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Prediction of unsaturated shear strength of an adobe soil from the soil–water characteristic curve

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HIGHLIGHTS

- Adobe masonry exists in unsaturated conditions and its strength is affected by water content.
- Unsaturated shear strength of adobe was predicted from SWCC, effective strength and available models.
- This prediction does not require shear strength testing with suction control.
- The predicted failure envelopes in the shear strength–matric suction plane were nonlinear.
- After the air-entry value, the slope of the failure envelopes decreased with soil suction.

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ABSTRACT

This paper studied the unsaturated shear strength properties of a soil with the gradation characteristics of the material typically used in adobe construction. The main goal was to predict the unsaturated shear strength of the adobe soil using the soil–water characteristic curve (SWCC) and the effective cohesion and friction angle of the material. Specimens were trimmed from adobe bricks made according to the traditional technique of the southwestern region of the United States. The SWCC of the adobe soil was constructed using data obtained with the filter paper test. The effective cohesion and friction angle were found to be 11.7 kPa and 31.4°, respectively, from the results of consolidated drained direct shear tests. In addition, unconsolidated undrained direct shear tests were done on specimens at different water contents to determine the apparent shear strength parameters. The predicted shear strength was found to increase significantly with decreasing water content, and the strength increase was approximately 350 kPa between near saturation condition and water content of 6.01%. The predicted failure envelopes in the shear strength–matric suction plane were nonlinear; their initial slope was close to the (saturated) effective friction angle, and the slope decreased as the suction increased.

1. Introduction

In the southwestern parts of the United States of America (USA), many historic landmarks as well as contemporary buildings and residential construction are built with sun-dried mud bricks, regionally called adobe. The traditional adobe brick production is environmentally friendly and sustainable as it uses locally available soils and requires very little energy and water. The soils used to make adobe bricks typically contain fractions of clay, silt and sand. Cut straw is often added to the adobe mixture to help obtain even drying and in turn reduce shrinkage cracking of the bricks. Adobe walls are constructed by laying the brick units and mud mortar in an alternating fashion as in conventional masonry construction. Mud mortar is made of the same soil as the adobe bricks.

A serious concern related to adobe construction is its susceptibility to moisture penetration and weakening caused by seasonal wetting and drying cycles, capillary rise and rain [1]. Significant moisture damage in adobe walls has been reported in historic landmark buildings in the USA, such as the Franciscan church at the Mission San Jose de Tumacacori National Monument, New Mexico, built in 1828 [2], the Amador Hotel in Las Cruces, New Mexico, built in 1866 and expanded in 1885 (Fig. 1), and the Andres Pico Adobe residence, built circa 1816 to 1860 with several later additions and restorations [3].

The strength of sun-dried adobe bricks, and consequently adobe masonry, can be reduced considerably with increasing water content of the soil material within the walls [4]. The detrimental effects of moisture in adobe include material weakening due to substantial loss of soil suction and adobe weathering. Cracks in the plaster and capillary rise from the foundation are means for

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(a)


(b)

Fig. 1. The Amador Hotel in Las Cruces, New Mexico: (a) street view of the building in 2013, and (b) lower part of an adobe wall showing extensive brick degradation and material loss due to moisture damage (the plaster was removed during restoration work).

the water to enter the adobe walls. Greater moisture damage is often reported in the lower portions of walls [2,5] as penetration of capillary water at the base is a major source of moisture. The problem may be aggravated in adobe walls treated with impervious surface coating because the water is forced higher into the wall before it can reach the surface and evaporate [5]. Moisture affects negatively the static and seismic performance of adobe walls through different mechanisms. For example, a through-wall shear plane may develop in a wall with weakened wet base during ground shaking and result in sliding or collapse of the part of the wall above this plane [6,7]. Wetting of the wall base at water content near or over the plastic limit may induce bulging or sagging of the lower part of the wall under self-weight and service loads.

Despite the importance of the changes in material properties resulting from wetting of adobe walls during service, these changes are not considered explicitly in the practice and the material strength properties are usually determined by testing air-dry adobe bricks. Adobe is mostly in unsaturated conditions in its natural environment. The authors aimed at emphasizing the importance of considering unsaturated soil principles when studying the material and structural performance of adobe masonry. However, laboratory testing to determine unsaturated soil strength with controlled suction is expensive and requires specialized equipment and training. In the practice, direct suction measurements may not be required as they could be evaluated more easily from the soil–water characteristic curve (SWCC) of the soil [8,9]. In this context, the main goal of this paper is to predict the shear strength of unsaturated adobe soil using the SWCC and the effective shear strength parameters of the adobe soil.

2. Shear strength of unsaturated soil

The shear strength of unsaturated soil can be described using the extended Mohr–Coulomb failure criterion proposed by Fredlund et al. [10], given by

$$\tau_f = c' + (\sigma - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi^b \tag{1}$$

which could be written as

$$\tau_f = c' + (\sigma - u_a)_f \tan\phi' + c'' \tag{2}$$

where τ_f is the shear stress on the failure plane at failure, c' and ϕ' are the effective shear strength parameters (effective cohesion and effective friction angle, respectively), $(\sigma - u_a)_f$ is the net normal stress on the failure plane at failure, $(u_a - u_w)_f$ is the matric suction at failure, σ is the total normal stress, u_a is the pore-air pressure, u_w is the pore-water pressure, ϕ^b is a variable that describes the rate of change in shear strength relative to changes in matric suction [11], and c'' is the capillary cohesion. The net normal stress and the matric suction are two independent stress-state variables. In this model, the shear strength failure envelope is a planar surface in the space of net normal stress, matric suction and shear stress [10].

Experimental results reported in the literature indicate that the failure envelope in the shear strength–suction plane is nonlinear for matric suction values greater than the air-entry value and within the desaturation zone [11–14]. In this suction range, the rate of increase in shear strength with suction decreases [11,12]. After reaching the residual state, the shear strength of unsaturated soils may increase, remain constant or decrease depending on the amount of water remaining in the pores to transmit suction among the soil particles [12]. Bai and Liu [14] showed that the shear strength–matric suction curves for compacted Nanyang soil were nonlinear, with ϕ^b decreasing from 11.1° (=ϕ') to about 2° at matric suction of approximately 2000 kPa. In compacted specimens of Ankara clay [13], the shear strength–total suction curves were nonlinear too. Under normal pressure of 150 kPa, the shear strength increased from 50 kPa for specimens with water content (w) greater than optimum (w = 22.8%, 24.8%, 26.8%) to about 250 kPa for w drier than optimum (w = 14.8%, 16.8%, 18.8%).

Modified triaxial or direct shear testing equipment in which the matric suction is controlled by axis-translation or osmotic technique is used to determine the shear strength of unsaturated soils [15,16]. Alternatively, results from conventional direct shear test on saturated specimens and the SWCC can be used as input in predicting models of the shear strength of unsaturated soils, e.g. [11,12,17]. The SWCC describes the relation between suction and water content of the soil. This curve is dependent on the soil type. To establish the SWCC, soil suction must be determined directly or indirectly using one or several techniques, such as pressure plate extractors, filter paper test, tensiometers, and psychrometers. The filter paper test is a reliable, inexpensive and relatively simple method to measure soil suction [18] and thus was used in this study.

The semi-empirical model proposed by Vanapalli et al. [12] predicts the unsaturated soil shear strength as a function of matric suction using the effective (saturated) soil shear strength parameters and the SWCC. Vanapalli et al. [12] proposed modifications to Eq. (1) as follows:

$$\tau_f = c' + (\sigma - u_a)_f \tan\phi' + (u_a - u_w)_f \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) \tan\phi' \tag{3}$$

where $(u_a - u_w)_f$ is the matric suction (ψ_m) from the SWCC at the water content of the specimen at failure, θ is the volumetric water content at the corresponding suction, θ_s is the volumetric water content of the saturated soil, and θ_r is the soil residual volumetric water content. The term $\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)$ is the normalized water content.

3. Experimental program

The experimental program consisted of laboratory measurements of total and matric suction and shear strength parameters