Soil Dynamics and Earthquake Engineering 95 (2017) 96–105

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Small-strain stiffness and damping of Lanzhou loess

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A R T I C L E I N F O

Keywords:
Loess
Small-strain stiffness
Small-strain damping
Water content
Confining pressure
Consolidation time
Structure effect
Resonant column test

A B S T R A C T

This study examines the small-strain stress-strain properties during cyclic loading of Lanzhou loess deposits, characterized by a very high void ratio (> 0.9). Torsional resonant column (RC) tests are performed in order to investigate the effect of water content, confining pressure, consolidation time and soil structure strength on the small-strain stiffness (G_0) and damping (D_{min}) of loess. It is proved that shear modulus G_0 at low strain levels is very sensitive to water content while the effect of water content on small-strain damping D_{min} is relatively small. As water content W approaches the plastic limit PL, there is a dramatic decrease of G_0 compared to drier loess specimen; G_0 has the tendency to reach a stable or constant value with further increase of water content which is more than the PL of loess. The small strain damping D_{min} decreases continuously with water content for unsaturated loess and then tends to increase slightly for almost fully saturated loess. A linear relationship between G_0 and confining pressure σ'_m in log-log coordinates for different water contents is observed for Lanzhou loess. Similarly, D_{min} decreases linearly with σ'_m. A power function is proposed to describe the relationship between G_0 and confining pressure σ'_m where the exponent m varies with the water content of loess. G_0 is also affected by the consolidation duration and a power function is proposed between normalized G_0 and normalized consolidation time. G_0 is finally strongly affected by the structure of loess and the type of specimen. For undisturbed loess samples, G_0 is always higher than reconstituted ones and the difference decreases with the degree of saturation; for fully saturated samples the influence of the structure strength between undisturbed and reconstituted samples becomes insignificant. Likewise, D_{min} of undisturbed loess is higher than that for remolded loess under the same confining pressure and the difference between them reduces with the degree of saturation as well.

1. Introduction

China loess is a kind of aeolian deposited loess, covering more than 6.3% of the country's land area (named loess plateau) distributed mainly at the northwest regions of China as overlaying soil [34,35]. The thickest loess profile reported in Lanzhou is more than 400 m [11], which is one of the most representative loess profiles in the world. Due to the unique structural fabric which exhibits high void ratio (commonly exceeding 0.9) and high sensitivity of its engineering properties to water [13,15–17], Lanzhou loess can be considered as a problematic soil stimulating research activities. While the strength properties of loess under monotonic loading have been investigated quite extensively [12,19,20,33,48,6,68], studies on the stress-strain properties of loess during cyclic loading, especially considering the effect of various factors, e.g. water content, confining pressure, duration of consolidation and soil structure, are rather limited [52,57]. The lack of the knowledge becomes more important considering that Lanzhou city is located in an earthquake-prone area. Throughout history, several destructive earthquakes occurred around Lanzhou, causing severe damages and fatalities [69]. This is actually the motivation of this paper to evaluate the stress-strain properties during cyclic loading of Lanzhou loess at a first stage at small strains. A comprehensive program of resonant column tests has been conducted in the Laboratory of Soil Dynamics and Geotechnical Earthquake Engineering of Aristotle University in Thessaloniki, Greece (sdgee.civil.auth.gr) on undisturbed and reconstituted loess samples provided by the laboratory of soil mechanics of Lanzhou University, China. The objective of the work presented herein is to study the small strain shear modules G_0 and damping D_{min} and the parameters affecting them.

Laboratory tests such as resonant column, bender elements, torsional shear testing and cyclic triaxial testing [27,50,51,64] are widely used to study the stress-strain properties during cyclic loading of soils, in particular for the measurement of stress-strain properties during cyclic loading of soil at small shear strain levels/amplitudes (γ <

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http://dx.doi.org/10.1016/j.soildyn.2017.01.041
Received 28 September 2016; Received in revised form 22 December 2016; Accepted 25 January 2017
0267-7261/

10^{-2}%). Several recent researches on the stress-strain properties during cyclic loading of loess are conducted in the laboratory by using conventional cyclic triaxial testing [55,58,59,67], while the cyclic strains investigated in these studies are large (> 10^{-2}%) due to the lack of sensitive LVDT with high precision. In this research work, a resonant column device has been used to evaluate the stress-strain properties of soil under relatively fast cyclic loading conditions from small to medium shear strains ($10^{-5}\% < \gamma < 10^{-2}\%$). A comprehensive set of resonant column tests are conducted in order to (a) present and discuss results regarding the effect of the most influencing parameters of loess like the water content, the confining pressure, the duration of consolidation and the soil structure, and (b) to propose simple relationships for the estimation of small-strain shear modulus and damping ratio including the mean confining pressure and the water content.

2. Test program

2.1. Testing material

The undisturbed loess specimens were provided from a geotechnical borehole campaign conducted during site exploration for infrastructure construction in National New Area of Lanzhou, Northwest of China (Fig. 1). The representative soil profile of the studied site is shown in Fig. 2 with the corresponding SPT blows and the shear wave velocity obtained from down-hole measurements included as well. Apart from limited thickness of the top cultivated soil layer (about 1.5 m), loess-like silt (about 40 m thickness), which is commonly designated as Q_4 loess [36] in China based on the age of deposition and physical properties, comprises the major part of the top 70 m investigated soil strata. Below that, a 16.8 m thick layer of silty clay is to be found underlain by a 1.4 m thick breccia layer and another 10.0 m thick layer of silty clay. The bedrock is composed by mudstone of good quality and high strength due to the great burial depth (approximately estimated at 69.8 m or more). As shown in Fig. 2, the variation of SPT blows for loess ranges from 6 to 9 within the top 25 m thickness, which can be attributed to the metastable structure of loess with high void ratio. In addition, shear wave velocity of loess obtained from down-hole measurements increases monotonically with depth indicating relatively homogeneous soil strata with depth. The water table is not detected during site exploration, which means that there is no stable water recharging in this research area. In that case, it can be assumed that soil water content should be greatly influenced by seasonal strong rainfall [13,14]. In order to keep the initial condition of undisturbed loess specimens untouched, all loess blocks with a length of 300 mm were initially cut off from the same borehole. The blocks with different burial depth were then trimmed carefully into column samples of 100 mm in diameter and 200 mm in height and wrapped up instantly by plastic film and mounted into sampling thin tubes (100×200 mm). The small gaps between the sample and tube were filled by loess powder trimmed from original samples. After that, the sampling tubes were packaged into a big metal box and sponge was filled into the gaps between tubes in order to eliminate disturbance during shipment from China to the laboratory in Greece.

In accordance with the experimental program, two groups of parallel specimens were collected. One group was shipped to the laboratory of soil mechanics of Lanzhou University to timely determine the physical properties of natural undisturbed loess; meanwhile, the other one was delivered by express shipment to the Laboratory of Soil Dynamics and Geotechnical Earthquake Engineering of Aristotle University in Thessaloniki, Greece, to investigate the stress-strain properties during cyclic loading of Lanzhou loess at small to medium levels of shear strain ($10^{-5}\% < \gamma < 10^{-2}\%$) through a series of resonant column tests. The physical properties of testing loess are summarized in Table 1 and the corresponding characteristics of particle size distribution are shown in Fig. 3.

It can be seen from Table 1 that the natural water content of Lanzhou loess increases a little with the burial depth and commonly it is less than the plastic limit of loess, which can be attributed to the arid and semi-arid climate in the northwest of China. Due to the unique open soil structure, the void ratio of Lanzhou loess is very high (around 1.0), which means that loess would be expected to be collapsible very

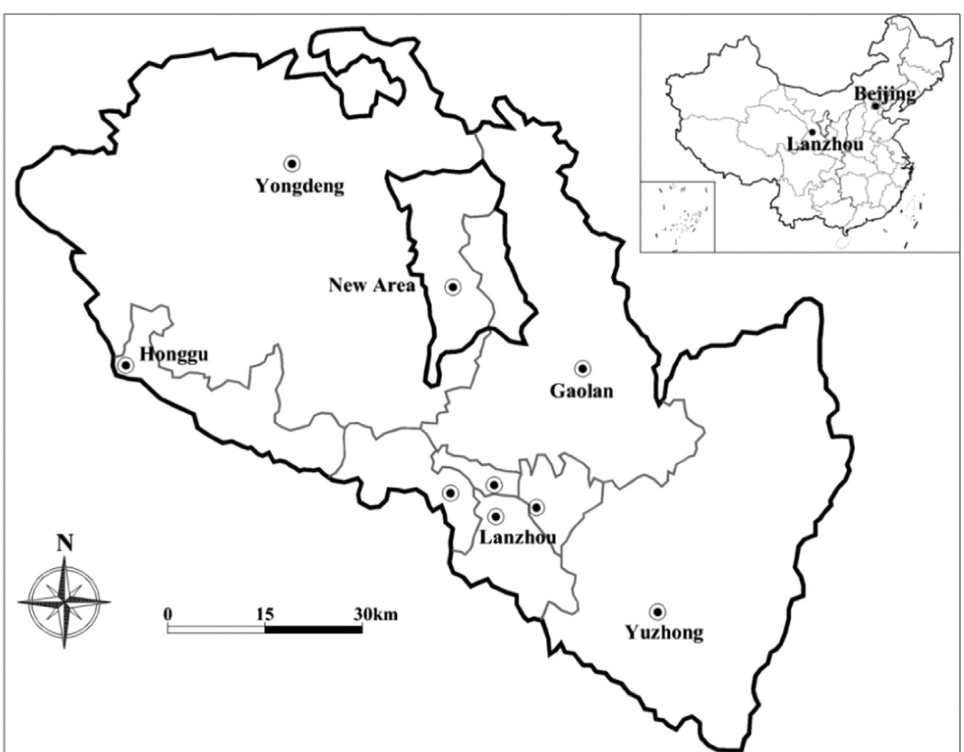

Fig. 1. Location of National New Area of Lanzhou, China.