State dependent characteristics of Bagmati sand

Caractéristiques dépendantes d'État de sable Bagmati

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ABSTRACT

Sand subjected to shear, under drained conditions, shows unique behavior depending upon its density and applied confining pressure. Loose sand contracts accompanied by strain hardening and dense sand dilates accompanied by strain softening. Strength, dilatancy and plastic shear work characteristics of sand is dependent on both the relative density and confining pressure. Here an attempt has been made to investigate pressure and density dependent characteristics of Bagmati sand using drained triaxial compression tests. Evolution of mobilized angle of internal friction, dilatancy characteristics, peak friction angle, critical state friction angle and maximum dilation angle of Bagmati sand are obtained and analyzed. It has been reported that excess friction angle varies linearly with maximum dilation angle with a slope ranging from 0.28 to 0.4. In case of Bagmati sand, the slope is found to be 0.34 and is in well agreement with available empirical relationships.

RÉSUMÉ

Le sable fait subir pour tondre, dans les conditions égouttées, montre la conduite unique selon sa densité et pression de confinant appliquée. Les contrats de sable desserrés accompagnés par l'effort le sable durcissant et dense se dilatent accompagné par l'adoucissement d'effort. La force, dilatancy et les caractéristiques de travail de tondage de plastique de sable dépend tant de la densité relative que du confinant de la pression. Ici un essai a été fait pour enquêter sur la pression et les caractéristiques de personne à charge de densité d'utilisation de sable Bagmati ont égoutté des épreuves de compression triaxial. L'évolution d'angle mobilisé de friction intérieure, dilatancy les caractéristiques, la friction maximale l'angle de friction, critique et l'angle de dilatation maximum de sable Bagmati est obtenue et analysée. Il a été annoncé que l'angle de friction d'excès varie d'une façon linéaire avec l'angle de dilatation maximum avec une pente aux limites de 0.28 à 0.4. En cas du sable Bagmati, la pente est trouvée pour être 0.34 et est dans bien l'accord avec les rapports empiriques disponibles.

Keywords : sand, triaxial compression, plastic work, dilatancy

1 INTRODUCTION

It has now been established that, subjected to a shear under drained conditions, loose sand contracts accompanied by strain hardening and dense sand dilates accompanied by strain softening. Both loose and dense sands ultimately achieve a critical state at which there is no change in volumetric strain. State of sand whether it is loose or dense depends on both the relative density and applied confining pressure. The combined influence of pressure and density on shear behavior of sand has been observed in experimental results (Been and Jefferies 1985, Vaid and Sasitharan 1992, Verdugo and Ishihara 1996). A review of the experimental results and suggestion of empirical relationship for practical use has been proposed, for example by Bolton (1986) and Yang and Li (2004) for pressure and density dependent characteristics of sand.

Pressure and density dependent characteristics of sand should be taken into account for engineering design and development of a constitutive model. Some of the constitutive models that takes account of pressure and density dependent characteristics of sand has been proposed by Been and Jefferies (1985), Cubrinovski and Ishihara (1998), Wan and Guo (1999), Li (2002), among others. Peak friction angle, critical state angle and maximum angle of dilatancy are often the important parameters to characterize the state dependent characteristics of sand and to define a suitable constitutive relationship. There is an existing extensive laboratory investigation on the combined effect of relative density and confining pressure and based on such extensive data-base, empirical relationships to determine the strength of sand are available. The objective of the present study is to characterize the pressure and density dependent characteristics of Bagmati sand and to investigate the major characteristics of sand such as peak friction angle, critical state friction angle and maximum dilation angle. The excess friction angle for Bagmati sand is correlated with maximum dilation angle and the obtained relationship has been compared with existing empirical relationships.

2 SOIL TESTED AND CALCULATION PROCEDURE

Sand samples from Bagmati River, Kathmandu, Nepal has been used in this study. Bagmati sand is clean, uniform sand with mean particle size of 0.6 mm, maximum and minimum void ratios as 0.946 and 0.61, respectively. The sand grains are mostly angular with quartz as a major constituent mineral.

Drained triaxial tests are conducted on Bagmati sand for varying relative densities and confining pressures. The stress and strain invariants for the conventional triaxial test under axisymmetric condition are defined as:

$$p = (\sigma_1 + 2\sigma_3)/3, q = \sigma_1 - \sigma_3 \tag{1}$$

$$\varepsilon_v = \varepsilon_1 + 2\varepsilon_3, \varepsilon_q = 2(\varepsilon_1 - \varepsilon_3)/3 \tag{2}$$

$$\varepsilon_v^p = \varepsilon_1^p + 2\varepsilon_3^p, \varepsilon_q^p = 2(\varepsilon_1^p - \varepsilon_3^p)/3 \tag{3}$$

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where p is the mean effective stress, q is the deviatoric stress, σ_1 is the effective axial stress, σ_3 is the effective radial stress, ε_v is the volumetric strain, ε_q is the equivalent (deviatoric) shear strain. In constitutive relations, the stress and strain variants are generally expressed in incremental form and it is usual to divide the total strain increment $d\varepsilon_{ij}$ into two parts, the elastic part $d\varepsilon_{ij}^e$ and the plastic part $d\varepsilon_{ij}^p$, hence

$$d\varepsilon_{ij} = d\varepsilon_{ij}^e + d\varepsilon_{ij}^p \qquad (4)$$

$$d\varepsilon_v = d\varepsilon_v^e + d\varepsilon_v^p ,\ d\varepsilon_q = d\varepsilon_q^e + d\varepsilon_q^p \qquad (5)$$

where the subscripts e and p denote elastic part and plastic part, respectively. Similarly, total and normalized plastic work done under triaxial shearing are:

$$dW^p = \sigma_1 d\varepsilon_1^p + 2\sigma_3 d\varepsilon_3^p = p d\varepsilon_v^p + q d\varepsilon_q^p \qquad (6)$$

$$\frac{W^p}{p} = \sum \frac{dW^p}{p} \qquad (7)$$

where ε_v^p is the plastic volumetric strain, ε_q^p is the deviatoric plastic strain, W^p is the plastic work, W^p/p is the normalized plastic work. The elastic strain increments are simply determined from generalized Hooke's law and defined as:

$$d\varepsilon_v^e = \frac{dp}{K}; d\varepsilon_q^e = \frac{dq}{3G} \qquad (8)$$

where G and K are elastic shear modulus and bulk modulus, respectively given by:

$$G = 125 p_a \frac{(2.97-e)^2}{1+e}\sqrt{p'/p_a} \qquad (9)$$

$$K = G\frac{2(1+\upsilon)}{3(1-2\upsilon)} \qquad (10)$$

where p_a is the atmospheric pressure (101.3 kPa) and υ is the Poisson's ratio.

3 RESULTS AND DISCUSSIONS

Fig. 1 illustrates the typical stress ratio-axial strain and volumetric strain behavior of the sand with an initial relative density of D_r=25% and D_r=49% subjected to mean initial pressure of 100 kPa and 400 kPa. For the same relative density, the responses are influenced by confining pressure. When the sand is confined at a lower pressure of 100 kPa, a peak stress ratio and strain softening after the peak are observed for both the two initial densities considered. For a given initial density, the stress ratio (q/p') eventually reaches the same critical state as shown in Figs. 1a and 1b. For the confining pressure of 400 kPa, D_r=25%, strain softening and dilation is not observed (Fig. 1c) while for D_r=49% shows strain softening having a less dilation than that for 100 kPa (Fig. 1d).

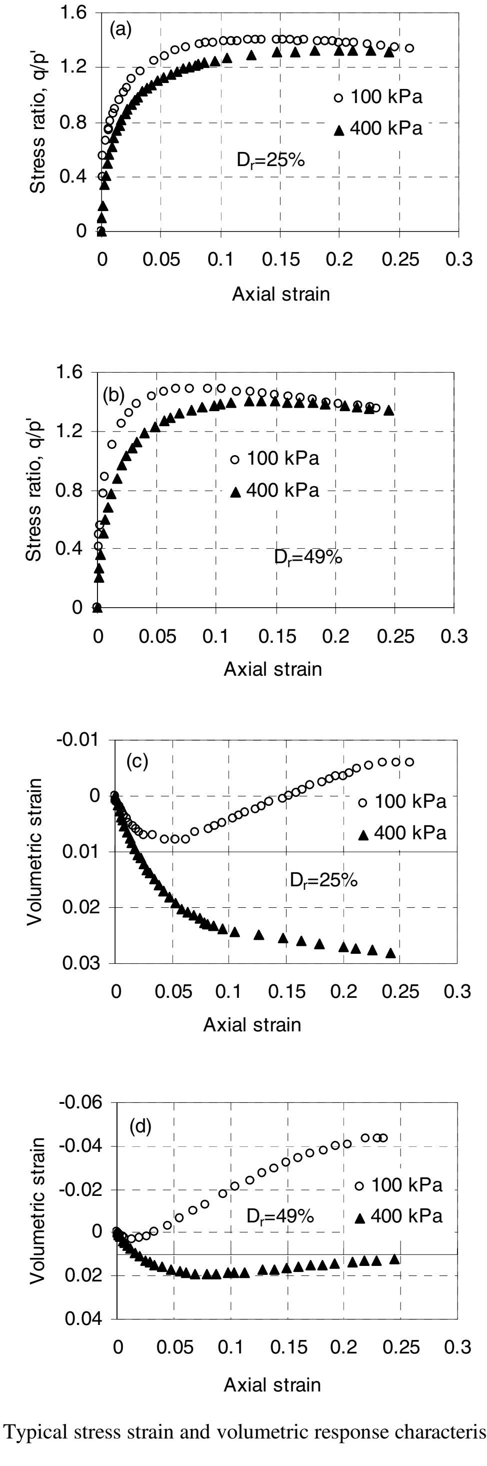

Figure 1. Typical stress strain and volumetric response characteristics of sand

Fig. 2 shows the evolution of the mobilized friction angle for loose and dense states of sand. The mobilized angle of shearing resistance is given by:

$$\sin\phi'_m = \frac{3\eta}{6+\eta} \qquad (11)$$

where $\eta = q/p'$ is the stress ratio.

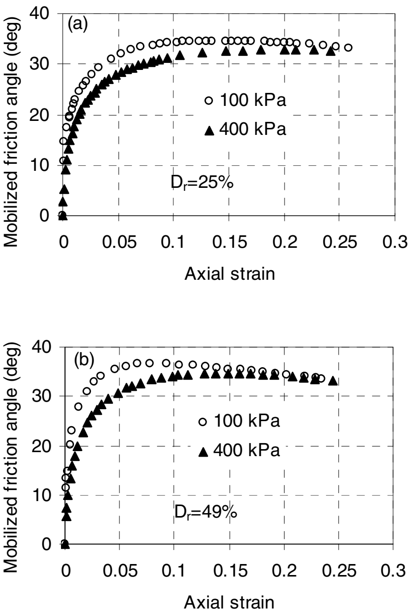

Figure 2. Evolution of mobilized friction angle

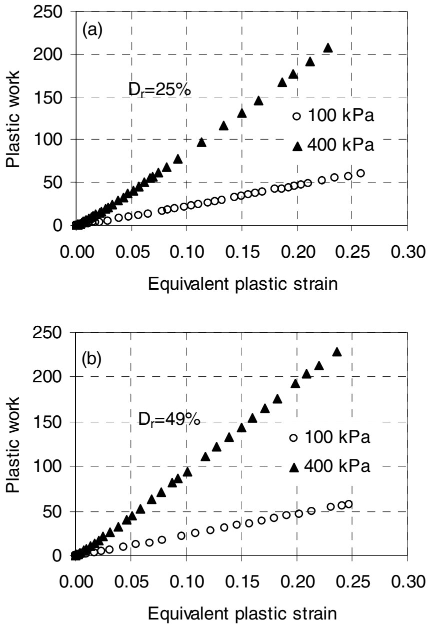

Figure 3. Plastic work versus equivalent plastic strain

For the sand in a dense state (for example, D_r=49%, confining pressure=100 kPa), the angle of friction is mobilized very fast at the early stage of deformation. A peak friction angle of 36.6° is developed followed by a reduction in the shearing resistance and eventually attaining a critical state angle of 33°. For loose sand, the mobilization of friction angle is slow and it attains a critical state at very large strain. In some cases, this strain for very loose sand may not be achieved and the critical state may not be obtained as for the case shown here for initial density of 25% and a confining pressure of 400 kPa.

Fig. 3 shows the plastic work versus equivalent plastic strain for two different relative densities and confining pressures and Fig. 4 show the normalized plastic work where it is shown that the relationship between normalized plastic strains with equivalent plastic strain is independent of relative density and confining pressure. Cubrinovski and Ishihara (1998) have shown that such relationship is independent of the relative density, mean pressure, overconsolidation ratio and inherent anisotropy.

Fig. 5 shows the influence of initial density and confining pressure on the peak friction angle (φ'_p) for Bagmati sand. For a given confining pressure, there is an increase in peak friction angle as the relative density increases. Similarly, for a given relative density, as the confining pressure increases, there is a decrease in peak friction angle. Critical state angle (φ'_{cs}) provides the lower limit of peak friction angle and the excess friction angle $(\varphi'_p - \varphi'_{cs})$ can be correlated with initial density (Bolton 1986) as:

$$\phi'_p - \phi'_{cs} = 3[D_r(10 - \ln p'_f) - 1] \qquad (12)$$

where D_r is expressed in fraction and p'_f is the mean effective stress at failure (kPa). Since it is not appropriate to treat failure stress as a constant input parameter, Yang and Mu (2008) modified Equation 12 as:

$$\phi'_p - \phi'_{cs} = 3D_r\left(10 - \ln\left(p'_0 \Big/ \left(1 - \frac{2\sin\phi'_p}{3 - \sin\phi'_p}\right)\right)\right) - 3 \qquad (13)$$

where p'_0 is the initial mean effective stress.

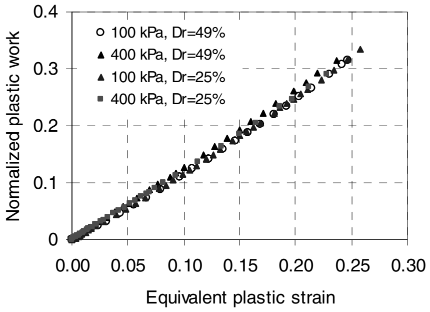

Figure 4. Normalized plastic work versus equivalent plastic strain

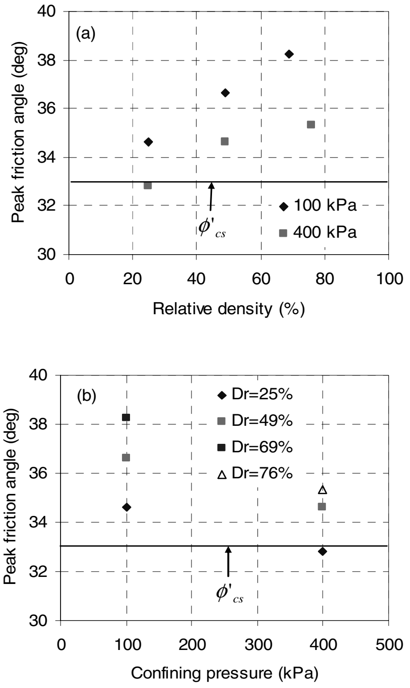

Figure 5. Peak friction angle for varying relative density and confining pressure

Equation 13 is plotted in Fig. 6 for two relative densities and it can be seen that the experimental results are in good agreement with model predictions.

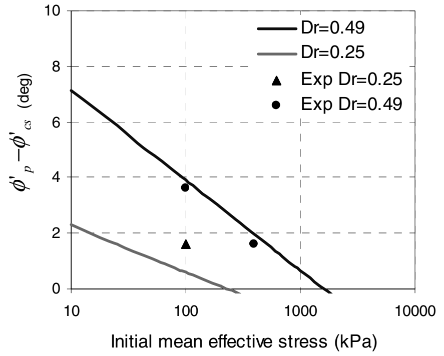

Figure 6. State dependent effective friction angle

The peak friction angles are often related with critical state angle and maximum dilation angle. The dilatancy angle ψ is commonly used to represent the dilation characteristics of sand. The dilation angle has been uniquely defined for plane strain conditions but in a different ways under triaxial loading conditions (Frydman et al., 2007). Yang and Li (2004) uses the following expression for the maximum dilation angle:

$$\sin\psi_{\max} = \frac{2}{3}\left|\frac{d\varepsilon_v^p}{d\varepsilon_q^p}\right|_{\max} = \frac{2}{3}\left|d\right|_{\max} \tag{14}$$

where $d = d\varepsilon_v^p / d\varepsilon_q^p$ is dilatancy. Similarly, for triaxial compression, Frydman et al. (2007) uses the following expression for dilation angle:

$$\sin\psi = -\frac{d\varepsilon_v^p}{d\gamma^p} = -\frac{d\varepsilon_1^p + 2d\varepsilon_3^p}{d\varepsilon_1^p - d\varepsilon_3^p} \tag{15}$$

where $\gamma^p = \varepsilon_1^p - \varepsilon_3^p$, is the plastic shear strain.

The two definitions in Equations 14 and 15 are identical; however, Schanz and Vermeer (1996) suggest an alternative definition for dilation angle as:

$$\sin\psi = -\frac{d\varepsilon_v^p}{2d\varepsilon_1^p - d\varepsilon_v^p} = -\frac{d\varepsilon_1^p + 2d\varepsilon_3^p}{d\varepsilon_1^p - 2d\varepsilon_3^p} \tag{16}$$

In this study, Equations 14 or 15 is used to determine the maximum dilation angle for Bagmati sand. Based on existing literatures, excess friction angle can be correlated with maximum dilation angle ($\psi_{\max}$) as:

$$\phi'_p - \phi'_{cs} = \alpha.\psi_{\max} \tag{17}$$

where α is a constant given as: α =0.8 (Bolton, 1986 for plane strain conditions), α =0.33 (Vaid and Sasitharan, 1992), α =0.28 (Yang and Li, 2004) and α =0.4 (Frydman et al., 2007). Fig. 7 shows the relation between excess friction angle and maximum dilation angle and from the limited number of experimental results of Bagmati sand, the value of α is obtained to be equal to 0.34, which is in very close agreement with Vaid and Sasitharan (1992). However, a range of α from 0.28 to 0.4 can be assumed for practical purposes.

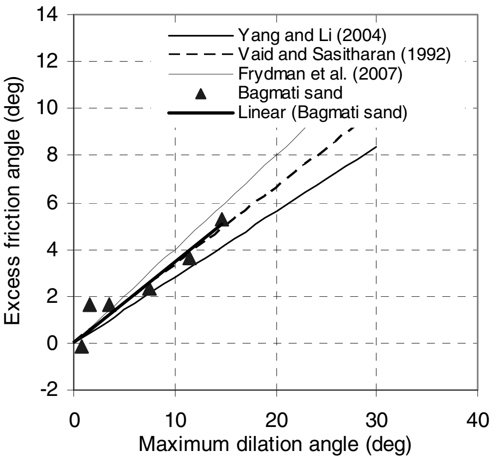

Figure 7. Relationship between peak friction angle and maximum dilation angle

4 CONCLUSIONS

Dilatancy and shear work characteristics of Bagmati sand have been discussed. Dependency of excess friction angle with respect to relative density and confining pressure shows unique relationship. In all cases, the critical friction angle of 33° provides the lower limit except for the case where the critical state has not been reached during laboratory test conditions. Dependency of peak friction angle with maximum dilation angle observed for Bagmati sand shows similar trends obtained for other sands and is in well agreement with empirical relationships. The observed and compared results of Bagmati sand will be very useful in modeling the behavior of Bagmati sand and its further use in geotechnical design.

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