

DEFORMABILITY AND STRENGTH CHARACTERISTICS OF THE SAND DUNES OF KARAKALPAKSTAN BASED ON TRIAXIAL TEST RESULTS

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Abstract:

This paper presents the results of an experimental study of how the initial density of dune sand from the vicinity of Nukus, Karakalpakstan, affects its deformability and strength. Air-dry specimens were tested in a triaxial compression apparatus (stabilometer) using a consolidated-drained scheme with strain-controlled loading, at confining pressures of 100, 200 and 300 kPa and initial void ratios of 0.53, 0.65, 0.80 and 1.0. The dependences of deviator stress on vertical strain are nonlinear and convex toward the stress axis, and the volumetric strain changes only marginally during deviatoric loading. As the void ratio decreases from 1.0 to 0.53, the internal friction angle increases from about 38.7° to 42.3° , the cohesion from about 30 to 43 kPa, and the deformation modulus (at 100 kPa) from about 35 to 48 MPa; each parameter is described by a power function of the void ratio with R^2 of 0.94–0.99. These dependences can be used in the design of sand cushions under shallow foundations in Nukus, provided they are applied within the tested range of stresses and densities.

Keywords: Dune sand, triaxial compression, deformation modulus, internal friction angle, cohesion, void ratio.

Introduction

Several modern civil buildings are currently planned in the city of Nukus, Republic of Karakalpakstan. The buildings already constructed and designed there mostly have shallow strip foundations, and alluvial Quaternary deposits serve as the bearing strata. The soils of the city territory are represented by fine- and medium-grained (predominantly fine-grained) light-gray sands with interlayers of fine-earth material up to 0.4 m thick, light dusty loams, light-gray and yellowish-gray clays, sand layers,

and greenish-gray, dark-gray and ochre-colored clays up to 0.3 m thick [1]. The engineering-geological framework for evaluating such soil sequences is described in.

Where weak soils occur within the active zone of a foundation, they are commonly replaced with stronger material. A sand cushion placed under the footing increases the load-bearing capacity, reduces settlement and, owing to its high permeability, prevents groundwater from accumulating under the foundation. The seismic intensity of a construction site is first taken from the seismic zoning map of the Republic of Uzbekistan and is then corrected for the soil category. Replacing water-saturated clayey soils with a compacted sand cushion is therefore also recommended in practice as a means of improving the ground conditions of the site with respect to seismic effects [2].

Dune sands, which are abundant around Nukus, are an attractive local material for such cushions. Earlier work examined their physical and mechanical properties in order to evaluate this possibility. Compressibility was determined in a compression (oedometer) device using a consolidated-drained scheme, and strength was determined in a direct shear device, in both fully water-saturated and air-dry states, on specimens with initial void ratios of $e = 0.785$ and 0.580 . The mechanical properties were found to depend on both the initial density and the degree of water saturation [3]. In the dense state, saturation practically did not affect the strength of the sand, whereas in the loose state a slight increase in the internal friction angle was observed. The deformation modulus, however, decreased on saturation by 38% for loose sand ($e = 0.785$) and by 50% for dense sand ($e = 0.580$), and in the water-saturated state the modulus in the pressure range of 0.1–0.2 MPa did not depend on the initial density. It was concluded that dune sands can be used as foundations for buildings and structures in the compacted state [4].

Oedometer and direct shear tests, however, constrain the specimen to a prescribed deformation mode (zero lateral strain in the oedometer, a predetermined failure plane in the shear box). The triaxial test, by contrast, allows the stress state, drainage conditions and volumetric strain of a specimen to be controlled and measured, and it is generally regarded as the most reliable laboratory method for determining the strength and deformation parameters of soils. The mechanical behavior of granular soils depends strongly on density and confining stress through the interlocking and dilatancy of the grains and studies of dune sands in other regions have likewise examined the effect of the compaction state on their shear strength, compressibility and collapse potential [5].

The objective of this study is to quantify, using triaxial compression tests, the influence of the initial density on the deformation modulus, internal friction angle and cohesion of air-dry dune sand from the vicinity of Nukus, and to derive empirical relationships that can be used in the design of sand cushions for foundations [6].

Method

Material and specimens. The tests were performed on dune sand from the vicinity of the city of Nukus in the air-dry state. To evaluate the influence of the initial density, specimens were prepared at four initial void ratios (referred to as the “porosity coefficient” in the Russian-language literature): $e = 0.53$, 0.65 , 0.80 and 1.0 , which cover the range from dense to very loose packing.

Apparatus. The tests were carried out in a triaxial (three-axis) compression device, a stabilometer manufactured by GEOTEK (Russia). Fig. 1 shows a specimen in the cell after the test.



Figure 1. Dune sand specimen in the triaxial cell after failure

Test procedure. The sand was tested according to a consolidated-drained scheme, whose general principles are described, for example, in. Each specimen was first compressed hydrostatically until the volumetric strains had conditionally stabilized, and was then loaded under strain control at a rate of 0.016 mm/min until failure. The tests were conducted at hydrostatic (confining) pressures of $\sigma_3 = 100$, 200 and 300 kPa.

Data reduction. The deviator stress was calculated as

$$q = \sigma_1 - \sigma_3, \quad (1)$$

where σ_1 and σ_3 are the major and minor principal stresses, and was analyzed together with the relative vertical and relative volumetric strains. For each initial void ratio, the internal friction angle φ and the cohesion c were determined from the Mohr–Coulomb failure criterion

$$\tau_f = c + \sigma \tan \varphi, \quad (2)$$

fitted to the results obtained at the three confining pressures. The deformation modulus E was determined from the deviator stress–vertical strain curves at $\sigma_3 = 100$ kPa. The dependence of each parameter on the initial void ratio was approximated by a power function, and the quality of the approximation was assessed by the coefficient of determination R^2 .

Results

Stress–strain behavior. Fig. 2 shows the deviator stress as a function of the relative vertical strain for specimens with an initial void ratio of 0.53. The curves are nonlinear and convex toward the stress axis: the deviator stress rises steeply at small strains and then flattens toward a plateau, and the initial slope and the attained stress both increase with the confining pressure [7]. At a relative vertical strain of about 0.03, the deviator stress reaches approximately 0.56 MPa at $\sigma_3 = 100$ kPa, 0.87 MPa at 200 kPa and 1.36 MPa at 300 kPa (the last at a strain of about 0.029).

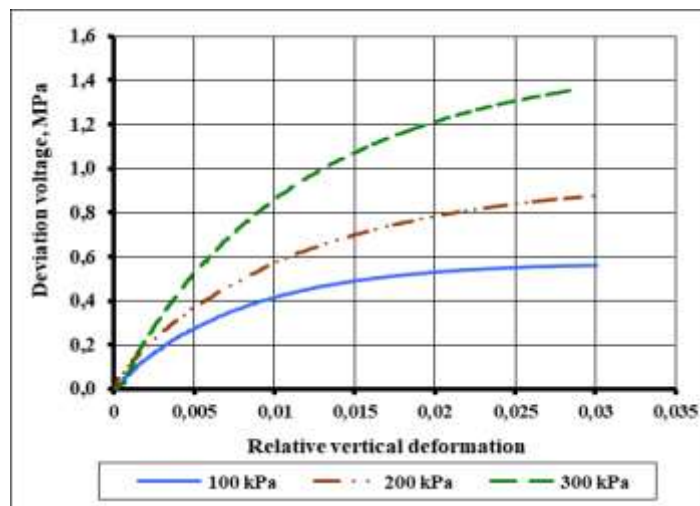


Figure 2. Dependence of deviator stress on relative vertical strain (initial void ratio $e = 0.53$)

Volumetric behavior. Fig. 3 presents the relationship between the relative volumetric strain and the relative vertical strain for the same specimens [8]. The relationships are linear and almost vertical at all confining pressures: during deviatoric loading, the volumetric strain changes by less than 0.02 over vertical strains of up to 0.03, with a very slight contraction at the beginning of shearing followed by slight dilation. The curves for higher confining pressures are shifted toward larger volumetric strains, which reflects the greater compression accumulated during the preceding hydrostatic stage.

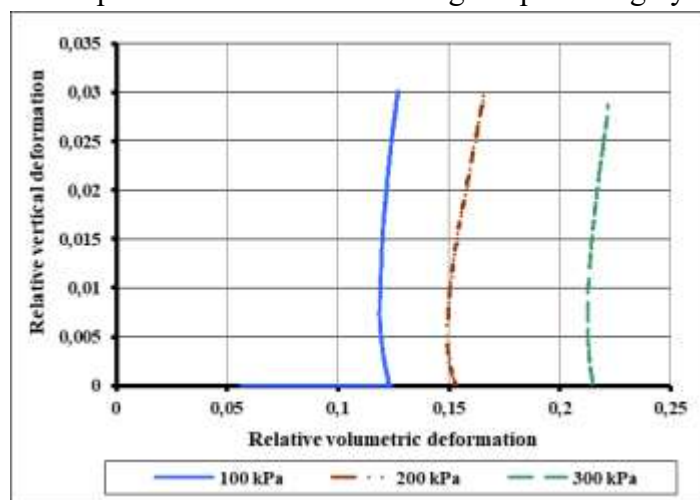


Figure 3. Relationship between relative volumetric strain and relative vertical strain (initial void ratio $e = 0.53$)

Influence of the initial density. Figs. 4–6 show the dependences of the internal friction angle, cohesion and deformation modulus on the initial void ratio, and Table 1 summarizes the values read from these figures [9]. As the void ratio increases from 0.53 to 1.0, the internal friction angle decreases from about 42.3° to 38.7° (a decrease of about 3.6° , or roughly 9%). The cohesion decreases from about 43 to 30 kPa, and it changes only slightly (from about 32 to 30 kPa) once the void ratio exceeds 0.8. The deformation modulus decreases from about 48 to 35 MPa, i.e., by roughly 27% relative to the densest state. The fitted power functions are $\phi = 38.942e^{-0.136}$ ($R^2 = 0.9627$), $c = 0.0294e^{-0.616}$ MPa ($R^2 = 0.943$) and $E = 35.359e^{-0.495}$ MPa ($R^2 = 0.9932$), where e is the initial void ratio.

Table 1. Mechanical characteristics of dune sand at different initial void ratios (values read from Figs. 4–6; E at $\sigma_3 = 100$ kPa)

Initial void ratio, e	Friction angle, φ (°)	Cohesion, c (kPa)	Deformation modulus, E (MPa)
0.53	42.3	43	48
0.65	41.3	40	44
0.80	40.5	32	40
1.0	38.7	30	35

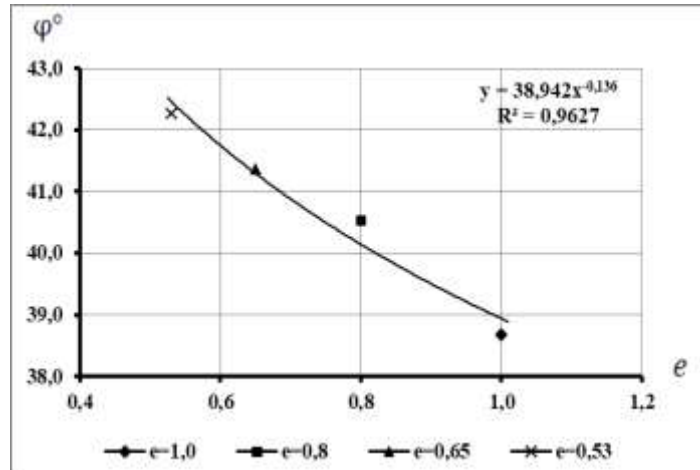


Figure 4. Dependence of the internal friction angle on the initial void ratio

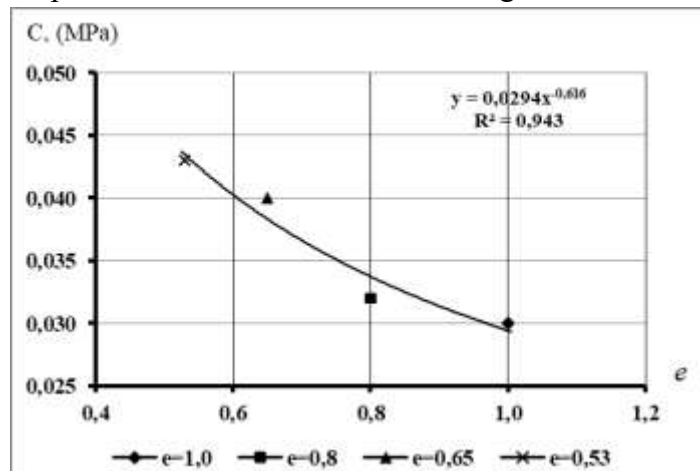


Figure 5. Dependence of the cohesion on the initial void ratio

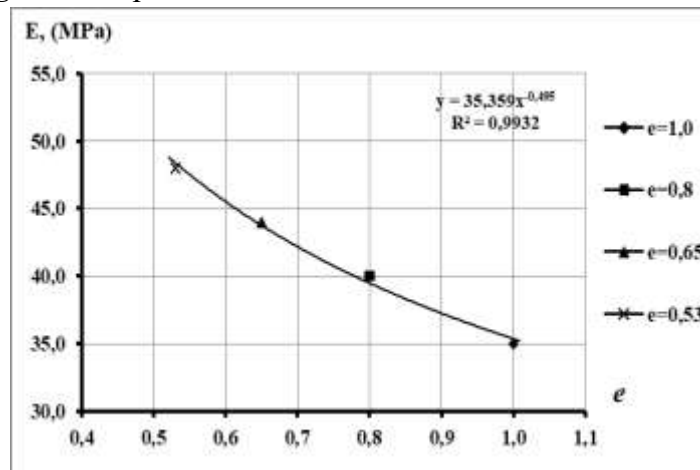


Figure 6. Dependence of the deformation modulus on the initial void ratio (confining pressure 100

Discussion

The results confirm that the strength and stiffness of the dune sand increase as its initial void ratio decreases. Within the tested stress range, the friction angle rose by about 3.6° when the void ratio decreased from 1.0 to 0.53. This agrees with the classical view that the strength of sand is the sum of frictional resistance and the additional resistance needed for the grains to dilate against the confining stress, so that denser packings, which have greater interlocking, mobilize higher strength [10]. The same direction of change was reported for the sands of this region in direct shear tests and studies of dune sands elsewhere likewise found that the compaction state governs their mechanical behavior.

The fitted exponents show that the three parameters respond differently to density. The exponent for the friction angle is small (-0.136), so ϕ is the least sensitive; the deformation modulus, with an exponent of -0.495 , varies approximately in inverse proportion to the square root of the void ratio; and the cohesion, with an exponent of -0.616 , is the most sensitive. A stiffness that grows as the void ratio falls is expected, because a denser packing has more grain contacts per unit volume and smaller deformations at each contact [11]. These relationships are empirical and should be used only within the tested range of void ratios (0.53–1.0).

The nonlinear, convex shape of the stress–strain curves is typical of granular soils. The dependence of such curves on confining pressure is commonly represented by hyperbolic relationships or by elastoplastic models and the data presented here could be used to calibrate such models for the dune sand, although this was not attempted in the present work [12]. The nearly constant volumetric strain during shearing (Fig. 3) is consistent with the view that, at confining pressures of 100–300 kPa, the tendency of a dense sand to dilate is suppressed, since dilatancy depends on the stress level as well as on the density.

The cohesion values of 30–43 kPa deserve comment. Air-dry sand with little or no fines and cementation would be expected to have little true cohesion, so c should be interpreted as an apparent parameter: it is the intercept of a straight Mohr–Coulomb line fitted to a failure envelope that is in reality curved, over a limited stress range of 100–300 kPa, combined with the contribution of grain interlocking [13]. It is therefore a fitting parameter that is valid only within the tested stress range, and extrapolating it to the lower stresses that occur near the base of a thin cushion could overestimate the strength.

For the design of sand cushions, Figs. 4–6 show the benefit of compaction: reducing the void ratio from 1.0 to 0.65 raises the friction angle from about 38.7° to 41.3° and the deformation modulus from about 35 to 44 MPa, and controlled compaction in layers is the standard way of achieving such densities in placed granular fill. However, the earlier tests showed that water saturation reduced the deformation modulus of the sand by 38–50%, whereas the present tests were performed on air-dry sand [14]. The moduli reported here should therefore be reduced or verified for saturated conditions wherever groundwater or leakage is likely. In addition, the tests are static and do not measure dynamic properties, so the effect of a dune-sand cushion on the seismic behavior of a site, including the liquefaction susceptibility of loose water-saturated sands, must be assessed separately by cyclic or dynamic testing. The study has further limitations. Only one sand source, one moisture state, four void ratios, confining pressures of 100–300 kPa and vertical strains of about 3% were considered. Particle shape, which is known to affect both the packing density and the strength of sands as well as the grain-size distribution and mineralogy of the Nukus dune sand, should be characterized in future work. Further tests on water-saturated specimens, at additional confining pressures and under cyclic loading, together with field plate-load tests on compacted cushions, would allow the relationships obtained here to be verified and

Conclusion

Consolidated-drained triaxial compression tests on air-dry dune sand from the vicinity of Nukus, performed at confining pressures of 100–300 kPa and initial void ratios of 0.53–1.0, showed that the deformability and strength of the sand depend markedly on its initial density. The deviator stress–vertical strain curves are nonlinear and convex toward the stress axis, and the volumetric strain remains nearly constant during shearing. As the void ratio decreases from 1.0 to 0.53, the internal friction angle increases from about 38.7° to 42.3°, the cohesion from about 30 to 43 kPa, and the deformation modulus at 100 kPa from about 35 to 48 MPa, and each parameter is described by a power function of the void ratio with a coefficient of determination of 0.94–0.99. These relationships can be used to select the compaction state and to estimate the design parameters of dune-sand cushions under shallow foundations in Nukus, provided that they are applied within the tested range of stresses and densities and that the reduction of stiffness on water saturation reported earlier is taken into account. The influence of such cushions on the seismic behavior of construction sites, as well as the behavior of water-saturated sand, remains to be established by dynamic and saturated tests.

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