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Implementation of a New Flexible Pavement Design Procedure for U.S. Military Airports

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Abstract

The U.S. Military (Army, Air Force and Navy) thickness design procedures for flexible airport pavements are based the CBR (California Bearing Ratio) method. This method was originally developed in the 1940's for design of flexible pavements to support the then new heavy bombers. The original airfield design curves were an extrapolation, based on shear stress, of the California pavement design curves for highway pavements. The extrapolated curves were modified and verified by extensive full scale field testing. The classical CBR equation was then developed from these curves. Recent research conducted at the U.S. Army Engineer Research and Development Center revealed that the classic CBR equation can be derived from a stress distribution represented by Frohlich's stress concentration factor equal to 2. This discovery led to the reformulation of the classical CBR equation into a more general equation in terms vertical stresses as computed with a stress concentration factor. This paper presents the implementation of this new formulation into a more comprehensive design procedure for airport pavements. The paper will present a brief description of the development of the new procedure, flowcharts describing its implementation, and pavement thickness comparison between the old and the new procedures. The importance and positive impact to the U.S. Military by the adoption of this new methodology will also be presented and discussed.

Keywords

CBR equation, Vertical Stress, Flexible Pavement Design, U.S. Military, Airfield, Implementation

1. Background

The California Bearing Ratio (CBR) procedure has been the principal method used for design of flexible pavements for both military roads and airfields since its development in the 1940s. This procedure has been very successful in the military, and it has been currently used throughout the world. Its simplicity, practicability, history, and field experience has motivated the U.S. Army Corps of Engineers to continue promoting and improving this technology. The criteria currently implemented is represented by equation

$$t = \alpha \cdot \sqrt{\frac{ESWL}{8.1 \cdot CBR} - \frac{A}{\pi}} \tag{1}$$

where: ***t*** = design thickness;
ESWL = equivalent-single-wheel load;
CBR = represents the soil strength at the depth "***t***"
A = contact area for the ***ESWL*** which is assumed be a constant and equal to the contact area of a tire in the gear assembly
α = thickness adjustment factor that is a function of traffic volume and number of tires in the tire group

Equation 1 can also be written in the form as shown in Equation 2, in which β is defined by Equation 3, and can be related to traffic volume in terms of coverages as shown in Figure 1.

$$t = \sqrt{\frac{ESWL}{\beta \cdot CBR} - \frac{A}{\pi}} \tag{2}$$

$$\beta = \frac{\sigma_z \cdot \pi}{CBR} \tag{3}$$

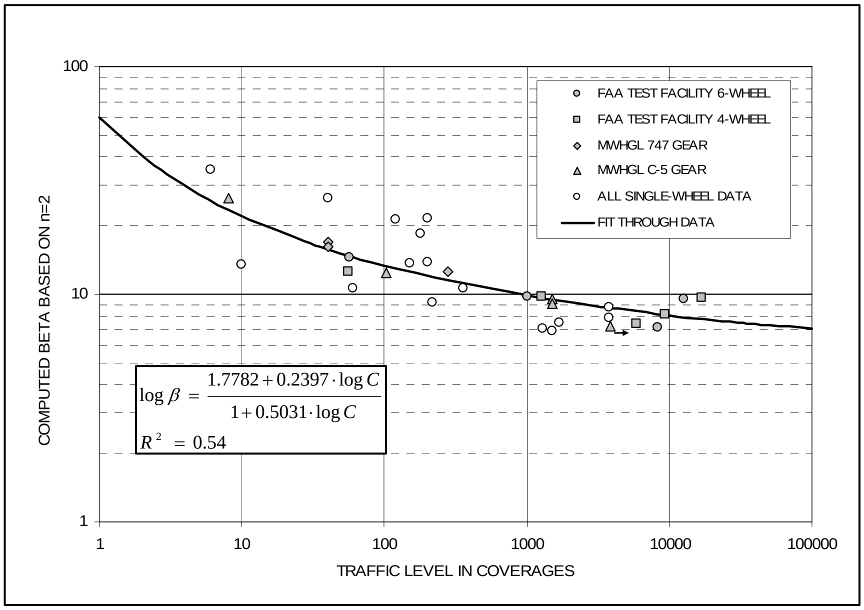

Figure 1. Beta (β) as Function of Traffic Volume in Terms of Coverages

For a given traffic level of an ESWL, the value of β can be determined from Figure 1, which may then be used in Equation 2 to compute the required pavement thickness. It was shown by Barker and Gonzalez (2006), that Equation 1 and thus Equation 2 represent a special case of the general solution as given in Equation 4 for the vertical stress in a half-space. The general solution for vertical stress (σ_z) in a half-space due to a point load (***P$_i$***) at the surface is given in Equation 4. Figure 2 provides the description for the parameters of Equation 4.

$$\sigma_z = \sum_{i=1}^{wheels} \frac{n \cdot P_i}{2 \cdot \pi \cdot R^2} \cdot \cos^n \theta \tag{4}$$

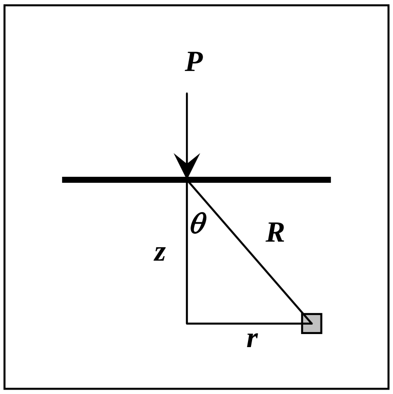

Figure 2. Parameter Definition for Equation 4.

The factor ***n*** in Equation 4 is Frohlich's concentration factor which modifies the distribution of vertical stress in the half-space system. When factor ***n*** is equal to 3, Equation 4 represents Boussinesq stress distribution; for values of ***n*** less than 3, Equation 4 represents stress dispersion; for values of ***n*** greater than 3, Equation 4 represents a stress concentration. It has been shown (Barker and Gonzalez,2006) that the current CBR criteria are based on a factor of ***n*** equal to 2. For the special case of stress under the center of a uniform circular load, Equation 4 can be rewritten in the closed-form given by Equation 5, in which ***r*** represents the radius of the loaded area and σ_0 is the surface pressure applied over the loaded area.

$$\sigma_z = \sigma_0 \cdot \left[1 - \frac{1}{\left\{ \sqrt{1 + \left(\frac{r}{z} \right)^2} \right\}^n} \right] \tag{5}$$

Although the current CBR design criteria are based on a Frohlich's concentration factor of 2, it has been argued by Barker and Gonzalez (2006) that the ***n*** should be a function of the subgrade CBR. Barker and Gonzalez also proposed to define ***n*** as a function of CBR as shown in Equation 6.

$$n = 2 \cdot \left[\frac{CBR}{6} \right]^{0.337} \tag{6}$$

Equation 4 is the basis for the general case solution for computing the vertical stress in a half-space due to multi-wheel tire groups. Computer software has been developed for computing, using numerical integration techniques, the vertical stress (σ_z) at the top of subgrade due to a multi-wheel tire group. For the special case of a single wheel, the stress can be computed in a closed manner using Equation 5. For single wheel designs, Equation 5 can be rearranged such that the required thickness may be determined directly (Equation 7).

$$\frac{t}{r}=\frac{1}{\sqrt{\left(\frac{1}{1-\frac{\beta\cdot CBR}{\pi\cdot p}}\right)^{\frac{2}{n}}-1}} \tag{7}$$

For a multi-wheel gear the stress must be computed for different positions within the gear to insure the maximum stress under the tire group is determined.

2.0 New Performance Criteria

The design criteria, to be referred to herein as the β-criteria, are to be defined as a relationship between traffic volume in terms of coverages to failure and the β parameter as defined by Equation 8. The β parameter was previously defined by Equation 3.

$$\log(C)=\frac{1.7782-\log(\beta)}{0.5031\cdot\log(\beta)-0.2397} \tag{8}$$

3.0 Traffic Volume

Traffic volume is defined in terms of coverages as described by the methodology developed by Brown and Thompson; and described in an instructional report by Taboza Pereira (197x). The methodology as presented by Barker-Gonzalez (2006) is defined by Equations 9 and 10. Using Equations 9 and 10 the traffic in terms of coverage (C_x) at particular point, defined by an offset distance (x_o) from the center-line of the traffic lane, can be computed for each tire group.

$$C_x=n_o\cdot\sum_{i=1}^{m}P_i \tag{9}$$

$$P_i=\int_{x_o-\frac{w}{2}}^{x_o+\frac{w}{2}}\frac{1}{\sigma\cdot\sqrt{2\cdot\pi}}\cdot e^{-\frac{1}{2}\cdot\left(\frac{x-x_i}{\sigma}\right)^2}dx \tag{10}$$

The other variables in Equations 9 and 10 are defined as: P_i is the probability that a tire (i) will traverse a point; x_i is the distance from the centerline of the aircraft to the tire; w is the width of a tire; σ is the standard deviation of the traffic distribution, and n_o is the number of operations of the particular aircraft. The traffic distribution is represented by the wander-width defined as the width of pavement in which 75% of the traffic is applied. The standard deviation will be one-half of the wander-width divided by 1.15. For the airfield runways and taxiways, wander-widths of 70 and 140 inches respectively are used for the traffic distributions. When designing a pavement for traffic of a single vehicle or aircraft, the design coverage level is found by computing the coverage levels at various points across the pavement and selecting the maximum coverage level for design.

3.1 Mixed Traffic

For design of pavements considering a mixture of vehicles or aircraft types, it is necessary to combine the effects of the different loadings and traffic volumes. This is to be accomplished through the use of the cumulative damage concept (Miner's hypothesis). In the cumulative damage concept, the damage caused by a single operation of a vehicle or aircraft is the inverse of the allowable number of operations, and can be summed to obtain the damage for all operations and all vehicles/aircraft. The cumulative damage concept is represented by Equation 11.

$$D_{total} = \sum_{i=1}^{vehicles} \frac{n_i}{C_i} \tag{11}$$

In Equation 11, D_{total} is the total cumulative damage for all vehicles; n_i is the applied coverage level for the i^{th} vehicle, and C_i is the allowable coverage level of the i^{th} vehicle. The pavement thickness is to be selected such that the total cumulative damage shall not exceed one. Since computing a value of C_i requires a value of thickness, the design process requires an iterative procedure of successive approximation until a value of D_{total} is obtained that is sufficiently close to one.

4.0 Design Procedure

The general procedure for design of flexible pavements based on the CBR is described by the flow diagram given in Figures 3 and 4. The basic CBR design procedure shall remain unchanged except for the methodology for computing allowable coverage levels and handling mixed traffic. Procedures for selecting parameters, such as material properties, compaction requirements, design CBR, loads, tire pressures, and vehicles operations, shall be the same as in the current CBR procedure. The design procedure can be described for four loading cases:

(1) One single-wheel gear
(2) Mixed traffic composed of single-wheel gears
(3) One multi-wheel gear
(4) Mixed traffic composed of multi-wheel and/or single-wheel gears

Each of these loading cases is discussed in detail below.

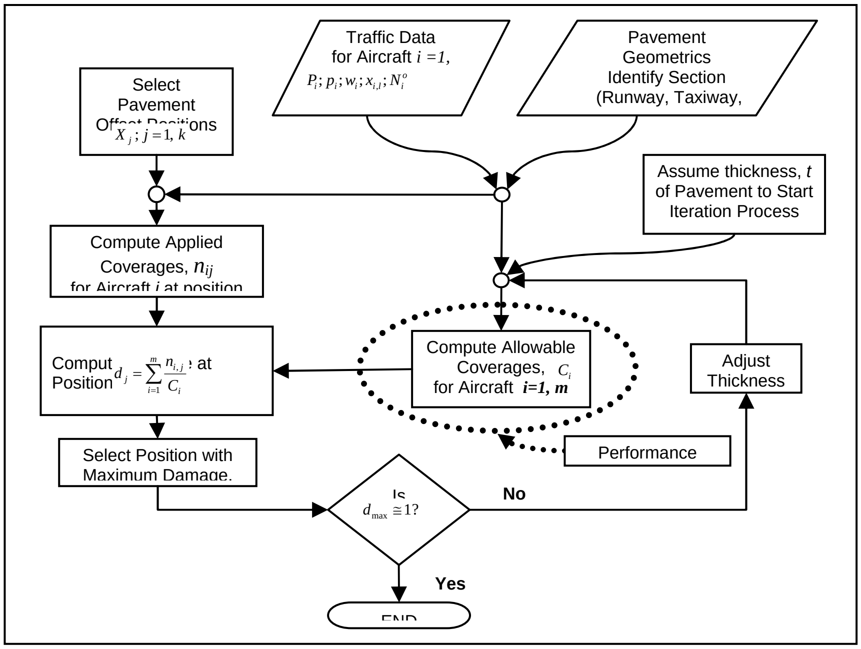

Figure 3. General Flow Diagram for Flexible Pavement Design

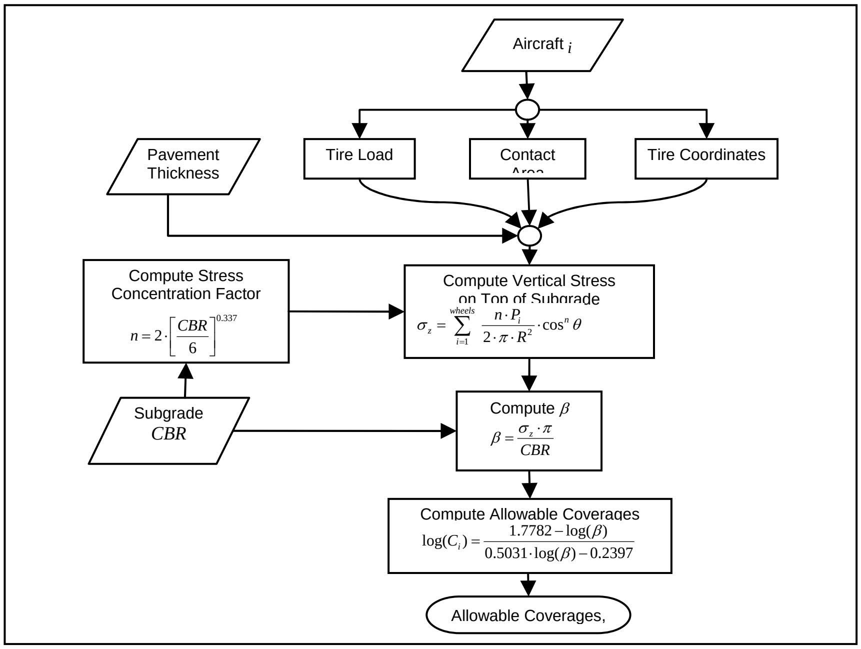

Figure 4. Performance Model for the CBR Design Procedure

4.1 Design Procedure for One Single-Wheel Gear

When a flexible pavement is designed based on a single-wheel gear, the thickness can be determined directly by Equation 7. In this case, the traffic volume used to compute the value of β can be determined from published pass-to-coverage ratios, or by Equation 12 which is a simplified version of Equation 10.

$$C = \frac{0.3989 \cdot w}{\sigma} \cdot n_o \tag{12}$$

In this equation, σ takes the value of 30.43 and 60.87 for taxiways and runways, respectively; w is the width of the contact area of a tire, and n_o is the number of operations of the aircraft.

4.2 Design Procedure for Mixed Traffic Composed of Single-Wheel Gears

The design procedure for mixed single-wheel gears is slightly more involved than designing for one single-wheel gear. In this procedure, the cumulative damage concept must be employed and various locations across the pavement must be chosen to determine the location of the maximum damage. The first step in the recommended procedure is to determine the required thickness for each vehicle using the procedure outlined for a single-wheel gear. The maximum thickness obtained can be used as the starting thickness for the iterative process for determining the required thickness. In most cases, the final thickness is not likely to be much thicker than the maximum thickness obtained for the individual aircraft. For the starting thickness the cumulative factor is computed for various locations (to locate the position of the maximum damage) across the pavement traffic lane. It should be noted that the position of maximum damage will normally occur under the center of the traffic distribution of the tire requiring the maximum thickness of pavement. In computing the cumulative damage, the value of β for a given thickness is first computed for each vehicle. Equation 7 can be rearranged in the form of Equation 13 below, such that, given the thickness, β can be computed directly for each vehicle.

$$\beta = \left[1 - \left(\frac{r^2}{t^2} + 1 \right)^{\frac{-n}{2}} \right] \cdot \frac{\pi \cdot p}{CBR} \tag{13}$$

With the value of β computed, the allowable traffic in terms of coverages is computed based on the performance criteria given by Equation 8. It should be noted that the allowable coverages for a particular vehicle will remain constant across the traffic lane, thus it will only be necessary to compute the applied traffic for the different positions. The traffic applied by each vehicle and for each position is computed based on the general equation for coverages. Having determined the applied traffic (n_i) and the allowable traffic (C_i), the damage factor can be computed by Equation 11. By selecting the initial thickness in this manner, the damage factor for the initial thickness will be less than one, thus the second iteration will involve increasing the thickness and re-computing allowable traffic (C_i) for the new thickness. It should be noted that for a single-wheel gear, the location for the maximum damage will not change from iteration to iteration and the applied traffic will remain at the same location for all iterations.

4.3 Design Procedure for One Multi-Wheel Gear

The design case for one multi-wheel gear is similar to the design procedure for one single-wheel gear in that it is not necessary to consider different positions across the traffic lane (other than to determine the pass-to-coverage ratio), nor is the cumulative damage computation necessary. The difference between the two cases is that the thickness can not be directly computed but must be determined by an iterative procedure. The basic procedure is that the design traffic volume in terms of coverages is first determined. From the design traffic and design CBR, the value of β is determined from the β-criteria. Using Equation 14 below, the allowable vertical stress $(\sigma_z)_{allow}$ at the top of the subgrade is computed.

$$(\sigma_z)_{allow} = \frac{\beta \cdot CBR}{\pi} \qquad (14)$$

The design problem is then a problem of finding the thickness for which the stress at the top of the subgrade, due to the design aircraft, is approximately equal to the allowable stress. For multi-wheel gears, the thickness can not be determined directly but must be determined using an iterative procedure. For a starting thickness, it is suggested that the thickness be computed using Equation 7 for a single wheel of the gear. This thickness will be somewhat less that the final thickness, but, as was the case for the mixed single-wheel gears, the final thickness will be somewhat greater than the thickness required for a single tire. The vertical stress at the top of the subgrade for the initial thickness will be compared with the allowable stress. If required, the thickness should be increased and the process repeated. With a few iterations the data from the computation could be used to estimate the thickness for which the computed stress would be approximately equal to the allowable stress.

4.4 Design Procedure for a Mixed Traffic Composed of Multi-Wheel Gears

The design procedure for mixed traffic composed of multi-wheel gears represents the general case as shown in Figure 3. In general, the thickness design for mixed multi-wheel gears involves computing the traffic volume, in terms of coverages (n_i), for each vehicle at offsets across the traffic lane. Using an assumed thickness, the allowable traffic volume (C_i) for each vehicle is computed as has been discussed previously. For a given vehicle, the allowable traffic (C_i) will be constant across the traffic lane. The cumulative damage factor can then be computed using Equation 11 for various offsets across the traffic lane. The initial thickness for the iterative process can be determined directly using Equation 7 and the data for the tire having the heaviest loading. The iterative process is continued, as described for the special cases, until the thickness corresponding to a maximum cumulative damage factor is approximately equal to one.

4.5 Software for the Design Procedure

The algorithms and equations for the new CBR design procedure have already been developed and are available from the Airfield and Pavements Branch, ERDC Vicksburg, MS. The new design procedure will be incorporated into the PCASE software for the design of airfield flexible pavements.

4.6 Comparison Between Current and Proposed Design Procedure

Figure 5 illustrates a thickness design comparison between the current design procedure and the new proposed CBR procedure based on vertical stress. This comparison was done for a range of subgrade CBR values and 10,000 coverages of the C-17 aircraft. It can be observed that for low subgrade CBR values, the new design procedure will yield thinner pavement sections than the current procedure. However, at higher CBR values (i.e. CBR>10 for this particular aircraft), the pavement thickness resulting form the new procedure is approximately equal to or slightly higher than the current procedure. This typical result shows that for low CBR values, the current implementation of the CBR procedure tends to overestimate the pavement thickness.

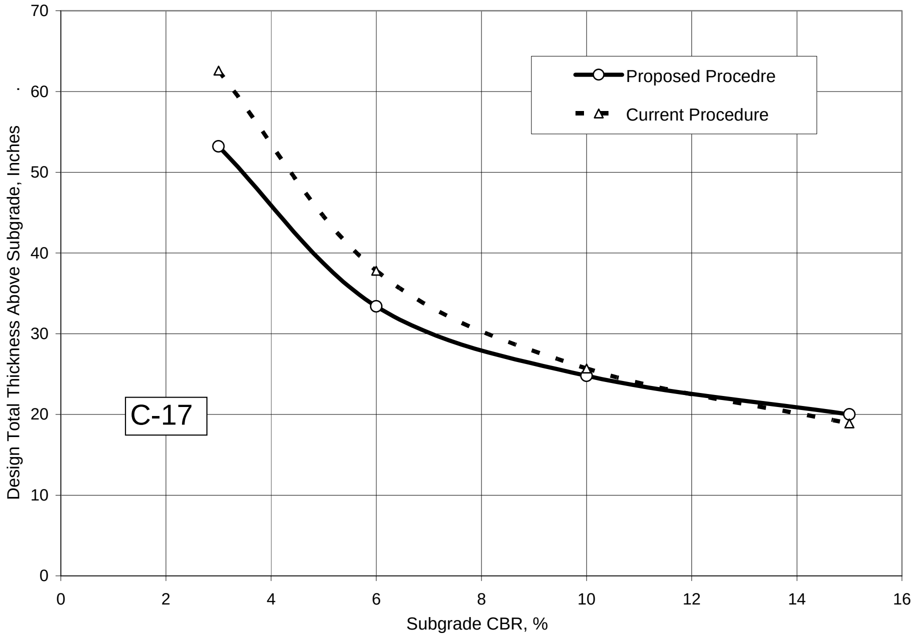

Figure 5. Comparison Between the Current Design Procedure and the New Proposed Procedure

5.0 Conclusions

A new procedure for the design of flexible airfield pavements has been presented. This procedure uses a stress-based approach that is considered to be more robust than the current implementation. This new CBR implementation brings this methodology to par with existing state-of-the art design procedures based on layered elastic systems. It has been proven that the new renovated CBR procedure has a mechanistic basis while still keeping its simplicity of use and implementation.

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