Bearing capacity analysis of pavement structures for short term flooding events

M. Elshaer, M. Ghayoomi & J.S. Daniel
University of New Hampshire, Durham, NH, USA

ABSTRACT: Flooding is recognized as a catastrophic event and a threat to the load carrying capacity of pavement structures around the world. During a flood event, the moisture content within the pavement layers can increase significantly, resulting in reduced bearing capacity of the pavement system. Road agencies must decide to what extent traffic should be restricted to avoid the potential damage that could be caused if the capacity of the pavement structure is exceeded in the flooded condition. This study presents a methodology to evaluate the structural capacity of flooded pavements to provide an engineering basis for application of short-term load restrictions during and post flood events. Conventional Terzaghi's bearing capacity formulation and the concept of effective stress in unsaturated soils were used; apparent cohesion was introduced to account for the suction in unsaturated soils. Bearing capacity under traffic loading was calculated by changing the soil condition from unsaturated to the fully saturated flooded condition. The flooded condition was simulated by raising the water table from an initial hydrostatic capillary pressure distribution for different cross sections with a range of subgrade soils. A significant reduction was observed in bearing capacity mainly when the pavement structure was in the fully saturated condition, but the road could regain its capacity with desaturation and recession of water level. Finally, layer elastic analysis was performed to predict the maximum tire loads on the pavement surface that the road could withstand without any sudden shear failure.

1 INTRODUCTION

The assessment of the load carrying capacity of a flooded pavement structure is complex due to numerous unknown parameters. The necessity of applying load restrictions on pavements that have been flooded mainly depends on the integrity of the pavement structure. This makes it difficult for agencies to decide based on visual inspection alone because of the unknown behavior or conditions of the saturated unbound materials beneath the pavement surface subjected to traffic loads. An incorrect assessment of the bearing capacity of an inundated pavement may lead to severe damage or sudden failure of the pavement structure.

Unbound layers in pavement structure such as base, subbase, and subgrade soil play a critical role in the overall performance of the pavement, particularly when moisture contents are at or near fully saturated conditions. The changes in water content can result in degradation of the stiffness and strength of the pavement materials and consequently reduction of the load bearing capacity of the road. A large portion of pavement damage is attributed to the presence of excess pore water in soils that led to lower effective stress and strength. Heavy traffic loading can potentially cause pavement failure during flooding if no traffic restrictions are enforced. Thus, it is essential to investigate the effect of water saturation on the soil bearing capacity and whether the soil can carry the loads applied on the pavement without experiencing excessive deformation or shear failure.

In pavement engineering practice, load bearing capacity can be obtained using tests such as Falling Weight Deflectometer (FWD), Dynamic Cone Penetrometer (DCP), or California Bearing Ratio test (CBR). In geotechnical engineering, the bearing capacity is controlled by the shear strength mobilized on the failure slip surface. The concept of foundation bearing capacity in saturated soil was developed by Terzaghi (1943) using conventional soil mechanics. Recently, several researchers investigated the bearing capacity of unsaturated soils where the soil layer is above the groundwater table (Broms 1963, Steensen-Bach et al. 1987, Miller and Muraleetharan 1998, Costa et al. 2003). All these studies have shown substantial influence of matric suction on the bearing capacity of unsaturated soils.

The type of pavement failure depends on the factors influencing the pavement structure; including: 1) functional failure that occurs due to the degree of surface roughness 2) Structural
failure where the pavement structure is incapable of sustaining the imposed loads on the pavement surface (Christopher et al. 2006). The latter failure might be expected if it occurs due to the repeated loads over time at the end of the pavement design life or unexpected when very small number of cycles of excessive overload are applied or the pavement material is weakened. Soil bearing capacity failure is categorized as a structural failure where the subgrade soil cannot further sustain the required capacity. Therefore, the shear failure in flexible pavements under excessive water and post-flooding loading could be assessed using the concept of shear failure in soils.

The objective of this investigation is to provide a methodology to evaluate the structural capacity of flooded pavements in order to avoid sudden failures due to relatively small number of passes over a severely weakened pavement structure. This is accomplished by estimating the bearing capacity of pavement systems with saturated and unsaturated soils by incorporating a matrix suction profile, the saturated shear strength parameters (i.e. c’ and φ’), and Soil Water Characteristics Curves (SWCC). The bearing capacity was calculated under different moisture conditions ranging from unsaturated to flooded, fully saturated condition. The flooded condition was achieved by raising the water table from an initial hydrostatic pressure distribution for a generic site. The load distribution in the subgrade soil was estimated assuming a 1:1 slope in depth. Finally, the maximum tire load on the pavement surface was back calculated based on the computed load bearing capacity of the soil layer using layer elastic analysis. Layer elastic analysis was performed by incorporating matric suction in resilient modulus of unsaturated subgrade soil layer divided into sublayers (152.4 mm each) up to the groundwater table to evaluate the nonlinearity of the soil layer. This information can assist agencies and town planners determine when traffic should be allowed considering ultimate failure criteria.

2 MATERIALS AND METHODS

2.1 Material characterization

Three different pavement sections (Table 1) with three different types of subgrade soil and varying Ground Water Table (GWT) levels were evaluated. The subgrade soils represent a range of common subgrade materials from across the U.S. For this study, the soil physical properties were obtained from Arizona State University soil map application (NCHRP 9-23b, 2012) for sites in New Hampshire, Texas, and Vermont.

<table>
<thead>
<tr>
<th>Section #</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>76.2, 152.4</td>
</tr>
<tr>
<td>2</td>
<td>152.4, 304.8</td>
</tr>
<tr>
<td>3</td>
<td>203.2, 406.4</td>
</tr>
</tbody>
</table>

Table 1. Pavement cross sections and material properties.

Measured laboratory values were not available for all of the soil properties required for the analysis in this project. Therefore, established relationships were used to estimate the water content, degree of saturation, specific unit weight, void ratio, and dry densities from physical soil indices. The equations from the Enhanced Integrated Climate Model (EICM) in the Mechanistic—Empirical Design guide (MEPDG) developed under NCHRP projects 1-37 A were used and are shown in Equations 1-6 below:

\[
S_{opt} = 6.752(WPI)^{0.147} + 78
\]

\[
G_s = 0.041(WPI)^{0.29} + 2.65
\]

\[
S \times e = W \times G_s
\]

\[
\rho_{dry} = \frac{G_s \times \gamma_v}{1 + e}
\]

\[
W_{opt} \% = 8.6425D_{60}^{-0.1038}\quad \text{If PI = zero}
\]

\[
W_{opt} \% = 1.3(WPI)^{0.73} + 11\quad \text{If PI > zero}
\]

where:

- WPI = Percent of passing#200 \times \text{plasticity index}
- D60: Grain diameter corresponding to 60% passing by weight or mass (mm), S_{opt}: degree of saturation at the optimum moisture content, W_{opt}: optimum moisture content, \(e\): void ratio, \(\rho_{dry}\): max dry density of the soil, G_s: specific gravity.

Table 2 shows the estimated soil properties determined from the above equations and the effective cohesion (c’) and effective internal friction angle (φ’) estimated based on the soil properties from the Swiss Soil Standard.

To begin the analysis, the water table was placed at an elevation equivalent to the top of the subgrade layer to simulate a fully saturated soil. The water table was then lowered in 152.4 mm intervals down to 25 meter below the pavement surface. The matric suction was set to zero for saturated soils while a hydrostatic capillary suction was calculated from Equation 9 for soils above the water table. The
subgrade soil above the water table was divided into sublayers where the matric suction in each sublayer was calculated at the mid height with an initial hydrostatic capillary pressure distribution.

\[ u_u - u_w = \gamma_w h \]  

(9)

where: \( u_u \) is pore air pressure = zero in this case, \( u_w \) is pore water pressure = \( -\gamma_w h \), \( \gamma_w \) is unit weight of water, \( h \) is the average distance from the point of interest to the groundwater table for a period of time for which the GWT has been fairly stable.

The Soil-Water Characteristic Curve (SWCC) proposed by Fredlund and Xing (1994) available in the EICM and widely used in the pavement practice was used to predict the degree of saturation from suction at each layer, as shown in Equations 10 and 11 (NCHRP 1-37 A, 2000).

\[
S = C(h) \times \left[ \frac{1}{\ln\left(\exp(1) + \left(\frac{h}{a}\right)^b\right)} \right]^{-c} \\
C(h) = 1 - \left[ \frac{\ln\left(1 + \frac{h}{h_a}\right)}{\ln\left(1 + 10^{6}\right)} \right] \\
\]  

(10)

\[
\frac{b}{a} = \frac{1}{D_{60} + 9.7e^{-4}} \\
\]  

(11)

where \( \bar{b} \) = Average value of fitting parameter b.

Figure 1 depicts the predicted SWRC for New Hampshire soil (A-2-4), Texas soil (A-4) and Vermont soil (A-7-5) plotted as the relationship between the degree of Saturation (Sr) and matric suction (ua-uw) using the Fredlund and Xing and Perera’s correlation models. The soils with more fine materials and more plasticity have higher air entry values ranging from 2 kPa for A-2-4 to 14 kPa for A-4 and 90 kPa for A-7-5 soils. It means if the matric suction is beyond these specified values, the soil exhibits unsaturated condition rather than fully saturation condition. As expected, increasing the matric suction decreases the degree of saturation.

Available correlations between strength and stiffness of unbound materials and physical soil indices were employed to estimate the CBR and resilience Modulus (Mr) of the proposed soils at an optimum moisture content as in Equations 19 and 20, respectively.

\[
a = 0.00364(wPI)^{3.35} + 4(wPI) + 11 \\
b = -2.313(wPI)^{0.14} + 5 \\
c = 0.514(wPI)^{0.465} + 0.5 \\
\frac{h_a}{a} = 32.44e^{0.0166(wPI)} \\
\]  

(12)

(13)

(14)

(15)

(16)

(17)

(18)

- Correlations for Soils with PI = 0 (For granular soils with Plasticity Index equal to zero)

Table 2. Properties of the selected soils.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>A-2-4</th>
<th>A-4</th>
<th>A-7-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent passing # 200</td>
<td>22.5</td>
<td>80</td>
<td>92.5</td>
</tr>
<tr>
<td>Liquid Limit (L.L)</td>
<td>17.5</td>
<td>26</td>
<td>60</td>
</tr>
<tr>
<td>Plasticity Index (PI)</td>
<td>0</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Specific Gravity (G_s)</td>
<td>2.650</td>
<td>2.723</td>
<td>2.757</td>
</tr>
<tr>
<td>Void ratio (e)</td>
<td>0.34</td>
<td>0.52</td>
<td>0.80</td>
</tr>
<tr>
<td>Max dry density (gm/cm³)</td>
<td>1.980</td>
<td>1.798</td>
<td>1.535</td>
</tr>
<tr>
<td>( W_{optc} )</td>
<td>10</td>
<td>16.50</td>
<td>25.71</td>
</tr>
<tr>
<td>Sr_{opt} (%)</td>
<td>78</td>
<td>87</td>
<td>89</td>
</tr>
<tr>
<td>Cohesion (c')</td>
<td>0</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>Internal friction angle (( \phi' ))</td>
<td>39</td>
<td>41</td>
<td>31</td>
</tr>
</tbody>
</table>

![Figure 1. Predicted SWRC for the proposed soils.](image-url)
\[
C_{BR} = \frac{75}{1 + 0.728(wpI)}
\]

\[
M_r = 2555(C_{BR})^{0.64}
\]

Then, the resilience modulus of subgrade soil at different degrees of saturation was estimated using Witczak model in EICM (NCHRP 1-37 A, 2000) as provided in equation 21 given the optimum moisture content and the corresponding degree of saturation.

\[
\log \frac{M_R}{M_{opt}} = a + \frac{b - a}{1 + \exp \left[ \ln \left( \frac{b}{a} \right) + k_m \left( S - S_{opt} \right) \right]}
\]

where \( M_R/M_{opt} \) = resilient modulus ratio; \( M_R \) = resilient modulus at any degree of saturation; \( M_{opt} \) = resilient modulus at a reference condition; \( a \) = minimum of \( \log M_R/M_{opt} \); \( b \) = maximum of \( \log M_R/M_{opt} \); \( k_m \) = regression parameter; and \( S - S_{opt} \) = variation in degree of saturation expressed in decimals. Using the available data from the literature and assuming a maximum modulus ratio of 2.5 for fine-grained materials and 2 for coarse-grained materials, the values of \( a, b, \) and \( k_m \) for coarse-grained and fine-grained materials are summarized in Table 3 (Witczak et al., 2000).

2.2 Bearing capacity calculation procedure

In a pavement system truck loads are transmitted from the pavement surface to underlying layers including subgrade soil. In this study, the radius of the tire on the pavement surface \( r \) was computed based on the load of 40 kN and tire pressure of 0.827 MPa. Then, the tire on the soil surface was estimated based on 1:1 pressure distribution as a conservative distribution angle of the stresses on the soil. Then, the load distribution at the top of the subgrade was treated as a circular footing for bearing capacity analysis.

The conventional method to estimate the ultimate bearing capacity in saturated soils for circular footing was proposed by Terzaghi 1943 as in Equation 22.

\[
q_u = 1.3c'N_c + \gamma DN_q + 0.3\gamma BN_p
\]

where: \( q_u \) = ultimate bearing capacity; \( c' \) = effective cohesion; \( \gamma \) = unit weight; \( D \) = footing base level; \( m \); \( B \) = footing width; the diameter in the case of circular footing; \( N_c, N_q, N_p \) = bearing capacity factors.

Vanapalli et al. (1996) proposed a modified form of Terzaghi’s equation for a surface footing with respect to matric suction using effective shear strength parameters and shape factors proposed by Vesic (1973) in Equation 23. This equation is the same as Equation 22 if the matric suction is zero. Therefore, this equation can capture a smooth transition between saturated and unsaturated soil.

\[
q_u = 1.3 \left[ c' + (u_a - u_w)_{avg} S' \tan \phi' \right] N_c \left[ 1 + \left( \frac{N_q}{N_p} \right) \frac{B}{L} \right] + 0.3\gamma BN_p \left[ 1 - 0.4 \left( \frac{B}{L} \right) \right]
\]

where: \((u_a - u_w)_{avg} \) = average matric suction, \( \phi' \) = effective friction angle; \( S' \) = degree of saturation, \( \psi \) = bearing capacity fitting parameter proposed by Vanapalli et al. (2007).

The bearing capacity factors for cohesion (\( N_c \)) and surcharge (\( N_q \)) by Terzaghi were used in this analysis while the bearing capacity factor for the unit weight was utilized from Kumbhokjar (1993). The reason behind the proposed bearing capacity factors were because these show a good correlation between predicted and measured soil bearing capacity according to Vanapalli et al. 2007.

The average matric suction values for the selected soils were calculated from the soil surface to the bottom of the influence stress zone; in this study considered to be 1.5B to the depth that there is a significant distribution of stress in soil (Chen 1999). Then, the degree of saturation was estimated from the soil water retention curve (Figure 1). Figure 2 shows a schematic of the proposed method.

Finally, Layer elastic analysis using KENLAYER software was performed to back calculate

![Figure 2. Schematic to demonstrate the pavement cross section and the analysis approach.](image-url)
the vertical stress on the pavement surface layer that corresponds to the computed ultimate bearing capacity of the soil layer. Then, the maximum tire loads were computed based on the calculated stresses on the pavement surface that the road can withstand without shear failure. In the layer elastic analysis, subgrade layer was divided into sublayer (152.4 mm each) up to the GWT then the layer below GWT considered to be one fully saturated layer. The matric suction was computed from equation 9 at the middle of each sublayer and the degree of saturation was computed using SWRC (Figure 2) at each sublayer for all the proposed soils. Then, the resilience modulus at each sublayer was computed using equation 21. Due to the limited number of layers in KENLAYER (19 layers max), sublayers with 1-2% difference in resilient modulus values were combined into one layer to accommodate the simulation.

Using pavement layer thickness and material properties as shown in Table 1 and load of 40 kN and 0.827 MPa tire pressure the maximum vertical stress on the top of soil layer was predicted at different GWT levels using layer elastic analysis. Then, the estimated vertical stresses on the pavement layer from the ultimate bearing capacity on the soil was computed as a proportion of the actual vertical stress of 0.827 MPa on the pavement surface and the resultant stresses on the top of soil layer at different degrees of saturation.

3 RESULTS AND DISCUSSIONS

The changes in bearing capacity with groundwater table level for the selected subgrade soils and the three different pavement structures are shown in Figure 3. For the A-2-4 soil, the pavement structure has a significant impact on the bearing capacity, with the thickest pavement structure showing more than twice the bearing capacity of the thinnest pavement structure. The bearing capacity increases quickly as the water table drops (shallow slope at the top portion of the curve), and then continues to increase, but at a much slower rate once the GWT drops below an effective depth. The effective depth depends on the thickness of the pavement structure: 1 meter for the thinnest pavement structure and 2.30 meter for the thickest pavement structure. The silty (A-4) and clayey (A-7-5) soils show different behavior. There is only a small impact of the pavement thickness on the bearing capacity and the bearing capacity increases at a relatively constant rate as the GWT drops up to an effective depth. The effective depth for A-4 and A-7-5 soils are 6 meter and 12 meter from pavement surface respectively for all pavement structures. Then, below that effective depth the bearing capacity increases at a minimal rate then remains stable. For the A-2-4 soil, there is a discontinuity in the curves for the two thicker pavement structures at a depth of 1.5B where the degree of saturation changes from 85% to 60%.

Figure 4 shows the ratio of bearing capacity as the water table drops to the bearing capacity under full saturation conditions. The bearing capacity ratio increases quickly as the GWT drops to the effective depth then below that depth the bearing capacity increases at a slower rate for all soils. The bearing capacity ratio increases to 1.8 for A-2-4 soil and from 2.5 to more than 3 times for A-4 soil as the GWT drops to the effective depth with differences in ratios for the different pavement thicknesses. The pavement thickness does not significantly affect the ratio for the A-7-5 soil. The slope of bearing capacity ratio for the A-7-5 material is steeper than the A-2-4 and A-4 soil types. This is may be because of the gradation, plasticity and the infiltration rate of the material type. It can be seen from both Figures 4 and 5 that the load bearing capacity of the coarse grain soils is greater than the bearing capacity of the fine grain soils at specific water content due to the gradation and mechanical properties of the materials; i.e. c’ and φ’

![Figure 3. Variation of bearing capacity with groundwater table levels for the proposed soils.](image1)

![Figure 4. Ratio of bearing capacity with groundwater table levels for the proposed soils.](image2)
Figure 5 shows the maximum tire load (assuming a tire pressure of 0.827 MPa) that the pavement cross section could withstand without shear failure of the subgrade. Under most conditions evaluated, the pavements will have sufficient capacity to carry most practical tire loads. The trends in the results are still valuable for understanding pavement performance. It can be seen that for all soil types there is a significant impact from different pavement structures. A-2-4 soil type shows the largest difference between load magnitudes at three pavement cross sections and the lowest difference is for the A-4 soil type. This is may be because of the saturation of the soil and the influence of the stress zone. Despite the difference of the gradation, plasticity and shear strength parameters for A-2-4 and A-7-5 soil types; soil types behave similarly in the thin pavement structure.

4 SUMMARY AND CONCLUSIONS

With a goal of assessing the load carrying capacity of a flooded pavement structure and assisting agencies in decisions on when to apply traffic restrictions, the bearing capacity of the pavement structure post flooding were evaluated using the theory of shear failure in soils. The bearing capacity of the selected soils was calculated using modified Terzah’s formula including the effect of matric suction and shear strength parameters $c'$ and $\phi'$ for three different flexible pavement cross sections. Layer elastic analysis was used to back calculate the traffic load that meets the bearing capacity of the pavement system. The following conclusions are drawn based on the observations.

• The theory of shear failure in soils with contribution of matric suction and soil water characteristic curve can be applied to pavement practice to evaluate the potential for sudden failure of a flooded pavement structure. By incorporating the matric suction in the analysis, bearing capacities are larger than those determined from the fully saturated condition.
• The load bearing capacity of the pavement with coarse grain soil is greater than the ones of fine grain soils due to the higher shear strength.
• For A-2-4 and A-4 soils and thin pavement structures, of the location of the groundwater table does not have a large impact on the pavement bearing capacity. There is a significant impact from different pavement thicknesses and groundwater table variation on pavement bearing for A-7-5 subgrade soils.
• The effective water table zone in which dramatic changes in capacity occur was shown to be dependent on the subgrade material.
• The effective depth was shown to depend on the pavement thickness for A-2-4 soil type but not for A-4 and A-7-5 soil types.
• The pavement structure significantly changes the tire loads as the water table recedes down to the effective depth.
• For the thinnest pavement structure, the tire loads on the pavement surface are shown to be similar for all three subgrades despite the difference in ultimate bearing capacity for each soil.

The use of this information can be adapted to develop more comprehensive engineering-based approach for agencies to evaluate the bearing capacity of the flooded pavements to avoid any sudden failure. This study is limited to the three soil material types, it is essential to investigate more soil material types with different properties to verify and validate this approach. Future work will be investigated more soil material types and validate the approach using sections from SMP-LTPP at different environmental conditions.

REFERENCES

Arizona State University (ASU). Soil Map Application, http://nchrp923b.lab.asu.edu/
Swiss Standard SN 670 010b, “Characteristic Coefficients of soils”, Association of Swiss Road and Traffic Engineers.