaction susceptibility of cohesive soil, while Boulanger and Idriss (2006) described the failure criterion in terms of cyclic softening. Since pure clayey soils are not susceptible to liquefaction, the amount of clay present in the soil is one of the good indicators towards liquefaction susceptibility of such soil (Sancio et al., 2003; Tan et al., 2013). The variations in clay content can be best represented by PI. Several other liquefaction criteria were also proposed by the researchers, one of which is the Chinese criterion (Wang, 1979). According to this criterion, soil is susceptible to liquefaction if clay soil contains 15%–20% particles (by weight) smaller than 0.005 mm, $LL = 21\%–35\%$, $PI = 4\%–14\%$ and $w_c/LL > 0.9$. In a similar fashion, Andrews and Martin (2000) modified the upper limit of LL to be 32% and size of fine contents to be smaller than 0.002 mm (i.e. less than 10% by weight) while redefining the same criterion. Studies on the cohesive soil reported a failure criterion based on the number of loading cycles at which an arbitrarily predetermined double amplitude (DA) failure-axial-strain (e.g. 2.5%, 3%, 5%, 10%, 15% or 20%) is reached (Prakash and Sandoval, 1992; Yasuhara et al., 1992; Hyodo et al., 1994; Perlea, 2000; Li et al., 2011). Thus it is aptly clear that the possibility of liquefaction depends on the initial state of cohesive soils. Very recently seismic requalification studies of important structures located in high seismic zone have been initiated (Dammala et al., 2017a), where understanding of underlying soil behaviour is critical.

Cyclic triaxial test apparatus is the most common type of apparatus used for such experiments to understand the dynamic characteristics of cohesionless and cohesive soils. Hence, in this respect, the methodologies adopted in the present research do conform to the earlier researches. The highlight and importance of the present research lie in the application of cyclic triaxial test to identifying the dynamic properties and liquefaction behaviour of the regional red cohesive soil found in abundance in and around Guwahati region. Only limited literature is available about the dynamic characterisation of the soils in the said region (Guwahati and northeast region of India); moreover, all the literature deals with the dynamic response of cohesionless soils. This article provides the documentation of the dynamic response of the cohesive soil available in the region. The characterisation of the regional cohesive soil holds importance in its application to ground response analysis (GRA). In the absence of the dynamic response of the regional soils, it is a common practise to use the standard dynamic models (Vucetic and Dobry, 1991; Darendeli, 2001; Roblee and Chiou, 2004) for GRA studies. Similar approach has been practised for cohesionless soils (Seed and Idriss, 1970; Darendeli, 2001). However, Kumar et al. (2017) showed that the regional cohesionless soils can exhibit substantially different dynamic behaviours as compared to the standard models for similar soils. The same understanding holds good for cohesive soils as well. For conducting the tests, soil specimens were prepared at maximum dry density (MDD) of 1.75 g/cm^3, optimum moisture content (OMC) of 19.3% and field density of 1.5 g/cm^3 with varying water contents (8%, 15% and 25%). Since water content in the field varies significantly during seasonal variation, varying percentage of water contents was chosen to interpret the soil behaviour in the field during such seasonal conditions. The prepared specimens were subjected to different amplitudes of stresses (based on cyclic stress ratio (CSR)) having a loading frequency of 1 Hz.

2. Study region

The entire northeastern region of India is located at the most seismically active region in the world (IS 1893-1, 2002). Based on the past earthquake data, tectonic setup and geology, Guwahati City is found to be surrounded by six tectonic blocks, i.e. Shillong Plateau, Eastern Himalayas, Brahmaputra Valley, Surma Valley, Naga Hill and Arakan Yoma (Raghukanth et al., 2008). This region has experienced several devastating earthquakes of different moment magnitudes ranging from M5 to M8.7 (Nath et al., 2008). Raghukanth (2008) reported that during 1950 Assam earthquake, the region of Assam experienced extensive liquefaction, over an approximate area of 126 acres (1 acre = 4046.9 m^2). In this regard, owing to the scanty literature, it is imperative to investigate and evaluate the dynamic properties of northeastern soil. It is a common practise, on behalf of the geotechnical engineers, to perform GRA using the existing dynamic models for sand (proposed by Seed and Idriss, 1970), clay (proposed by Vucetic and Dobry, 1991), and combinatorial soil (proposed by Ishibashi and Zhang, 1993). In the absence of proper region-specific dynamic model, the use of the standard soil models might lead to the inaccurate estimation of the ground response parameters involved in aseismic design (Kumar et al., 2018). Estimation of dynamic properties of sandy soils is well reported for deposits in northeast India (Kumar et al., 2017). The study presents the dynamic properties and liquefaction evaluation of the typically available cohesive soil nearby Guwahati City (Assam region), which can be useful for the proper assessment of GRA in this region.

3. Test material and liquefaction susceptibility criterion

3.1. Description of test material

Cohesive soil available near Guwahati region was used for this study. The specific gravity (G_s) of the soil was found to be 2.65 (ASTM D854-14, 2014). As presented in Fig. 1, the particle size distribution of the soil obtained from wet sieve (ASTM D6913/D6913M-17, 2017) and hydrometer analysis (ASTM D7928-17, 2017) exhibited a composition of 21.23% clay (<0.002 mm), 48.5% silt (0.002–0.075 mm), and 30.27% fine sand (0.075–4.75 mm). The values of liquid limit (LL), plastic limit (PL) and PI were determined as 41.5%, 22.6% and 18.9%, respectively (ASTM D4318-17e1, 2017). The MDD and OMC of the soil were found to be 1.75 g/cm^3 and 19.3%, respectively (ASTM D698-12e2, 2012). As per unified soil classification system (USCS) (ASTM D2487-11, 2011), the soil is classified as low plastic cohesive soil. As per the

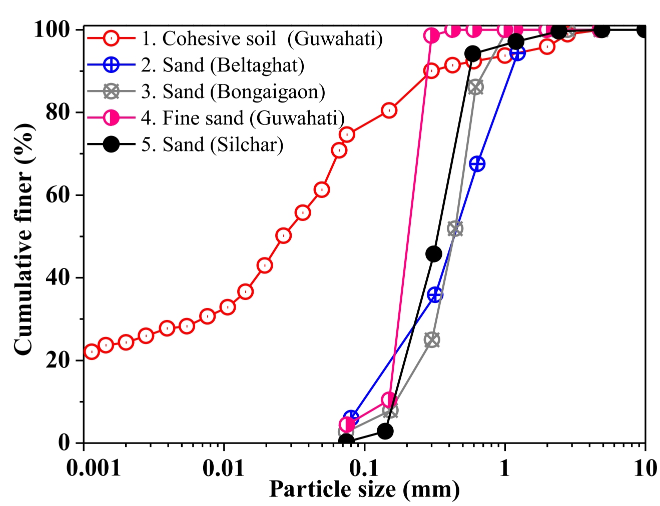

Fig. 1. Particle size distribution of prevalent soils of northeastern region of India (1 – Present study; 2 – Govinda Raju (2005); 3 – Dammala et al. (2017b); 4 – Kumar et al. (2017); 5 – Paul and Dey (2007)).

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