SHEAR STRENGTH DESIGN OF THIN PAVEMENTS AND UNBOUND ROADS

by

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Abstract

The behavior of thin pavements and unbound roads is markedly nonlinear. The design of thin pavements and unbound roads can be accomplished using an ultimate strength approach which assumes a plastic collapse of the pavement. The layers comprising thin pavements and unbound roads are usually unsaturated. Thin pavement and the unbound road design must account for the matric suction in the unsaturated layers.

Keywords: *matric suction, thin pavement, unbound roads, bearing capacity, shear strength, limit equilibrium, ultimate load, unsaturated soils, layered soils, factor of safety, load factor, environmental effects.*

Introduction

Thin pavements and unbound roads are made up of unbound granular base layers overlying natural subgrades. A surfacing layer, if it exists, protects the pavement structure from water infiltration but makes little contribution to the bearing capacity of the pavement. The response of the unbound pavement layers to traffic loading is nonlinear even at low stresses and the use of design methods based on the assumption of linear elasticity may not be valid. The design of such pavements is better accomplished using ultimate strength approaches which assume plastic collapse of the pavement and utilize the shear strength parameters, c' and ϕ', of the pavement materials. In addition, ultimate strength methods of design offer a number of advantages over elastic layer methods including: the shear strength parameters, c' and ϕ', are clearly defined and are easier to measure than the elastic parameters, E and ν required for elastic analysis; the approaches are less empirical and allow for the pavement to be designed to a known factor of safety and for a more realistic incorporation of environmental conditions in design.

The layers comprising thin pavements and unbound roads are usually compacted during placement and therefore exist in an unsaturated state. Furthermore, roads are exposed to the environment and are subject to seasonal variations in moisture conditions. A meaningful design process must account for the matric suction that arises from compaction and changes thereof caused by environmental fluctuations.

This paper reviews aspects of the soil mechanics of unsaturated soils that are relevant to the design of thin pavements and outlines an ultimate strength pavement design method that utilizes the shear strength parameters c', ϕ' and ϕ^b.

Bearing Capacity of the Pavement

The design of pavements based on bearing capacity theory is based on the fixed level of traffic approach which is mainly used in airport design. The traffic volume on thin pavements and unbound roads is low and comparable to the frequency of landing of aircraft in smaller airports. The fixed level of traffic approach involves the design of the pavement for a critical wheel load, usually the heaviest wheel load.

Traffic wheel loading is represented in the form of a contact pressure and dimensions of the loaded area. The pavement is idealized as a 2-layer system consisting of the base and subgrade layers. Each layer is made up of soil having cohesion, friction, and unit weight. The pavement is assumed to undergo a general shear failure mechanism due to traffic loading as shown in Fig.1. Since wheel loads are applied on the ground surface, the effects of surcharge are neglected in the analysis and the bearing capacity is assumed to be given by:

$$q_f = c_1 N_c + \frac{1}{2} B_e \gamma_1 N_\gamma \qquad [1]$$

where: c_1 = effective cohesion of base layer, γ_1 = unit weight of the base layer, B_e = effective width of the tire contact area, N_c = bearing capacity factor with respect to cohesion, N_γ = bearing capacity factor with respect self-weight.

The bearing capacity factors, N_c and N_γ are functions of the the dimensions of the loaded area, the depth of the base layer and the shear strength and the unit weight of both the base layer and the subgrade.

The bearing capacity factors are determined separately by considering the equilibrium of the passive and active soil wedges (Fig. 2) as proposed by Terzaghi (1943). The effective loaded width, B_e, is determined by idealizing the contact area between the tire and the pavement surface. The determination of the bearing capacity factors, N_c and N_γ are presented in Oloo (1994).

Overall Bearing Capacity

The bearing capacity factors N_c and N_γ are substituted into Eq. 1 to obtain the overall bearing capacity for the 2-layer pavement. The variation of the overall bearing capacity with the depth of the top layer, H_1, is shown in Fig. 3. The bearing capacity varies from a minimum value for $H_1 = 0$ to a maximum corresponding to the bearing capacity of the top pavement layer only. The proposed solution seems to give reasonable estimates of bearing capacity for a 2-layer pavement system.

Influence of Matric suction on Bearing Capacity

Seasonal moisture variations and the effects of compaction during placement result in pavement layers that are unsaturated. The shear strength and therefore bearing capacity of the unsaturated soils are defined in terms of two stress state variables, net normal stress, $(\sigma - u_a)$, and matric suction, $(u_a - u_w)$. Fredlund et al (1978) proposed the following equation for the shear strength of an unsaturated soil:

$$\tau_f = c'(\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b \qquad [2]$$

where: c', = effective cohesion of the soil, ϕ', = effective angle of friction, and ϕ^b, = friction angle associated with the matric suction in the soil.

The behavior of ϕ^b is nonlinear beyond the air entry value of the soil. The nonlinear relationship between shear strength and matric suction can be approximated by a bi-linear envelope (Fredlund et al, 1987) (Fig. 4). Matric suction can be visualized as contributing to the cohesion of the soil and Eq. 2 can be re-arranged as follows:

$$\tau_f = \left[c' + (u_a - u_w)\tan\phi^b\right] + (\sigma - u_a)\tan\phi' \qquad [3]$$

Equation 1 can be modified for the unsaturated pavement layers by using the appropriate cohesions as follows:

$$c_1 = c_1' + (u_a - u\ )_1 \tan\phi_1^b \qquad [4]$$

$$c_2 = c_2' + (u_a - u\ )_2 \tan\phi_2^b \qquad [5]$$

where: $(u_a - u_w)_1$ = average matric suction in the base layer, $(u_a - u_w)_2$ = average matric suction in the subgrade, ϕ_1^b, ϕ_2^b = friction angle with respect to matric suction for base and subgrade layers.

Equation 3 assumes that ϕ^b is constant. If ϕ^b is not constant, the value corresponding to the appropriate level of matric suction is used.

The effective shear strength parameters c' and ϕ' for the materials in the pavement layers can be determined using conventional triaxial or shear box tests on saturated samples. Specialized testing equipment and procedures are required for the determination of ϕ^b.

Measurement of ϕ^b

The shear strength parameter with respect to matric suction, ϕ^b, is determined on unsaturated samples using modified triaxial or modified direct shear apparatus (Bishop et al., 1960; Satija, 1978; Escario, 1980; Ho and Fredlund, 1982 and Gan 1986). A simple procedure for measuring ϕ^b for statically compacted soils has also been proposed by Oloo and Fredlund (1996).

Determination of B_e and L_e

The wheel contact area can be calculated from the tire inflation pressure using the following equation:

$$A_c = \frac{P}{2P_t} \qquad [6]$$

where: P = axle load, A_c = tire contact area., P_t = tire inflation pressure.

The contact area can be approximated by a rectangular area as proposed by PCA (1984). The dimensions of the equivalent rectangle are given by:

$$L_e = 0.8712\sqrt{\frac{A_c}{0.5227}} \qquad [7]$$

$$B_e = 0.6L_e \qquad [8]$$

where L_e and B_e are the length and width of the equivalent rectangular contact area, respectively. These dimensions are used in Eq. 1 for the determination of bearing capacity.

Equation 1 is valid for plane strain conditions. Since the contact area is assumed to be rectangular, the following correction factors are applied to account for differences in shape:

$$S_c = 1 + \frac{N_q}{N_c} \qquad [9]$$

$$S_\gamma = 0.6 \qquad [10]$$

where S_c and S_γ are correction factors to be applied to N_c and N_γ, respectively, and N_q is the bearing capacity factor with respect to surcharge for the base layer.

Design Wheel Stresses

A trial thickness of the base layer is assumed and used to calculate the ultimate bearing capacity for known shear strength parameters and matric suction of the base and subgrade layers using Eq. 1 with suitable correction factors for shape. The resulting bearing capacity represents the failure condition. It is necessary to apply a load factor to the ultimate bearing capacity to limit pavement deformations to acceptable levels.

The choice of a suitable factor of safety depends on the level of acceptable deformations in the pavement as dictated by its design standard. A tentative load factor of 2.5 is proposed based on the upper limit of deformations. The ultimate bearing capacity is divided by this load factor to obtain the design wheel stress.

Consideration of Traffic

The procedure outlined for the determination of the pavement bearing capacity is based on static loading. Pavements are, however, subjected to wheel loads that are both transient and repetitive. A method of incorporating the effects of repetitive and transient loading in the design process is required.

Most pavement design methods resort to empirically derived relationships to take into consideration repeated loading. The same approach is adopted for the design of thin pavements and unbound roads. The following fatigue relationship is widely used in the design of paved roads:

$$\left(\frac{N_s}{N}\right)=\left(\frac{P}{P_s}\right)^4 \qquad [11]$$

where: N_S = number of repetitions of an axle load, P_S, N = number of repetitions on a different axle load, P.

Recognizing that the static load corresponds to a single pass, Eq. 11 can be re-arranged to give the equivalent static axle load.

$$P_s=\frac{P}{\left(\frac{1}{N}\right)^{0.25}} \qquad [12]$$

where: P_S , = equivalent static axle load for use in bearing capacity analysis, P = design axle load, N = number of repetitions of the design axle load.

The equivalent static axle load obtained using Eq. 12 is used to calculate the tire contact dimensions, L_e and B_e. The equivalent contact pressure for a single axle with single tires is then given by:

$$P_e=\frac{P_s}{2L_eB_e} \qquad [13]$$

The design wheel stress is compared to the equivalent contact pressure given by Eq. 13. The design pavement thickness is obtained by adjusting the assumed thickness of the base layer until the design wheel stress and the equivalent contact stress are equal.

Design Example

The proposed method was applied to the design of a pavement with material properties and traffic loading conditions given in Table 1. The variation of bearing capacity with thickness of the base layer is shown in Fig. 5. The intersection between the allowable wheel stress and the equivalent tire pressure curves gives the design pavement thickness.

Conclusions

A design procedure for thin pavements and unbound roads which utilizes the shear strength parameters, c', ϕ' and ϕ^b is proposed. The procedure incorporates the influence of environmental conditions on the pavement through the use of matric suction and the unsaturated shear strength parameter, ϕ^b.

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Table 1 Data for pavement design example

Property	Base layer	Subgrade layer
Cohesion (kPa)	10	20
Friction angle (degrees)	40	20
Unit weight (kN/m^3)	20	20
ϕ^b (degrees)	5.8	8.5

Traffic data	
Axle load (kN)	80
Cumulative number of axle loads	2.5 x 10^5
Tire pressure (kPa)	480
Factor of safety	2

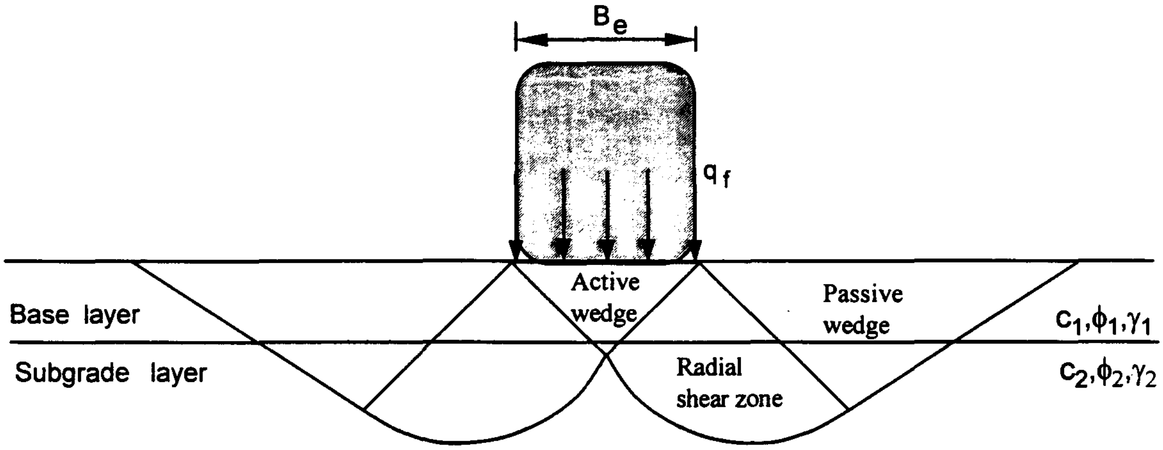

Fig. 1 Terzaghi's general shear failure mechanism.

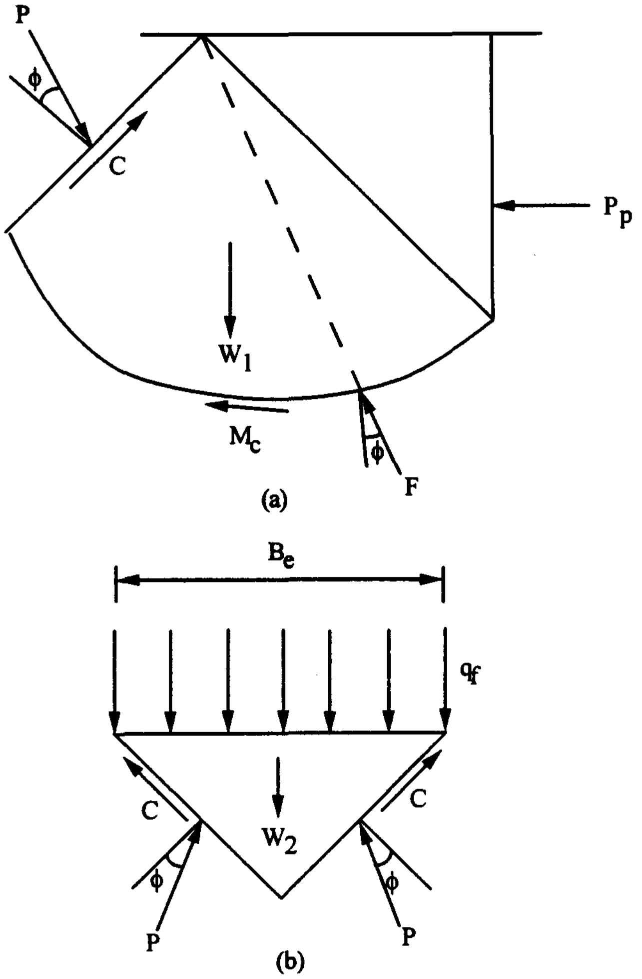

Fig. 2 Forces acting on the (a) passive wedge and radial shear zone (b) active wedge.

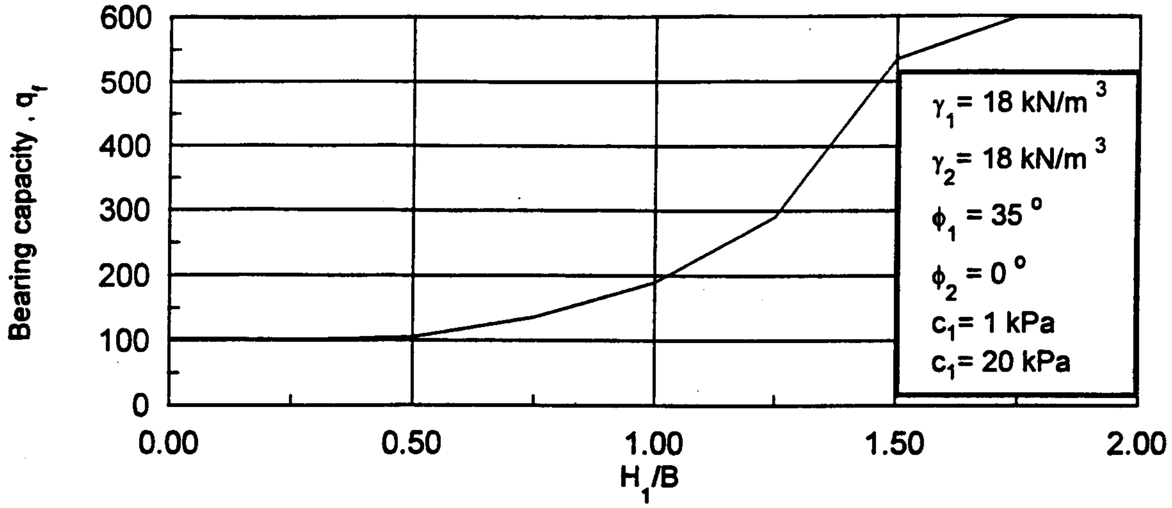

Fig. 3 Variation of pavement bearing capacity with thickness of the base layer.

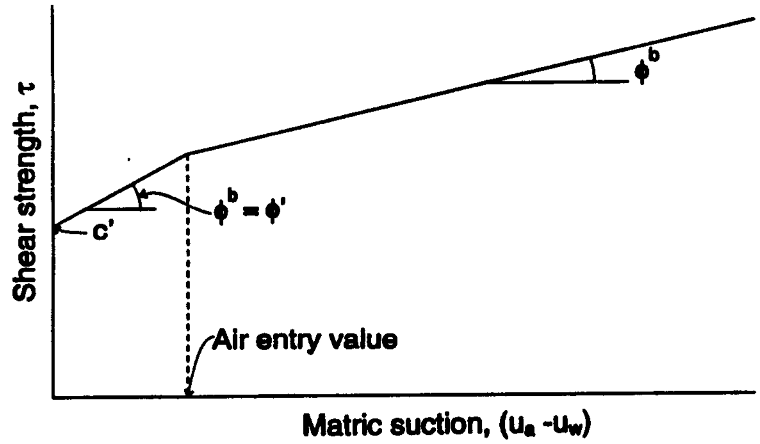

Fig. 4 Bilinear failure envelope with respect to matric suction.

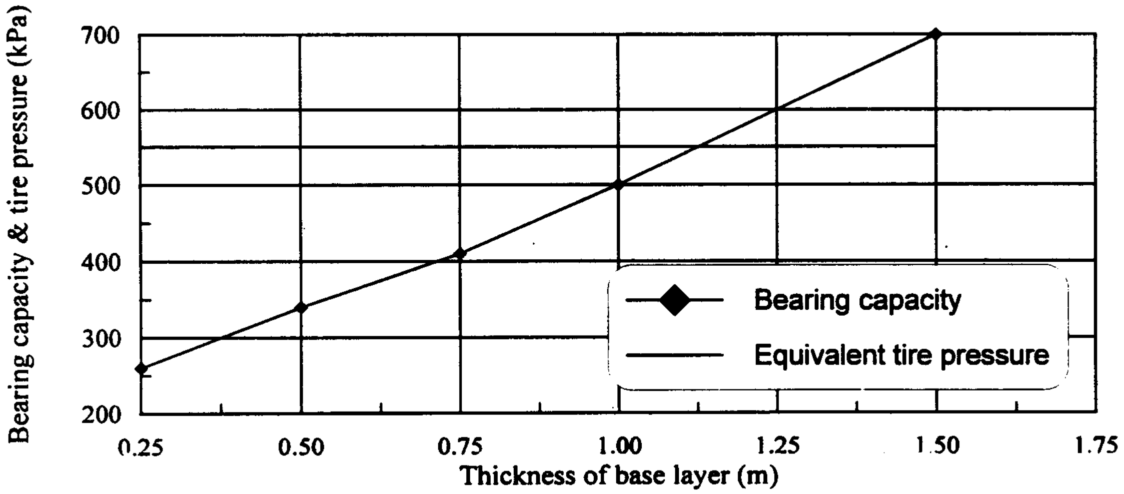

Fig. 5 Variation of tire pressure and bearing capacity with thickness of the base.