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Behavior of strip footing on fiber-reinforced cemented sand adjacent to sheet pile wall

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ABSTRACT

In urban areas, shallow foundations are often placed along the ground surface above a sheet pile wall. In this research, the potential benefits of reinforcing the active zone behind a model sheet pile wall by using polypropylene fiber and cement kiln dust have been investigated experimentally and numerically. Tests were conducted by varying parameters including fiber ratio (R_F), cement kiln dust (*CKD*) ratio, thickness of reinforced layer, footing location relative to the sheet pile wall and curing time of reinforced layer. Finite element computer code *PLAXIS 2D* foundation was used for numerical modeling. Close agreement between the experimental and numerical results was observed (maximum difference 14%). Experimental and numerical results clearly show that fiber insertion into the cemented soil causes an increase in ultimate bearing capacity of footing and significant reduction in the lateral deflection of the sheet pile wall. At higher fiber ratios ($R_F \geq 0.75\%$), the bearing capacity ratio (*BCR*) increased by about 42% and the effect of *CKD* ratio on *BCR* is more pronounced. The addition of fibers changed the brittle behavior of cemented sand to a more ductile one. Critical values of reinforcing parameters for maximum reinforcing effects are established.

1. Introduction

Shallow foundations, such as the roadway or continuous wall footings for buildings are often placed along the ground surface above a sheet pile wall. These foundations may impose significant lateral pressure on the sheet pile wall (Ghanbari and Taheri, 2012).

In earth-retaining problems, the subject of reinforcing the active zone has attracted a great deal of attention (Santos and PalmeiraBathurst, 2013). Nasr and Nazir (2013) studied the behavior of a sheet pile wall embedded in non-cohesive soil reinforced by geosynthetics in the active zone adjacent to the strip footing. The results indicate that the inclusion of geogrid reinforcement in the active zone leads to a reduction by about 48%–75% in the lateral deflection. Nasr (2009) showed that the provision of discrete vertical reinforcement behind the sheet pile wall has a significant effect in increasing the stiffness of the soil and decreases the lateral deflection of the sheet pile wall produced by the lateral stress of the strip load. Georgiadis and Anagnostopoulos (1998) used a model sheet pile wall embedded in sand to investigate the effect of surcharge strip loads on wall behavior. From the results, it was concluded that the bending moments along the sheet pile wall increase with increasing surcharge load and decreasing strip load distance to the excavation.

Several stabilization techniques have been used to stabilize and improve the properties of the sandy soil, but improvement with the addition of cement is the most generally and successfully used the technique. Natural or artificial cementation of soil particles contributes to settlement reduction and bearing capacity increase (Asghari et al., 2003), which are the two key design considerations in the field of geotechnical engineering. Shear strength behavior of cemented sands has been widely studied (Schnaid et al., 2001; Consoli et al., 2012). Ismail (2005) used cemented in situ soil for retaining walls. According to these studies, cementation of sand results in increased brittle behavior as peak shear strength increases. However, the high cost of cement motivated the search for a suitable alternative stabilizing material with low or no cost, such as cement kiln dust (*CKD*) for the stabilization of sandy soil. The high alkalinity and fine particle size of the *CKDs,* in addition to their cementitious properties, make these materials suitable for several applications: waste solidification (Conner et al., 1992; Mckay and Emery, 1992) and mineral fillers in asphalt paving and mine reclamation operations. According to Portland Cement Association (PCA, 2007), more than half million metric tons of *CKD* were used for soil stabilization and as a binder in soil stabilized base and subbase pavement applications.

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The behavior of fiber reinforced sand has been studied by a number of researchers (Park and Tan, 2005; Chauhan et al., 2008; Ahmad et al., 2010; Diambra et al., 2010; Lovisa et al., 2010; Falorca and Pinto, 2011; Tang et al., 2007). These studies showed that adding fiber to sandy soil results in greater peak shear strength and more ductile behavior. In particular, when applying cemented soils at a shallow depth, the degree of brittle failure may be more pronounced due to a low confining stress. A number of studies have also reported on the influence of both cement and fiber on the mechanical behavior of sandy soils. Maher and Ho (1993) conducted static and dynamic triaxial compression and extension tests on cemented sand containing randomly distributed fibers and reported more shear strength and energy absorption for soil containing fiber. Consoli et al. (1998, 2004) conducted consolidated drained triaxial tests on sand reinforced with fiber and cement. They found that the addition of fiber increased peak and residual shear strength and reduced residual dilation. The addition of fiber to cemented soil produces bonding and friction between the soil and the fibers. A fiber-reinforced cemented soil can sustain a load even after failure of a cemented soil and thus, can effectively improve the brittle behavior of the soil.

From the above literature, only limited information has been reported on the use of fiber-reinforced cemented sand in active zone behind the sheet pile wall. Therefore, the present work describes a study of the behavior of the strip footing resting on fiber-reinforced cemented sand adjacent to the sheet pile wall.

2. Experimental investigation

2.1. Material used for the testing

2.1.1. Sand

The experiments were carried out on clean, oven dried, commercially available sand. Mineralogical analysis showed that sand particles are predominantly quartz. According to the Unified Soil Classification System (ASTM, 2010), the soil is classified as poorly graded sand with letter symbol (*SP*). The sand was placed in a test tank at a unit weight of 15.57 ± 0.15 kN/m^3, which corresponds to relative density (D_r) of 50%. The friction angle of the sand (Ø) at 50% relative density, as determined from standard Unconsolidated Undrained (*UU*) triaxial compression tests on a dry sand sample, was found to be 36°. Other physical properties of the sand are summarized in Table 1.

Table 1
Physical and mechanical properties of sand used in the model tests.

Property	Value
Specific gravity, G_s	2.64
Grain size analysis	
Effective grain size, D_{10} (mm)	0.10
Average grain size, D_{50} (mm)	0.30
Uniformity coefficient, C_u	3.80
Coefficient of curvature, C_c	1.05
Coarse to medium sand, %	30.0
Fine sand, %	68.5
Fines (<0.075 mm)	1.50
Classification (*USCS*)	SP
Maximum dry unit weight, $\gamma_{d\ max}$ (kPa)	17.10
Minimum dry unit weight, $\gamma_{d\ min}$ (kPa)	14.30
Maximum void ratio, e_{max}	0.811
Minimum void ratio, e_{min}	0.515
Compaction study	
Optimum moisture content, *Wc*(%)	9.50
Maximum dry density, (kPa)	16.90

2.1.2. Fiber

Polypropylene fiber is the most widely used inclusion in the laboratory testing of soil reinforcement (Ple and Le, 2012; Tang et al., 2007). Therefore, white monofilament polypropylene fibers with circular cross section were used throughout this investigation to reinforce the cemented sand. Short fiber was used in this present study to be consistent with model tests. The fibers were 12 mm in length and 0.023 mm in diameter (consequently aspect ratio of 521), with a specific gravity of 0.91, tensile strength of 350 MPa, and elastic modulus of 6 GPa. Also, the fiber used is a hydrophobic and chemically inert material which does not absorb or react with the soil moisture.

2.1.3. Cement kiln dust (CKD)

The chemical composition of *CKD* used in this study was determined by *X*-ray fluorescence and is given in Table 2. For comparative purposes, the chemical composition of ordinary Portland cement (from the same company) is also included in Table 2. Relative to cement compounds, *CKD* contains the main oxides in proportions that produce intrinsic cementitious properties as indicated by the calculated hydration modulus (Kamon and Nontananandh, 1991). The beneficial properties of *CKD* and its cost effectiveness compared with other types of stabilizers have led to its use as a popular stabilization agent in recent times (Miller and Azad, 2000). Kamon and Nontananandh (1991) have suggested that in order that reactions take place, the hydration modulus must be greater than 1.7.

$$\text{Hydration modulus} = \frac{\text{Cao}, \%}{\text{Sio}_2, \% + \text{AL}_2\text{o}_3, \% + \text{Fe}_2\text{o}_3, \%} \geq 1.7 \tag{1}$$

Based on the values of each component in Table 2, the hydration modulus (Eq. (1)) of *CKD* and Portland cement are found to be 2.30 and 2.17, respectively. This indicates that *CKD* can be considered a soil stabilizer.

2.2. Test tank

A series of laboratory model tests was executed in a test tank made of steel, having inside dimensions of 1.50 m long, 0.5 m wide, and 0.9 m high. These tank dimensions were chosen to ensure that the failure zone did not extend up to the walls (based on preliminary results of Plaxis *2D* and other investigators such as Nasr and Nazir, 2013. To ensure the rigidity of the tank, the sides of the tank were braced with vertical and horizontal stiffeners to prevent any deflection during the loading process. Furthermore, to achieve almost frictionless side faces, the inside fixed walls of the tank were polished smooth. Then, the longitudinal sides of the tank were coated with lubricating oil in order to reduce the effect of side wall friction. A schematic diagram of the model test configuration is

Table 2
Chemical composition of *CKD* and ordinary Portland cement.

Chemical composition	Analysis method	Composition (% by weight)	
		CKD	*OPC*
SiO_2	XRF	15.42	21.20
Al_2O_3	XRF	3.92	4.95
Fe_2O_3	XRF	2.95	2.82
CaO	XRF	51.23	62.81
MgO	XRF	2.73	4.0
SO_3	XRF	4.36	2.63
Na_2O_3	XRF	0.35	0.2
K_2O	XRF	1.91	0.3
Loss on ignition (*LOI*)	ASTM C575	19.82	1.72
Specific gravity, G_s	ASTM D 854	2.78	3.13