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Influence of Shear Stress on Cyclic Behavior of Marine Sand

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ABSTRACT

Static and cyclic bearing capacity of marine soil is important for design of offshore wind turbine foundation. Undrained Cyclic bearing capacity of soil deposits depends upon the number of loading cycles, vertical effective stress, cyclic shear strain amplitude, relative density, and combination of cyclic and average shear stress. Cyclic direct simple shear (CDSS) tests are performed with relative density of 85%, vertical effective stress 300 kPa, and failure criteria of either 15% double amplitude cyclic shear strain (γcyc) or permanent shear strain (γp) are adapted. The influence of shear stress on the cyclic behavior of marine sand is presented in the form of design contour diagrams.

KEYWORDS: CDSS; Undrained cyclic bearing capacity; cyclic behavior; Marine sand.

INTRODUCTION

Research on the cyclic behavior of marine soils has significantly increased over the last three decades. Andersen et al. (1988) presented general marine soil behavior under cyclic loading and provided a database which can be used to determine soil parameters for early feasibility studies of gravity structures on clay. Goulois et al. (1985) studied the effect of average or sustained shear stresses on the cyclic degradation of clay

This paper presents the influence of shear stress on the behavior of marine sand. The cyclic behavior of marine sand is examined in terms of cyclic and average shear stresses.

A soil can be subjected to many different stress conditions, being purely cyclic stress, static or average stress, or a combination of both. Andersen, (2009) shows this clearly in a study on Drammen clays In this study cyclic simple shear tests have been performed with both zero static or average shear stress ($\tau_a = 0$) or significant average shear stress ($\tau_a \neq 0$).
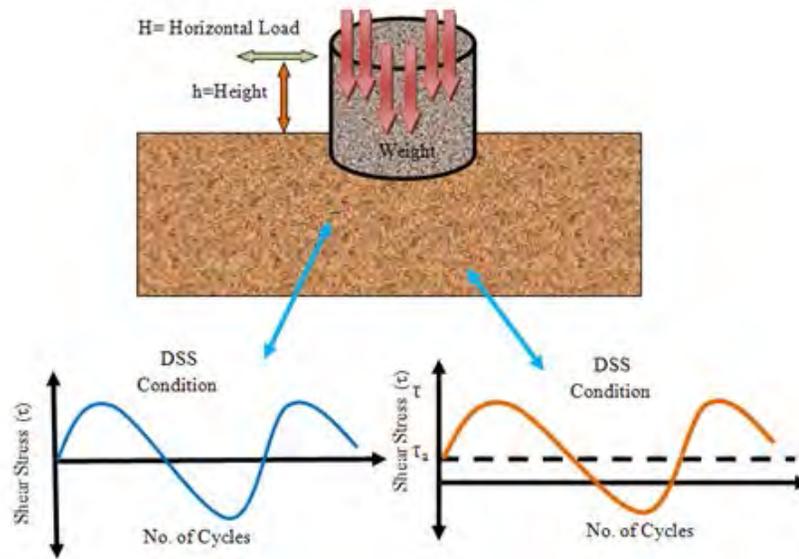
Figure 1: Simplified stress conditions along a potential failure surface in the soil beneath a structure under cyclic loading.

Fig. 1 shows a simplified image of the stress conditions along a potential failure surface beneath a gravity structure. The development of pore pressure and shear strain with time for a soil specimen subjected to undrained cyclic loading in Fig. 2. The cyclic loading generates permanent and cyclic pore pressure component. The increase in pore pressure results into increase in permanent (γ_p) and cyclic (γ_{cy}) shear strains.
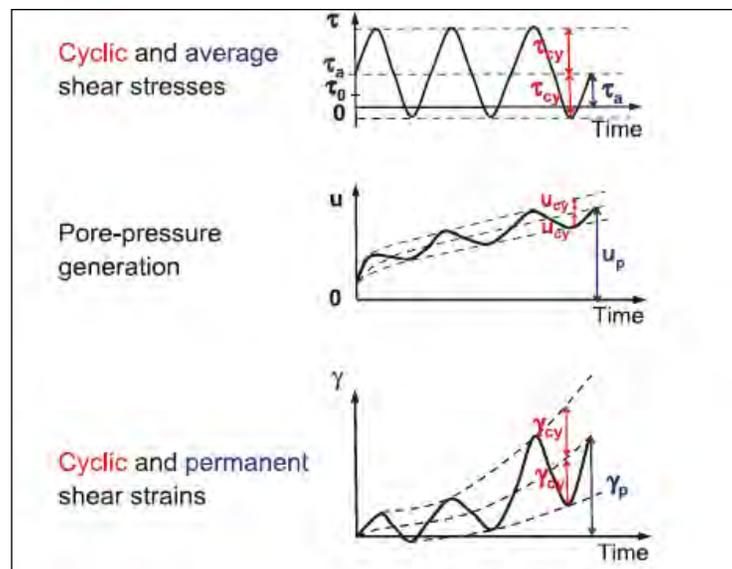
Figure 2: Pore pressure and shear strain as a function of time under undrained cyclic loading, *u* pore pressure, γ shear strain, τ_0 initial consolidation shear stress (Andersen, 2009)

The general behavior of soil subjected to cyclic loading is shown in Fig.3
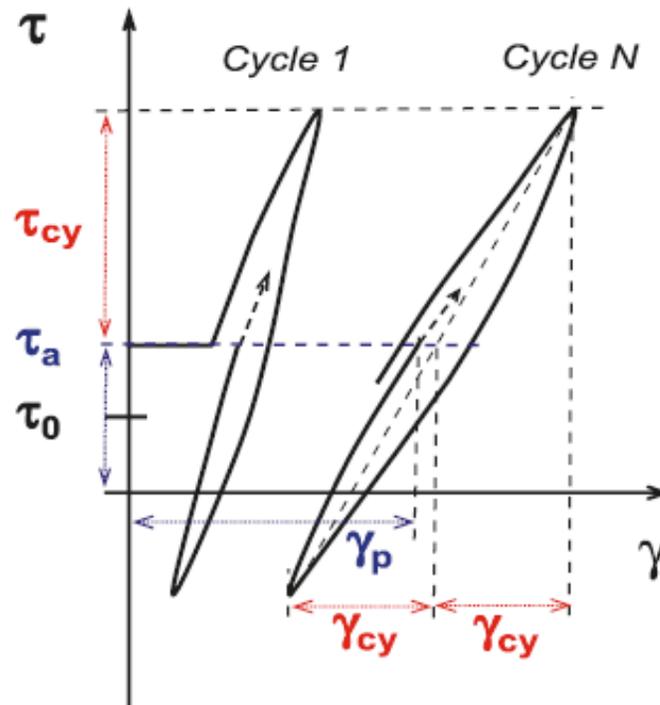
Figure 3: Stress- Strain behavior under cyclic loading (Andersen, 2009)

CONTOUR DIAGRAMS

Andersen(1998) reported the importance of the average and cyclic shear stress components for the cyclic behavior of plastic Drammen clay. Fig. 4 (a) Presents the results of 1 monotonic and 9 cyclic tests and (b) presents the contour diagram with the same number of cycles to failure based on the data in part (a): $\tau_{a,f}$, average shear stress at failure; $\tau_{cy,f}$, cyclic shear stress at failure; SuDSS, static shear strength. Randoph and Gourvenec, (2011) also produced such contour diagrams. They carried out the unsymmetrical cyclic direct simple shear test on normally consolidated Drammen clay, and the number of cycles to failure was defined by γ_p or $\gamma_{cy} = 15$ %. Nielsen and his collegues (2012) compared the normalizing parameter for cyclic and average shear stress. When normalizing cyclic and average shear stresses for use in design diagrams vertical effective stress (σ'_{vc}) is found insufficient to use as a normalization parameter in the undrained case, as it does not take pore pressure into account. This is important, since the undrained shear strength for dense sand is governed by cavitation. Therefore, the undrained shear strength, C_u, is used as normalization parameter for the modified design graph and should be used for other design graphs in the undrained case (Nielsen et al., 2012).
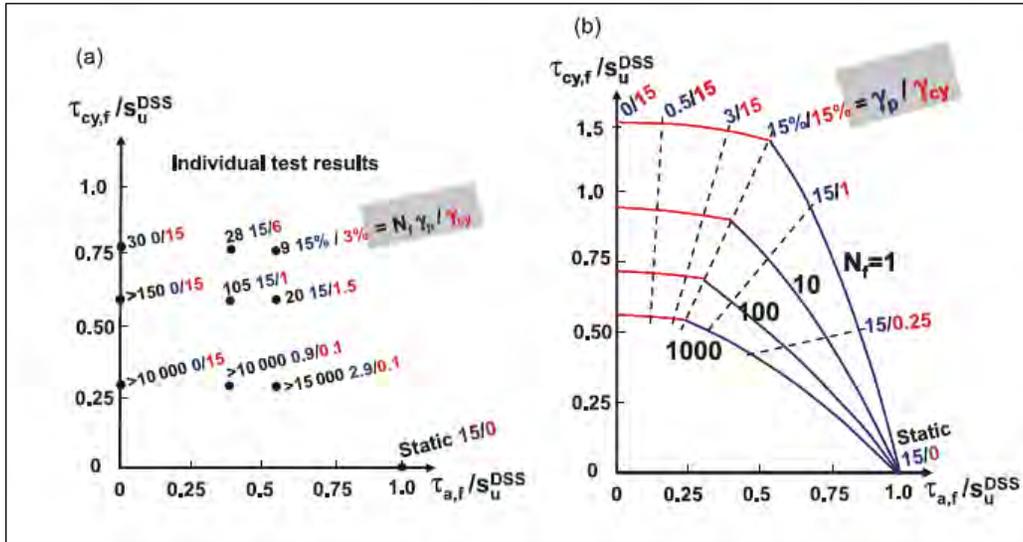
Figure 4: Number of cycles to failure and failure mode as a function of average and cyclic shear stresses for cyclic DSS tests on normally consolidated Drammen clay (Andersen, 2009)

Andersen and Berre (1999), however, studied the effect of average and cyclic shear stress and produced same design graph using vertical effective stress as a normalization parameter (σ'_{vc}). Also, the tests were conducted on Baskarp sand having relative density (D_r) of 95 % with cyclic or permanent shear strain failure criteria of 3%. This paper used vertical effective stress (σ'_{vc}) as a normalizing parameter for cyclic stress and average stress.

Nielsen and his collegues (2012) conducted tests with a relative density of 80 % in order to simulate offshore conditions where relative densities are relatively high. The purpose was to develop design diagrams, which can be used to estimate the undrained cyclic behavior of Frederikshavn Sand.

LABORATORY CYCLIC TEST

Cyclic direct simple shear (CDSS) apparatus using wire-reinforced membrane is employed to investigate the undrained behavior of marine silty sand. The CDSS test procedure is based on that of a constant-volume direct simple shear testing of soils, which has been studied extensively and is described in the standard ASTM D6528-07. The sample is consolidated under a normal load within a wire-reinforced membrane that provide lateral confinement. Once consolidation is complete, a horizontal shear force is applied to one end (Monotonic) or two sides (cyclic) of the sample. The sample height is continuously maintained during shear to ensure constant volume. Rather than measuring pore pressures, which would require complete saturation of the sample, the pore pressure response is inferred from the change in vertical stress which is monitored throughout the test (Baxter et al, 2010).

In this way changes in applied vertical stress (σ'_{vc}), which are required to keep the sample height constant, are assumed to be equal to the excess pore water pressure (Δu) that would develop if the test were truly undrained with pore pressure measurements (Dyvik et al. 1987).

TEST RESULTS

Cyclic loading from traffic and earthquakes have lower cyclic loading periods than wave loading and this needs to be taken into account (Andersen, 2009). The tests are thus performed at a frequency of 0.1 Hz. All the tests are performed on relative density of 85%. The failure criteria of 15% cyclic double amplitude shear strain or permanent shear strain is selected for all the tests except for CSR = 0.30 and τ_a = 60 kPa. Specific gravity of material tested is G_s =2.652. For marine silty sand, a normal consolidation stress of 300 kPa is applied in steps for all specimens.

Several methods of sample preparation are available in the literature. Most commonly used sample preparations are air pluviation, water pluviation, slurry deposition, dry deposition and moist tamping. The major factors which affect the relative density of air pluviated sands are height of particle drop (Vaid and Negussey, 1988) and rate of deposition (Miura et al, 1982). The oldest laboratory reconstitution technique is moist or dry tamping of soil in layers (Lambe, 1951). The technique consists of placing the consecutive layers of specified thickness into a sample former tube, and tamping each layer flat with a specified force and frequency of tamping before the next layer is placed. Water pluviation sample preparation technique has been used by several researchers (Lee and Seed, 1967; Vaid and Negussey, 1984). But, particle size segregation is an issue in water pluviation of well-graded or silty sand. During this study, dry tamping approach and dry deposition approach are used. A sample weight of 100 g is used and laid in 3~5 layers in wire-reinforced membrane (diameter = 63.5 mm) to obtain the required relative density. Marine silty sand has minimum voids ratio of 0.7446 and maximum voids ratio of 1.1834. Fig. 5 shows the sample prepared in wire-reinforced membrane for the test.

Figure 5: Enlarged View of Sample within Wire-Reinforced Membrane

Influence of average and cyclic shear stress on cyclic shear strength is examined. Fig. 6 (a) shows the development of shear strain with increasing number of loading cycles. The figure also shows the typical behavior of soil subjected to no initial shear stress (τ_a = 0) and symmetrical loading reaching to cyclic shear strain of 15%.

(a)

(b)

(c)
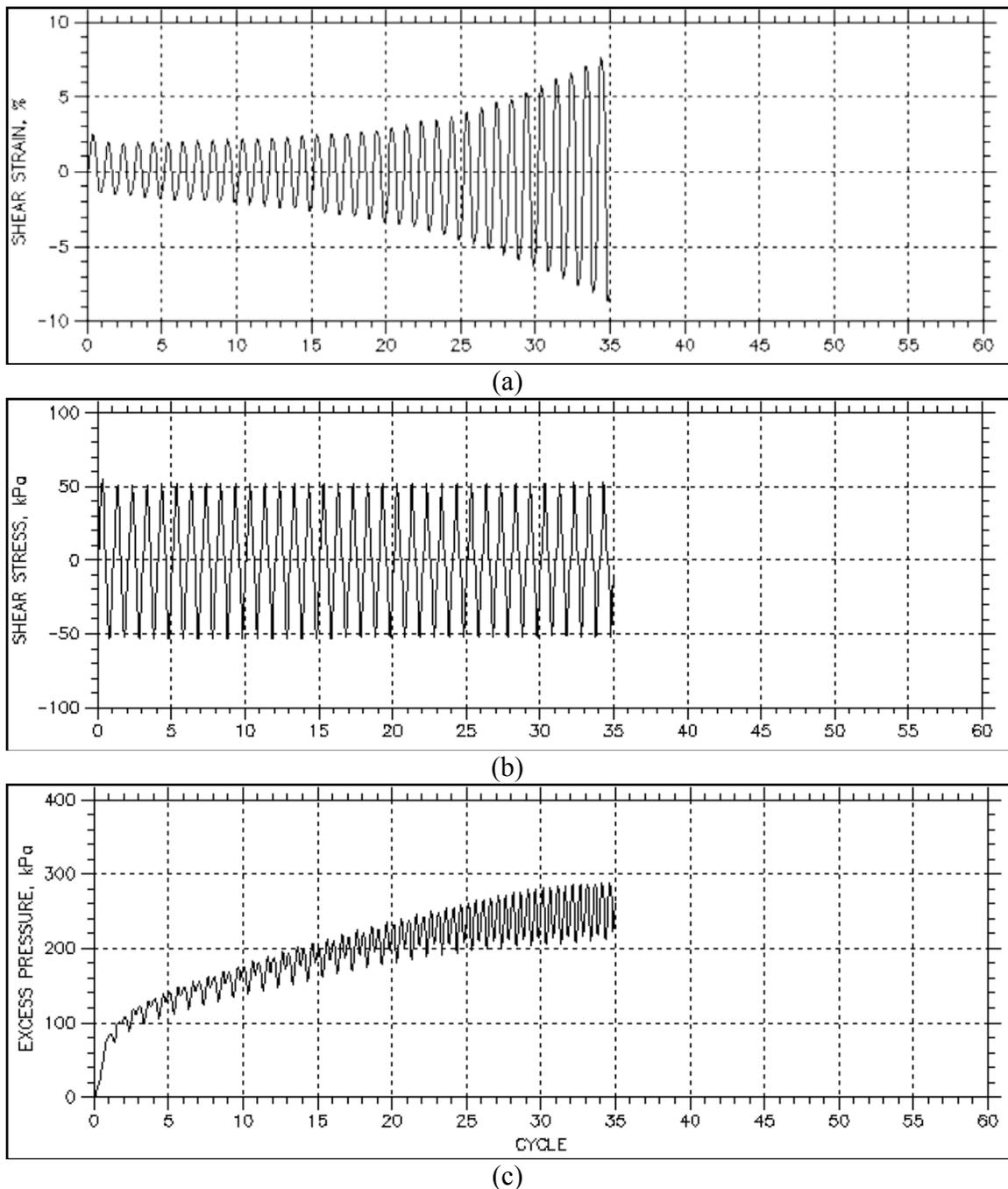
Figure 6: (a) Development of cyclic shear strain versus number of loading cycles, (b) Shear stress versus number of loading cycles, (c) Excess pore water pressure versus number of loading cycles to reach failure of 15 % double amplitude cyclic shear strain or permanent shear strain
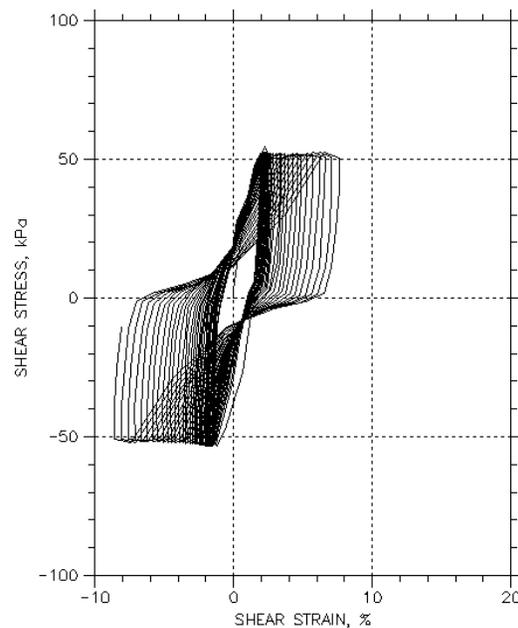
The maximum shear stress mobilized is the sum of average and cyclic shear stresses at failure. Fig. 6 shows that in case of symmetrical loading condition ($\tau_a = 0$), the shear strain failure ($\gamma_p = 0$ & $\gamma_{cy} = 15\%$) is reached at about 35 loading cycles. In case of unsymmetrical loading condition ($\tau_a \neq 0$), cyclic shear strain is developed ($\gamma_{cy} = 1.10$ %) and permanent shear strain ($\gamma_p = $

15%) after about 72 of loading cycles. The permanent shear strain is more dominant than the syclic shear strain with increase of average shear stress.

The range of cyclic shear stresses and average shear stresses is shown in Table. 1. The corresponding cyclic shear strain and permanent shear strain can be found in the design graphs. As the average shear stress increases, the soil fails in small numbers of cycles. It is found that when average shear stress ratio increases the cyclic shear strain component decreases and permanent shear strain component increases.

Table 1: Summary of Testing Program

| Test ID	Cyclic Shear Stress $(\tau_{cyc}/\sigma'_{vc})$	Average Shear Stress $(\tau_a//\sigma'_{vc})$
CDSS_01	0.20	0
CDSS_02	0.20	0.20
CDSS_03	0.20	0.35
CDSS_04	0.20	0.5
CDSS_05	0.30	0
CDSS_06	0.30	0.20
CDSS_07	0.30	0.35
CDSS_08	0.30	0.5
CDSS_09	0.40	0
CDSS_10	0.40	0.20
CDSS_11	0.40	0.35
CDSS_12	0.40	0.5
CDSS_13	0.50	0
CDSS_14	0.50	0.20
CDSS_15	0.50	0.35
CDSS_16	0.50	0.5

Figure 7: Shear Stress versus shear strain with CSR = 0.20 Shear strain = 15 %, (τ_a = 0) or symmetrical loading, vertical effective stress σ'_{vc} = 300 kPa

In case of symmetrical loading condition, with increase of cyclic shear stress, the number of cycles to reach shear strain failure criteria decreases and no significant permanent shear strain is observed(Fig. 8).
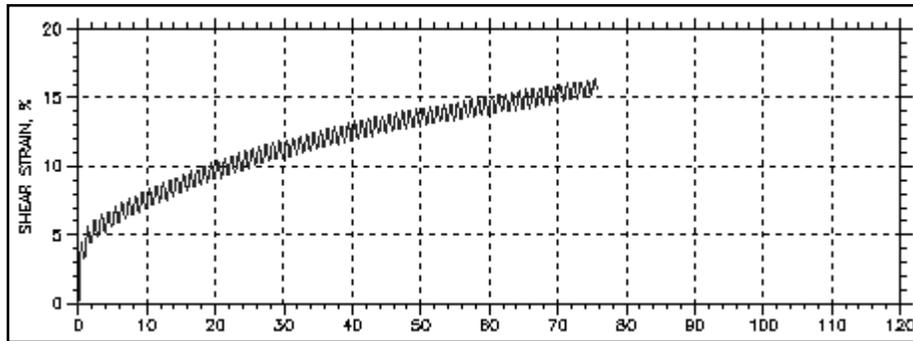
Figure 8: Shear Stress versus shear strain with CSR = 0.20 Shear strain = 15 %, (τ_a = 105 kPa) or unsymmetrical loading, vertical effective stress σ'_{vc} = 300 kPa

For higher cyclic and average stress ratios, the number of cycles significantly decreases to reach either cyclic double amplitude shear strain or permanent shear strain failure criteria(Fig. 9).
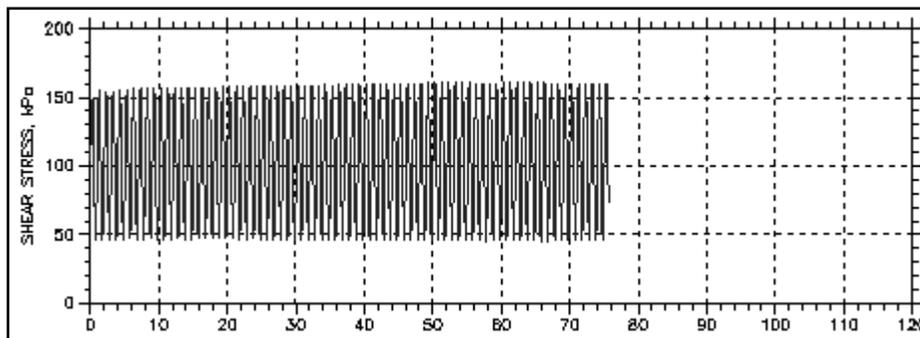
Figure 9: Shear Stress versus normal stress with CSR = 0.20 Shear strain = 15 %, (τ_a = 105 kPa) or unsymmetrical loading, vertical effective stress σ'_{vc} = 300 kPa

CONCLUSIONS

The influence of shear stress on cyclic shear strength of marine sandy soil is presented. Cyclic direct simple shear apparatus is used and 16 tests are performed. Due to higher values of shear stress, samples reach failure criteria less than 35 numbers of loading cycles in most cases. Average shear stress tends to decrease the strength of sandy soil and also the number cycles to failure. In case of no average shear stress, the cyclic shear strain is the governing failure mode but in case of significant average shear stress, the permanent or progressive shear strain failure is the governing failure mode. The results fairly agree with the previous studies found in the literature and can be used for the design of wind turbine and offshore structure foundations.

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