Bearing capacity of unpaved roads

Simon Y. Oloo, D.G. Fredlund, and Julian K-M. Gan

Abstract: Elastic layer theories may be valid for relatively stiff pavement materials and pavements subjected to low traffic stresses; however, the assumption of linear elastic behavior is not suitable for thin pavements and unpaved roads consisting of untreated granular bases over cohesive subgrades. The behavior of such pavements, even at low traffic stresses, is markedly nonlinear. Pavement design methods based on a bearing capacity theory are more applicable to roads with thin pavements. This paper outlines an ultimate strength method of designing low-volume roads. A procedure for determining the ultimate loads in layered systems, incorporating the effect of matric suction, is also presented. Existing empirical relationships that account for traffic loading are utilized in the proposed design procedure.

Key words: bearing capacity, unpaved roads, nonlinear theory, ultimate strength.

Résumé : Les théories de couches élastiques peuvent être relativement valides pour les matériaux de pavage et les pavages soumis à de faibles contraintes de trafic; cependant, l'hypothèse de comportement élastique linéaire ne convient pas à des pavages minces et à des routes non pavées constituées de fondations granulaires non traitées reposant sur des infrastructures cohérentes. Le comportement de tels pavages, même sous de faibles contraintes de trafic, est nettement non linéaire. Les méthodes de conception de pavages basées sur la théorie de capacité portante s'appliquent mieux aux routes avec des pavages minces. Cet article expose une méthode de résistance ultime pour concevoir des routes à faible volume de trafic. L'on présente une procédure pour déterminer les charges ultimes dans des systèmes à plusieurs couches, incorporant l'effet de succion matricielle. Des relations empiriques existantes qui tiennent compte des charges de trafic sont utilisées dans cette procédure de conception.

Mots clés : capacité portante, routes non pavées, théorie non linéaire, résistance ultime.
[Traduit par la rédaction]

Introduction

Elastic layer theories hypothesize that stresses and strains are only dependent on the elastic modulus and Poisson's ratio. The assumption of isotropic elastic behavior may be valid for relatively stiff pavement materials and pavements subjected to low traffic stresses. In thin pavements and unpaved roads consisting of untreated granular bases over cohesive subgrades, the assumption of linear elastic behavior is not suitable. The behavior of such pavements, even at low traffic stresses, is markedly nonlinear.

In using ultimate strength methods, it is assumed that shear failure of the pavement structure occurs if traffic stresses are sufficiently high. Pavement material behavior is assumed to be plastic rather than elastic. The assumption of plastic response is more realistic for thin pavements and unpaved roads in which traffic stresses invariably exceed the elastic range of the pavement materials. The same may apply to thick pavements subjected to high traffic stresses.

The implementation of elastic layer theories in the pavement design process requires the quantification of the elastic modulus and the Poisson's ratio. Difficulties associated with the determination of these parameters for pavement materials are well known. Ultimate strength methods of pavement design are based on the shear strength parameters c' and ϕ' (and also ϕ^b, in the case of unsaturated material), which are more clearly defined.

Ultimate strength methods allow for the design of pavements with known factors of safety. The quantification of a factor of safety, which is lacking in elastic layer methods, allows for the assessment of pavement damage due to any loading condition. This flexibility is particularly useful in load zoning of light pavements and for the issuing of overweight vehicle permits.

Ultimate strength approaches suffer from the disadvantage that deformations prior to pavement collapse cannot be quantified. Deformations during the life of the pavement determine its serviceability and must be controlled. Difficulties associated with the prediction of displacements during the service life of the pavement can be surmounted through the judicious selection of the factor of safety to limit deformations.

Literature review

The relative merits of ultimate strength methods have been recognized. There have been attempts by McLeod (1953, 1954) and Broms (1963, 1964) to extend traditional bearing capacity theory to the design of pavements. More recently Milligan et al. (1989), Bender and Barenberg (1978), and Giroud and Noiray (1981) have used bearing capacity theory to analyze the contribution of geotextiles to the load carrying capacity of unpaved roads. These methods represent a more rational idealization of pavement behavior but fall short of providing an adequate quantification of the subgrade portion of the pavement design problem. The shortcomings can be attributed to

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(1) uncertainty in the prediction of the ultimate loads in layered pavements, (2) difficulties associated with the incorporation of environmental changes in the bearing capacity formulation, and (3) lack of a suitable method to deal with traffic loading.

This paper outlines an ultimate strength method of designing low-volume roads based on new procedures for determining ultimate loads in layered systems and for incorporating the effect of matric suction on bearing capacity. Existing empirical relationships are utilized to account for traffic loading in the proposed design procedure.

Idealization of pavement geometry

A typical unpaved road cross section consists of an unbound base layer directly overlying the subgrade. A surfacing layer may or may not be present. Where a surfacing layer exists, it serves to protect the underlying layers from variations in the surface flux but makes little contribution to the bearing capacity of the pavement. If a subbase layer is present, it is assumed that its shear strength characteristics (i.e., c', ϕ', and ϕ^b parameters) are not significantly different from those of the base. For the purpose of determining the bearing capacity, the unpaved road can be idealized as consisting of the base and subgrade layers only (i.e., a two-layer system).

The wheel loads are assumed to be applied at sufficient distance from the pavement shoulders to avoid slope failure or other edge effects affecting the layout of the general shear failure mechanism. The process of pavement design becomes one of determining the depth of the base layer required to carry the design traffic.

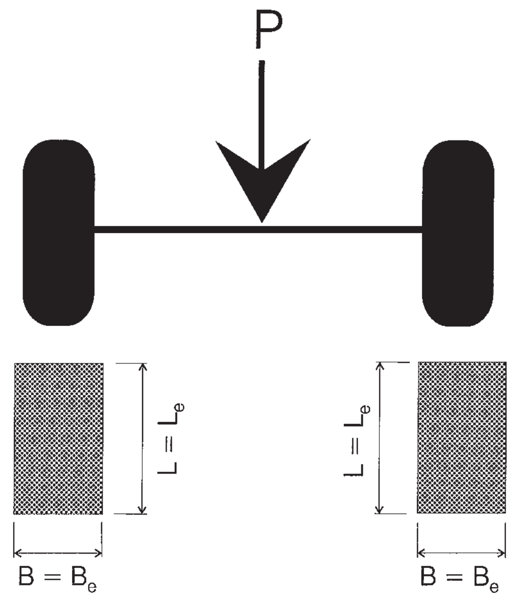
Determination of contact area and pressure

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

The fixed level of traffic approach requires the determination of an equivalent single wheel load (ESWL) in cases where there is more than one wheel. Design methods based on elastic theory define the ESWL in terms of the relative influences of single and multiple wheel configurations on stresses or strains. In contrast, methods based on bearing capacity theory require the representation of the wheel configurations in terms of a contact pressure and the dimensions of the contact area.

The contact area was assumed to be rectangular for rigid pavements by the Portland Cement Association (PCA 1984). Although the idealization by the PCA was intended for rigid pavements, it is frequently used for flexible pavements and is herein adopted for unpaved roads. The actual pressure and area to be used in the bearing capacity analysis depends on the configuration of axles and number of tires. The following cases were considered: (1) single axle with single tires, and (2) single axle with dual tires.

Fig. 1. Idealization of the tire contact area for a single axle load with single tires.



Single axle with single tires

The arrangement of single tires on a single axle is shown in Fig. 1. The tire contact area is calculated from the axle load using the following equation:

$$[1] \quad A_c = \frac{P}{2P_t}$$

where
P is the axle load;
A_c is the tire contact area; and
P_t is the tire inflation pressure.

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

$$[2] \quad L = 0.8712\left(\frac{A_c}{0.5227}\right)^{1/2}$$

and

$$[3] \quad B = 0.6L$$

where L and B are the length and the width of the equivalent rectangle, respectively.

The dimensions to be used in the determination of bearing capacity for a single axle with single tires are similar to the length and width of the equivalent rectangle and are given by

$$[4] \quad L_e = L$$

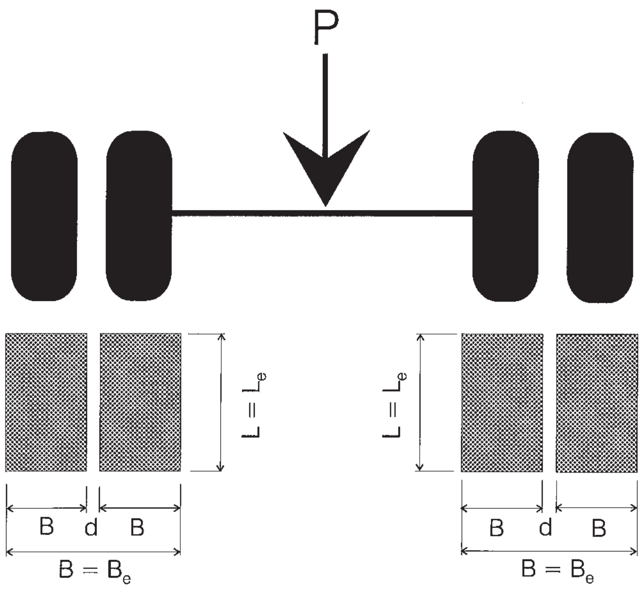
and

$$[5] \quad B_e = B$$

where L_e and B_e are the dimensions of the equivalent contact area to be used in the bearing capacity analysis. The equivalent contact pressure, P_e, is given by the following equation:

$$[6] \quad P_e = \frac{P}{2\,L_e B_e}$$

Fig. 2. Idealization of the tire contact area for a single axle load with dual tires.



Single axle with dual tires

The layout of dual tires on a single axle is shown in Fig. 2. The dual tires can be analyzed by assuming that the soil between the tires is mechanically associated with the tires. The two tires, therefore, behave as a single entity in distributing the axle load to the soil.

The contact area due to each tire is given by

[7] $$A_c = \frac{P}{4P_t}$$

The dimension of the equivalent rectangular area for each tire is given by [2] and [3]. The equivalent contact pressure of the dual tire assembly is assumed to be acting over the area enclosing both tires. The dimensions of the equivalent contact area for the single axle with dual tires configuration are given by

[8] $$B_e = (2B + d)$$

and

[9] $$L_e = L$$

where d is the the clear distance between the dual tires.

The clear distance between the dual tires, d, is given by the following equation:

[10] $$d = S_d - B$$

where S_d is the center to center spacing between the dual tires. The equivalent contact pressure is given by [6].

Determination of strength parameters

The determination of the bearing capacity of an unpaved road requires a knowledge of the effective shear strength parameters c' and ϕ' for the materials comprising the base and subgrade. The shear strength parameter with respect to matric suction, ϕ^b, is also required in cases where the pavement soil layers are unsaturated. The shear strength parameters, c', ϕ', and ϕ^b can be determined using triaxial or direct shear tests. The determination of ϕ^b in the triaxial test and in the direct shear test are described by Ho and Fredlund(1982) and Gan and Fredlund (1988), respectively.

Mixtures of coarse aggregates and fine-grained soil are the preferred materials for the base layer. Stability requirements demand the existence of a small fraction of fines in the base layer. The presence of fines in the aggregates often increases cohesion to an extent that the base layer cannot be treated as being purely frictional. Under these circumstances, design methods that ignore cohesion in the base can be unnecessarily conservative. The presence of fines also enhances the contribution of matric suction to the shear strength of the base layer. The characterization of shear strength should include the determination of ϕ^b to include the contribution of matric suction to shear strength.

Estimation of matric suction

Pavement designs are commonly based on the saturated shear strength parameters of the subgrade. In many cases, the water content in the subgrade does not reach saturation and the assumption of saturation leads to over design.

Moisture conditions in the pavement layers are controlled by climatic and soil conditions. Russam (1965) proposed criteria for the determination of long-term equilibrium water contents depending on the depth of the water table and climatic conditions. The criteria recommended actual measurements of water contents in most cases and are widely used for design.

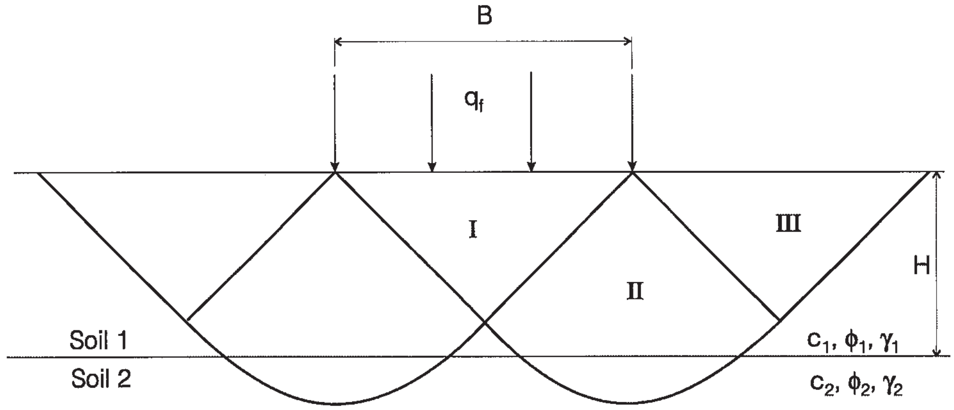
The distribution of moisture in a layered soil depends on the relative hydraulic conductivities and the water retention characteristics of the soil in each layer. Saturated–unsaturated flow modeling that takes into consideration the flux boundary conditions (Lytton et al. 1990; Barbour et al. 1992; Wallace 1977) is likely to give more insight into the moisture distribution within layered soils. The determination of the surface fluxes to be used in the modeling requires the characterization of climatic and ground surface conditions and the solution of a system of coupled heat and mass transfer equations. Lytton et al. (1990) presented a comprehensive model for the prediction of matric suction variations under pavements based on a finite difference solution of the coupled heat and mass transfer equations. The model also provides a means of characterizing climate. Solutions of the coupled heat and mass transfer equations have also been presented by Wilson (1990) based on the finite difference method and by Joshi (1993) based on the finite element method.

The estimation of equilibrium water contents and (or) matric suction profiles is prerequisite to the application of the bearing capacity theory to pavement design. Techniques are available for the prediction (Fredlund 1997) as well as the monitoring (Wilson et al. 1997) of matric suction in the field. It is assumed in this paper that equilibrium matric suction profiles in the pavement layers are known or can be estimated from soil and climatic information.

Determination of ultimate wheel loads

The bearing capacity based pavement design methods can be classified into two categories depending on the assumptions made with regard to the failure mechanism. The first method

Fig. 3. General shear failure mechanism in a two-layer soil.



considers the base layer as an elastic material whose sole purpose is to distribute the load to the subgrade (Broms 1963, 1964; Bender and Barenberg 1978; Giroud and Noiray 1981; Milligan et al. 1989; Sattler et al. 1989; Szafron 1991). The second method assumes a general shear failure type of mechanism involving all pavement layers (McLeod 1953).

The mobilization of the ultimate strength of the subgrade requires large deformations. Since the pavement must continue to behave as a continuous system, large deformations of the subgrade invariably translate into equally large deformations of the overlying layers. The base layer is unlikely to continue behaving elastically over the large deformations required to mobilize the ultimate strength of the subgrade. Furthermore, observations of pavement failure modes (McLeod 1953; Hveem 1958) have confirmed the occurrence of failure mechanisms involving all the pavement layers.

The assumption of a general shear failure type of mechanism involving all pavement layers as adopted by McLeod (1953) is more realistic for pavements. However, the method of solution proposed by McLeod is tedious and difficult to extend to more complicated situations. The upper bound solution proposed by Purushothamaraj et al. (1974) based on a general shear failure mechanism is complex, rendering the incorporation of pore-water pressures and matric suction difficult. A solution that can accurately predict bearing capacity in a two-layer soil and still retain sufficient simplicity to allow for the incorporation of matric suction and positive pore-water pressures is required.

The limit equilibrium method has been used extensively in geotechnical engineering to provide solutions to bearing capacity, lateral earth pressure, and slope stability problems. The simple formulation of the limit equilibrium method can easily handle such complex factors as soil layering and pore-water pressures. Furthermore, the suitability of limit equilibrium methods in providing reasonable solutions for bearing capacity in homogeneous soils (Terzaghi 1943; Meyerhof 1951) and layered soils (Button 1953; Raymond 1967; Meyerhof 1974; Meyerhof and Hanna 1978) has been demonstrated. Consequently, the limit equilibrium method was selected as the tool for the development of solutions for bearing capacity in layered soils and for the incorporation of the effect of matric suction on bearing capacity.

Idealization of the problem

A two-layer soil with varying cohesion, angle of internal friction, and unit weight, as shown in Fig. 3, was considered. The effect of surcharge was neglected in the analysis since wheel loads are usually applied to the surface of the pavement (i.e., there is no depth or overburden factor). The bearing capacity of the layered system was assumed to be given by the following equation:

$$[11]\quad q_{\mathrm{f}} = c_1' N_c + \frac{1}{2} B \gamma_1 N_\gamma$$

where

q_{f} is the bearing capacity of the pavement system;
c_1' is the cohesion of the top soil layer (i.e., base layer);
B is the width of the foundation;
γ_1 is the unit weight of the top soil layer (base);
N_{c} is the cohesion bearing capacity factor; and
N_γ is the surcharge bearing capacity factor.

The cohesion bearing capacity factor, N_c, and the surcharge bearing capacity factor, N_γ, in eq. [11] are a function of the shear strength and unit weights of *both* soil layers (i.e., base layer and subgrade).

The following assumptions were made in the development of the solution for bearing capacity of a two-layer soil:

(1) The Terzaghi general shear failure mechanism is valid for layered soils.

(2) The length of the footing is large in comparison to its width so that plane strain conditions apply.

(3) The footings are smooth and no shear stresses are developed between the soils and the footing.

(4) The soil in each layer is homogeneous and isotropic.

(5) Shear stresses at the interface between the soil layers are neglected.

(6) The shape of the log spiral is controlled by the shear strength parameters of both soils and the relative depth of the top soil layer.

(7) The principle of superposition is applicable to the individual components of bearing capacity.

Assumptions 2 and 3 are not rigorously adhered to but should be satisfactory for analytical purposes.

The bearing capacity of the soil was determined by considering the equilibrium of the passive and active soil wedges (Fig. 4) as proposed by Terzaghi (1943). Only the resultant

Fig. 4. Equilibrium of the soil wedges for the general case: (*a*) radial shear zone and passive wedge; (*b*) active wedge.

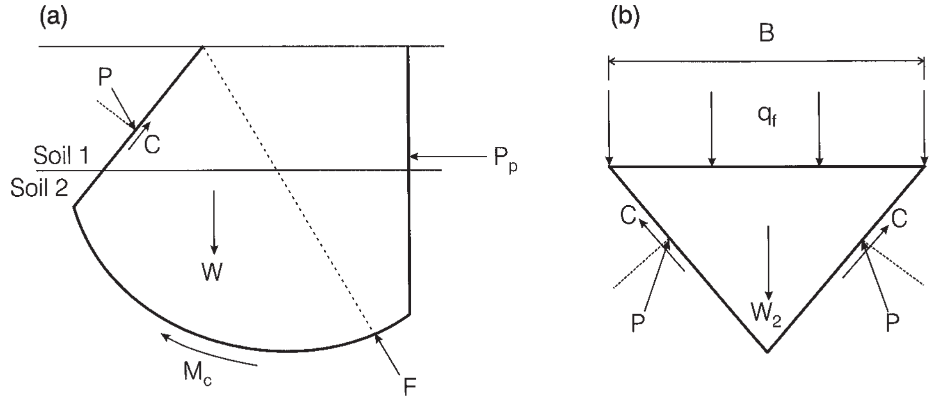
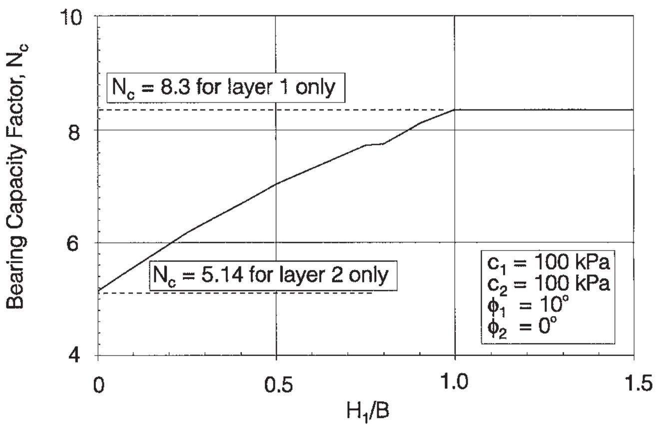


Fig. 5. Bearing capacity factor, N_c, versus ratio of depth of top layer, H_1, to foundation width, B, where the top layer is stronger than the bottom layer.



forces for the two soils are shown in Fig. 4 for simplicity of presentation.

The passive pressure on the side of the passive wedge can be determined from lateral earth pressure theory as follows:

$$[12] \quad p_p = \gamma z K_p + 2c'(K_p)^{1/2}$$

where

p_p is the passive pressure at depth z;

γ is the unit weight of the soil;

K_p is the passive pressure coefficient, which is equal to $[\tan^2(45° + \phi'/2)]$;

c' is the effective cohesion of the soil; and

ϕ' is the effective friction angle of the soil.

The moment, M_c, due to cohesion along the log spiral is calculated from the length of the log spiral and the cohesion of the soil. The resultant force, P, can be calculated by taking moments about the center of the log spiral. The resultant normal force, F, at the base of the log spiral is inclined at an angle equal to the angle of internal friction of the soil and therefore acts through the center. Since the resultant normal force has no moment, its value need not be determined. To solve for the resultant force, P, assumptions have to be made with regard to the points of action of the weights and passive forces.

Once the resultant force, P, has been determined, the bearing capacity of the footing can be calculated by considering the equilibrium of the active wedge in Fig. 4*b*.

A complete derivation for the bearing capacity of a two-layer soil based on the above procedure is given by Oloo (1994). Separate determinations were made for the components of bearing capacity due to cohesion and self-weight. Superposition was assumed to be applicable to layered soils so that the total bearing capacity could be determined by the summation of the cohesion and self-weight components of bearing capacity.

Results for the bearing capacity factor, N_c

The bearing capacity factor, N_c, for the two-layer system was determined by considering the equilibrium of a weightless soil with cohesion and friction. The component containing the factor N_γ is eliminated from [11], since the soil is assumed to have no weight.

The proposed solution gave values for the bearing capacity factor, N_c, that were equal to the Prandtl (1921) solutions for homogeneous soils. For a two-layered soil system, the proposed solution was found to give results that were consistent with the physical boundaries of the problem.

Typical results for a strong soil overlying a weak soil layer are given in Fig. 5. As the depth of the top layer, H_1, increases, the bearing capacity factor approaches the value of a homogeneous top layer. As the depth of the top layer, H_1, decreases, the bearing capacity factor approaches the value of a homogeneous bottom layer. The transition between the two extreme values of N_c is smooth.

Result for the bearing capacity factor, $N\gamma$

There are no known suitable solutions in the literature for the bearing capacity factor, N_γ, in layered soils against which the proposed solution can be compared. Although the upper bound solution of Purushothamaraj et al. (1974) provides a solution for this class of problem, the complexity of the equations precludes the possibility of making a comparison.

The effect of changing the depth of the top soil layer, H_1, is illustrated in Fig. 6 for a stronger soil overlying a weaker one. The bearing capacity factor approaches the value for the top soil layer as the depth increases. As the depth of the top soil layer approaches zero, the bearing capacity factor approaches the value for the bottom soil layer.

Fig. 6. Bearing capacity factor, N_γ, versus ratio of depth of top soil layer, H_1, to foundation width, B, where the top layer is stronger than the bottom layer.

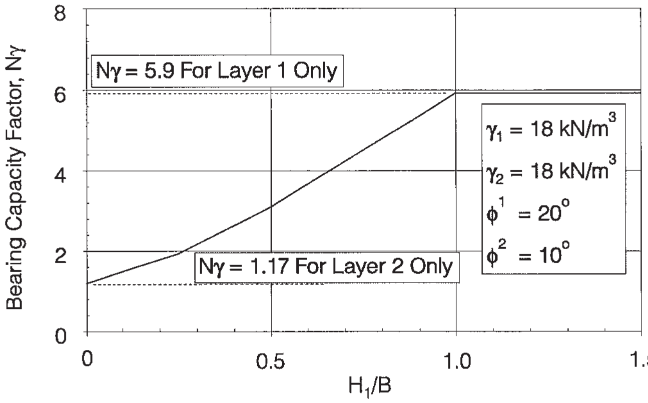


Fig. 7. Overall bearing capacity of a two-layer soil versus the ratio of depth of top soil layer, H_1, to foundation width.

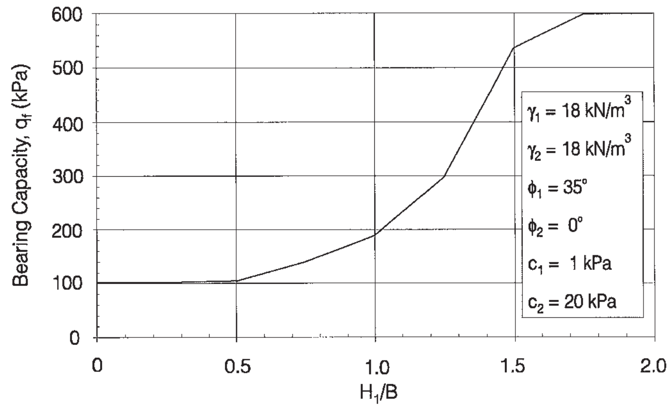
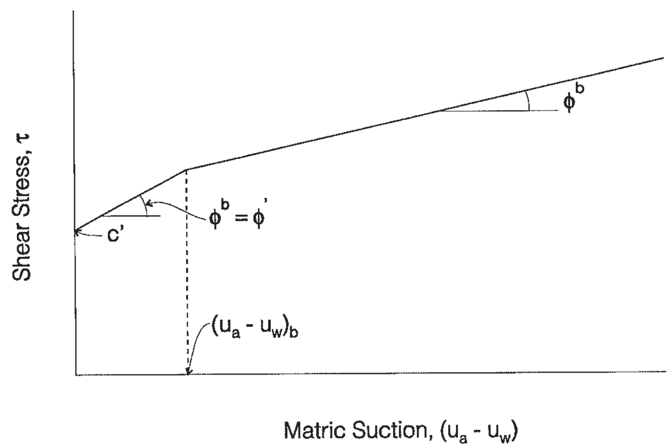


Fig. 8. Bilinear failure envelope for an unsaturated soil at zero net normal stress.



Overall bearing capacity

Independent derivations have been made for the components of bearing capacity due to cohesion and due to self-weight. Assuming the principle of superposition to be valid, the overall bearing capacity of a surface footing on a two-layer soil system is given by [11]. The variation of the overall bearing capacity for a two-layer soil with the depth of the top soil layer, H_1, is shown in Fig. 7. The bearing capacity varies between a minimum value for zero depth of the top soil layer to a maximum corresponding to the bearing capacity of the top soil layer. In general the proposed method appears to give reasonable estimates of bearing capacity.

Effect of matric suction on bearing capacity

When a soil is subjected to a negative pore-water pressure beyond its air-entry value, air enters the pores and the soil becomes unsaturated. The equilibrium of the unsaturated soil structure must then be assessed in terms of two independent stress state variables. The stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$, appear to be the most satisfactory for use in engineering practice (Fredlund 1979; Fredlund and Rahardjo 1987). The term $(\sigma - u_a)$ is referred to as the net normal stress, while $(u_a - u_w)$ is the matric suction. Both the net normal stress and the matric suction will determine the equilibrium of the soil wedges shown in Fig. 4. Since matric suction does not have a gravitational component, the influence of matric suction on the stability of the soil under the footing will arise from its contribution to the shear strength of the soil.

The shear strength of an unsaturated soil can be expressed as follows (Fredlund et al. 1978):

$$[13] \quad \tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi^b$$

where

ϕ' is the effective friction angle of the soil;
c' is the effective cohesion; and
ϕ^b is the friction angle associated with the matric suction of the soil.

The effect of matric suction is to pull soil particles together. The contribution of matric suction to shear strength is due to the forces between the soil grains arising from this pull. Matric suction can be visualized as a contribution to the cohesion of the soil, and the components of the equation for the shear strength of the unsaturated soil can be rearranged as follows:

$$[14] \quad \tau = [c' + (u_a - u_w)\tan\phi^b] + (\sigma - u_a)\tan\phi'$$

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 bilinear envelope (Gan et al. 1988), as shown in Fig. 8.

The equation for shear strength of an unsaturated soil at zero net normal stress, based on a bilinear envelope, is then given by

$$[15] \quad \tau = c' + (u_a - u_w)\tan\phi' + [(u_a - u_w) - (u_a - u_w)_b]\tan\phi^b$$

where

$\phi^b = \phi'$ if $(u_a - u_w) \le (u_a - u_w)_b$

and

$(u_a - u_w)_b$ is the air-entry value.

The entire shear strength, τ, at zero net normal stress given by eq. [15] is considered the total cohesion of the unsaturated soil.

If the net normal stress, $(\sigma - u_a)$, is greater than zero, the general equation for shear strength for an unsaturated soil based on a bilinear envelope becomes

Table 1. Recommendations for factors of safety used in the design of unpaved roads.

Source	Load factor	Remarks
Broms (1963)	2	Low traffic volume
Broms (1963)	3	High traffic volume
Bender and Barenberg (1978)	1.6	On shear strength of subgrade
Sellmeijer et al. (1982)	1.5	On shear strength of subgrade
Giroud and Noiray (1981)	1.6	On shear strength of subgrade

[16] $$\tau = \{c' + (u_a - u_w)_b \tan\phi' + [(u_a - u_w) - (u_a - u_w)_b] \tan\phi^b\} + (\sigma - u_a)\tan\phi'$$

The contribution of matric suction to bearing capacity can be determined using the limit equilibrium approach outlined for two-layer soils by considering the contribution of matric suction to the passive force and to the shear resistance along the length of the log spiral.

The influence of matric suction on passive pressure is the same as that of cohesion. The bearing capacity factor associated with matric suction is also the same as that associated with cohesion. The total cohesion for the unsaturated soil is given by eq. [15]. If the matric suction is uniform for the soil layer, the expression for bearing capacity is given by

[17] $$q_f = \{c' + (u_a - u_w)_b \tan\phi' + [(u_a - u_w) - (u_a - u_w)_b] \tan\phi^b\} N_c + \frac{1}{2}B\gamma N_\gamma$$

Equation 17 further simplifies as follows if the air-entry value of the soil approaches zero:

[18] $$q_f = [c' + (u_a - u_w)\tan\phi^b] N_c + \frac{1}{2}B\gamma N_\gamma$$

Ultimate wheel loads

The ultimate wheel load that a two-layer pavement system can sustain is determined by combining the solutions derived for bearing capacity in two-layer soils with the solution for the effect of matric suction on bearing capacity. The solution developed for the effect of matric suction on bearing capacity was restricted to a homogeneous soil. The influence of a nonuniform matric suction profile on the bearing capacity of layered soils is complicated and would require major modifications to the existing solutions. Difficulties associated with this limitation can be circumvented by approximating the matric suction profile in each layer with a constant value. The bearing capacity factor with respect to a constant matric suction is equivalent to that of cohesion, and the component of shear strength due to matric suction can be incorporated into the cohesion of the soil. Under these conditions, the form of the bearing capacity equation is retained for the layered soil.

The cohesion of the two soils is calculated from the following equations assuming the air-entry value for both soils approaches zero:

[19] $$c_1 = c_1' + (u_a - u_w)_1 \tan\phi_1^b$$

[20] $$c_2 = c_2' + (u_a - u_w)_2 \tan\phi_2^b$$

Table 2. Material properties for the base and subgrade layers used for analysis.

Soil property	Subgrade layer	Base layer
Cohesion (kPa)	1.0	1.0
Friction angle, ϕ'	20.0	40.0
Unit weight (kN/m^3)	20.0	20.0
$\tan\phi^b$	0.15 ($\phi^b = 8.5°$)	0.10 ($\phi^b = 5.7°$)

where

c_1 is the total cohesion of the base;
c_2 is the total cohesion of the subgrade;
c_1' is the effective cohesion of the base;
c_2' is the effective cohesion of the subgrade;
$(u_a - u_w)_1$ is the matric suction in the base layer;
$(u_a - u_w)_2$ is the matric suction in the subgrade;
$\tan\phi_1^b$ is the friction angle associated with matric suction (base); and
$\tan\phi_2^b$ is the friction angle associated with matric suction (subgrade).

The ultimate bearing capacity of a typical unpaved pavement section consisting of a base layer over a subgrade can be calculated from the following modification of [11]:

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

The bearing capacity factors, N_c and N_γ, are dependent upon the dimensions of the loaded area, the depth of the base layer, the unit weights, and the shear strength parameters of *both* layers (i.e., shear strength parameters, c_1', c_2', ϕ_1', ϕ_2', ϕ_1^b and ϕ_2^b where ϕ_1' and ϕ_2' are the effective friction angles of the base and the subgrade, respectively). The determination of the bearing capacity factors and of the equivalent contact width, B_e, have been discussed.

The derivation of [21] was based on the assumption of plane strain. Since the tire contact area is assumed to be rectangular, corrections have to be applied to account for the differences in shape. It is recommended that the shape factors proposed by De Beer (1970) be used.

The bearing capacity, q_f, is adjusted by changing the depth of the base layer, H_1, until a value for q_f equal to the equivalent contact pressure given by [6] is obtained. The depth of the base layer corresponding to this condition is equivalent to the required base depth for the given loading condition.

Determination of design wheel loads

The ultimate wheel load determined from [21] represents the failure condition. Wheel loads corresponding to the ultimate bearing capacity of the pavement would cause excessive deformation. 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 load factor value to be applied to the ultimate wheel load presents major difficulties. Existing pavement design methods based on bearing capacity theory adopt a variety of recommendations for the factor of safety or load factor (Table 1).

Broms (1963) recommended the use of an overall factor of safety depending on the traffic volume, while other authors

Fig. 9. Required thickness of the base layer versus tire pressure and axle load.

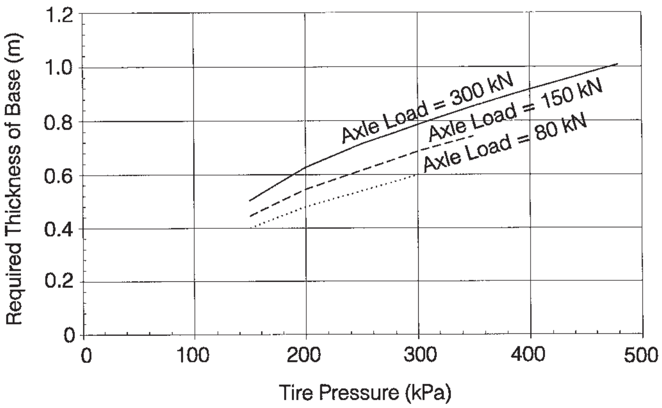


Fig. 10. Required thickness of the base layer versus the tire pressure for different levels of matric suction in the subgrade for a static axle load of 150 kN.

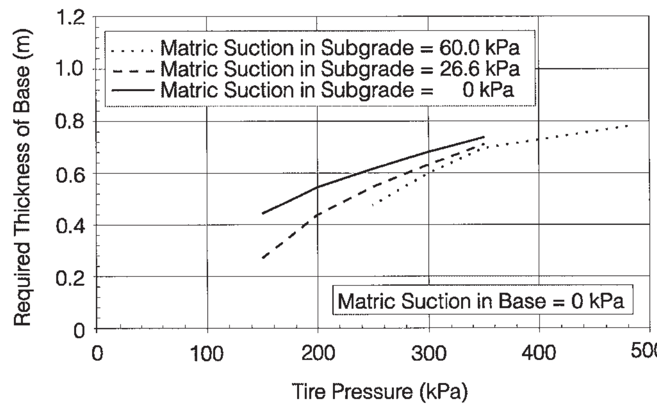
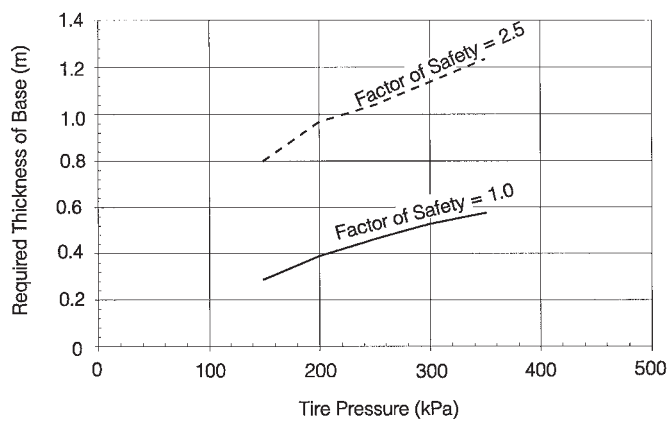


Fig. 11. Required thickness of the base layer versus tire pressure for different factors of safety for a static axle load of 300 kN.



recommended the use of partial factors of safety applied to the shear strength of the subgrade. Partial factors of safety applied to the shear strength account for uncertainties in the method of analysis and in the determination of the shear strength parameters. The partial factors of safety can be increased sufficiently to limit deformations as well.

The response of a pavement to applied wheel loads depends on the relative stiffness of the pavement system. The stiffness of the pavement depends on the shear strength properties and deformation moduli of its components, as well as on the depth of the base layer. The value of the load factor to limit settlements will depend on pavement stiffness and the level of acceptable deformations of the pavement dictated by its design standard.

A tentative load factor of 2.5 based on consideration of the upper limit of deformations from finite element analysis of typical pavement sections is proposed.

Consideration of traffic volume

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.

A theoretical analysis of the effects of repeated loading on pavements is beyond the current state of knowledge. Most pavement design methods resort to empirically derived relationships to take into consideration repeated loading. The same approach is adopted for the design of unpaved roads, using the following relationship:

$$[22] \quad (N_s / N) = (P/P_s)^4$$

where
N_s is the number of repetitions of an axle load, P_s; and
N is the number of repetitions of an axle load, P.

An equation similar to [22] was used by Giroud and Noiray (1981) for the design of unpaved roads. Equation 22 can be used to calculate the static axle load from a known number of repetitions of a transient axle load. Recognizing that the static load corresponds to a single pass, [22] can be rearranged to give the equivalent static axle load as

$$[23] \quad P_s = \frac{P}{(1/N)^{0.25}}$$

where
P_s is the equivalent static axle load;
P is the design axle load; and
N is the number of repetitions of axle load P.

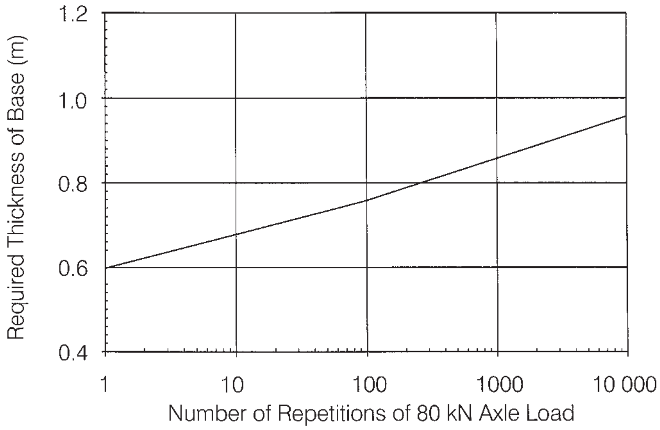
Equation [23] implies an equivalent static axle load that is usually larger than the transient axle load. Design based on the equivalent static axle load results in a pavement whose thickness is proportional to the number of axle load repetitions. The tire pressure is assumed to remain constant.

Typical design results

The proposed method of analysis and design was applied to a pavement section consisting of materials whose properties are given in Table 2. The results are presented in this section to illustrate typical variations in design pavement thickness as a function of the axle load, tire inflation pressure, load factor, and number of load applications.

The variation of design pavement thickness with tire pressure for different static axle loads is shown in Fig. 9. A load factor of one was used, and the matric suction was assumed to be zero in both layers. The required thickness of the base layer was obtained by using [21] to determine bearing capacity for

Fig. 12. Required thickness of the base layer versus the number of repetitions of the axle load, for a static axle load of 80 kN and a tire pressure of 300 kPa.



the known material properties. The bearing capacity of the pavement was obtained by varying the depth of the base layer until the calculated bearing capacity became equal to the equivalent contact pressure given by [6]. Single axle loading with single tires was assumed.

The required thickness of the base increases as the tire pressure and axle load increase. For each axle load, there is an upper limit of the tire inflation pressure that the pavement can sustain. This limit corresponds to the maximum bearing capacity of the pavement system where the failure mechanism is fully contained in the base layer. Most existing design methods for unpaved roads fail to recognize the existence of this limit (Broms 1963, 1964; Bender and Barenberg 1978; Giroud and Noiray 1981).

The contribution of matric suction to the bearing capacity of the pavement was investigated by assuming constant matric suction values in each of the pavement layers. The cohesion in each layer was increased by an amount equal to the product of (tan ϕ^b) and the matric suction. The values of (tan ϕ^b) given in Table 2 were deliberately chosen on the lower side to demonstrate the significant contribution of matric suction to bearing capacity.

The effect of increasing matric suction in the subgrade layer is illustrated in Fig. 10 for a static axle load of 150 kN. The thickness of the base layer required to support a given tire pressure decreases as the matric suction increases. The decrease in thickness is particularly significant at low tire pressures.

Factors of safety have not been applied to the results reported in Figs. 9 and 10. The effect of applying a load factor is to increase the required base layer thickness. This is depicted in Fig. 11 for an axle load of 300 kN. The value of the load factor depends on, among other things, the design standard of the road. Since the choice of the load factor has a significant effect on the design pavement thickness, every effort should be made to determine an appropriate value.

The effect of increasing the number of axle load repetitions is illustrated in Fig. 12 for an 80 kN axle load and a tire pressure of 300 kPa. The required depth of the base layer increases as the number of axle load repetitions increases. The increase is a reflection of the increase of design static axle load as given by [23].

Conclusions

A limit equilibrium method for bearing capacity in layered soils, incorporating the contribution of matric suction, has been presented for the design of unpaved roads.

The following conclusions can be made from the preceding discussions on the design of unpaved roads using the solutions for bearing capacity in two-layer soils.

The required thickness of the base layer depends on the shear strength and unit weight of both the base layer and the subgrade of the unpaved road. An upper limit of traffic loading exists for a given base and subgrade properties. Beyond this upper limit of traffic loading, increases in the base layer thickness do not increase the bearing capacity of the given pavement system.

Matric suction can have a significant effect on the bearing capacity of pavement structures.

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