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Effect of silt on post-cyclic shear strength of sand

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ABSTRACT

Adding non-plastic fines to sand can greatly change its behavior. Size difference between sand and silt particles is the main reason which causes this change. While post-cyclic and post-liquefaction behavior of clay and clean sand has been widely studied, silty sand is wrongly considered to behave like clean sand and researches usually do not focus on it. In silty sand, through low cohesion, applying cyclic load can displace particles and result in heterogeneity within the mixture. Even if liquefaction does not occur, rearrangement of soil particles can affect monotonic ultimate strength. This study, with a series of post-cyclic monotonic triaxial tests, has shown that in sand with a considerable amount of silt, cyclic loading can change the ultimate state strength. In sand with 15% silt it decreases and in sand with 30% silt it increase the ultimate state strength. Changes are negligible in clean sand or sand with 5% silt.

1. Introduction

In geotechnical engineering, the majority of experimental testing on frictional granular media involves clean sand. However, most sands in nature contain a considerable amount of silt or clay. Only in recent decades, the basic differences between behavior of clean sand and sand with fines has been understood. These differences are mainly due to disparity in size of sand grains and fine particles. Fine particles can occupy pore space between sand grains, leading to separation of grains and reduction in contact points, thereby resulting in the reduction in shear strength. In addition, when fine part has a considerable plasticity, cohesion can also be a factor in assessment of shear strength [1]. Thus changes in the sand behavior depend mainly on arrangement of fine particles and their plasticity. Applying a cyclic load can impress both of these factors because, on one hand, it changes the arrangement of soil particles and on the other hand, it can diminish strength of cohesive soils. The post-cyclic behavior of cohesive soils, such as clay, clayey sand and sandy clay, has already been studied [2–4]. However, research on non-plastic soils has been predominantly focused on soils with uniform particles like clean sand or silt [5–7]. In these types of soil, cyclic loading can change the soil fabric and even soil strength in some cases [8]. Undoubtedly, in soils such as silty sand, which are composed of two types of material with a significant size difference, this change would be more pronounced, as the displacement of particles due to cyclic loading exacerbates the heterogeneity within the soil mass and affects the soil structure.

In this study, 55 triaxial tests are performed on sand with different silt contents, under consolidated undrained condition (CU). Specimens are loaded in two stages; first they are loaded cyclically up to a certain pore water pressure ratio (r_u). This r_u should not result in failure or liquefaction. Then a monotonic compression load is applied to samples in undrained condition and the influence of cyclic loading on undrained post-cyclic behavior of silty sand with different silt contents is evaluated.

2. Background

2.1. Post-cyclic strength of sand

Studies about post-cyclic behavior of sand usually has been limited to clean sand. Initial studies on clean sand suggested that the type of loading, whether monotonic or cyclic, has no effect on the steady state strength of sand [9]. However, later studies on post-cyclic strength revealed that undrained cyclic loading can change the arrangement of sand grains. Changes in arrangement of very loose specimens can lead to formation of weak, metastable pores in soil structure that can be broken easily and result in structural collapse or flow failure. During these change, shear strength decreases abruptly and soil undergoes large deformations [10]. In specimens with higher densities, due to constant specimen volume, local rearrangement increases the specimen tendency for dilatation. Low plasticity silt also behaves like loose sand; after applying a cyclic load, the tendency for instability and flow failure increases in this type of soil [5].

Investigating the post-liquefaction behavior of sand has also proven

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Nomenclature

F_c	fines content (%)	CSR	cyclic stress ratio
f_c	fines content in decimal	N	number of cycles
e	void ratio	CP	confining pressure (kPa)
e_g	intergranular void ratio	q	deviatory Stress (kPa)
e^*	equivalent granular void ratio	p’	mean Effective stress (kPa)
b	an experimental value showing active fines	p'_{ss}	mean Effective stress at steady state (kPa)
r_u	pore water pressure ratio	ε_a	axial strain (%)
		S_u	ultimate state strength (kPa)
		RFD	resistance to further deformations

that strength and stiffness of soils are greatly reduced after liquefaction. But as axial strain increases, sand grains gradually reach a stable condition under the new arrangement. Hereafter specimen shows dilative behavior, both strength and stiffness increase [7]. In this case, the post-cyclic behavior of sand specimens significantly depends on maximum strain and pore water pressure induced by cyclic loading [11].

Generally, in uniform non-plastic soils, such as sand or silt, only the generated pore water pressure and arrangement of grains can affect the post-cyclic strength. Since soil arrangement depends on grain shape, which is in turn a material parameter, both decrease [6] and increase [11] in strength and stiffness after applying cyclic load have been reported.

2.2. Silty sand

Role of fines in silty sand can be different, while at low silt contents the role of fines in sustaining shear stress in soil structure is almost negligible, at silt contents higher than 10%, they can have an active role in soil structure. One of the first works that noticed active contribution of fines in sand belongs to Pitman et al. [12]. To model or explain behavior of silty sand, an idealized two-size particle packing can be assumed. This model considers silty sand as a material with only two grain sizes which are usually average grain size of sand and silt [13]. According to Fig. 1(a), when the silt content is very low, particles are trapped in some voids between sand grains and are not involved in sustaining shear stress; therefore they can be considered as voids [14]. In order to account for this phenomena, many studies redefined void ratio for this type of soil as Intergranular Void Ratio [15]:

$$e_g = \frac{(e + \quad f_c)}{(1-f_c)} \tag{1}$$

Where f_c is the ratio of fines to total solids by weight in dry condition.

In this case, due to inactivity of fine grains, the shear strength of silty sand is close to that of reference sand. Indeed, increase in confining pressure can put the sand grains into a denser packing and consequently, a small proportion of fines can take on an active role in soil structure, but this changes are negligible [15].

Fig. 1(b) shows when fines content increases, although the fines are not enough to completely fill voids, some of them come into effect as separator elements between sand grains and gradually reduce contact force between these grains. For example, analyzing the micro-structure of Firoozkooh silty sand has demonstrated that in sand with 15% fines, about a quarter of fines are placed between the sand grains. These particles form metastable sand-silt-sand contacts which can be broken easily, thereby leading to a loss of shear strength [16]. Compared to clean sand, confining pressure have more intense effects on steady state strength in these silty sands; an increase in confining pressure can noticeably increase the steady state strength [15].

As demonstrated in Fig. 1(c), with further increase in fines content, voids are completely filled with this particles. In this case, adding more fines results in dispersing of sand grains and their isolation in a matrix of fines. In other words this is a threshold fines content beyond which, silt particles constitute the main soil matrix and soil strength is closer to that of the host silt instead of the host sand. For values beyond the threshold fines content, amount of fines does not affect the strength significantly, although a small increase in strength has been seen at very high fines contents [16]. Higher pressure can compress sand grains, potentially leading to reestablishing contacts between sand particles, which can significantly increase the strength of soil [15].

When fines content increases, a part of fines participates in sustaining shear stress. In this condition, soil density can be defined as equivalent granular void ratio which equals to [15]:

$$e^* = \frac{e + (1-b)f_c}{1-(1-b)f_c} \tag{2}$$

Where b is an experimental value representing a fraction of fines that plays an active role in soil structure with a value between zero and one.

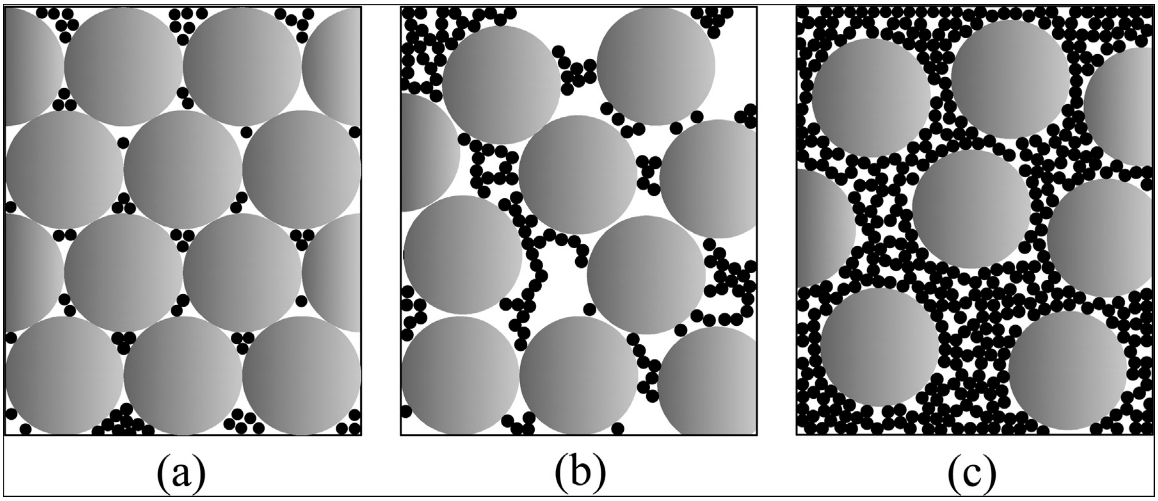

Fig. 1. Microstructure of silty sand in: (a) low fines content (b) moderate fines content (c) high fines content.