Automated Design-Based Compaction Criteria for Airport Pavements Using FAARFIELD

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ABSTRACT: A new computational procedure developed for the Federal Aviation Administration's (FAA) FAARFIELD program determines the degree of compaction required at various depths, based on the specific pavement thickness design and aircraft traffic mix. This procedure is run at design time and automatically generates a unique schedule of minimum required densities as part of the design report. The basis for computed compaction requirements is the compaction index (CI), which is defined as the CBR required at a given depth for a particular gear load. The procedure implements accepted empirical relationships between CI and degree of compaction that were developed for cohesive and non-cohesive soils from historical full-scale compaction data. Within FAARFIELD, the CI is determined as a function of the layered elastic vertical stress response, making use of the Frohlich's stress concentration factor (to correct for different stress distributions) and the beta factor to relate the computed stress to CBR. The approximate correlation obtained between layered elastic stresses and CI using this methodology is valid throughout the typical design CBR range and can be extended to any complex gear type. The method yields compaction criteria that are reasonable, integrated with the design, and consistent with observed field data.

KEY WORDS: Compaction, FAARFIELD, airport pavement design, CBR, CI.

1 INTRODUCTION

FAA design standards for both rigid and flexible pavements require compaction of soil materials to prevent further densification of those materials under in-service aircraft operations. The current FAA compaction requirements are published as table 3-4 of Advisory Circular (AC) 150/5320-6E (figure 1) and are basically independent of the FAARFIELD thickness designs. With the introduction of newer and more complex aircraft gears, it is necessary to rationalize the standards for compaction and to integrate them with the FAARFIELD thickness design software. In this new FAARFIELD procedure, compaction requirements at various depths are automatically generated using the compaction index (CI), which is in turn computed from vertical stress. The main reason for reintroducing certain CBR concepts into an otherwise fully layered elastic (LE)-based program is that by doing so we take full advantage of extensive, validated compaction performance data based on airport testing. The existing full-scale data on compaction are expressed in terms of CI. Furthermore, recent advances allow the CI to be computed reasonably accurately from LE stresses.

2 BACKGROUND

The concept that the degree of compaction for a given pavement depends on the magnitude of the aircraft load was established as far back as the 1940's by traffic tests conducted by the US Army (Ahlvin et al., 1959), and was first implemented in military design manuals of that era. A key study of airfield compaction requirements for flexible pavements was carried out by the US Army Engineers Waterways Experiment Station (WES) (Ahlvin et al, 1959). The WES study introduced the concept of the CI, and showed that CI can be reasonably well correlated to field compaction requirements for both cohesive and non-cohesive soil types. CI is defined as the "CBR required at a given depth for a particular wheel configuration, assembly load and tire pressure," a definition that is maintained in this paper. A second unpublished report prepared for the FAA (Ahlvin, 1989) examined the FAA compaction requirements then in effect and proposed replacement curves developed from the CI criteria (Figure 2). These curves were intended to enclose 80% of the analyzed data points from full-scale flexible pavement studies (with certain adjustments that are explained in the original report). However, the suggested curves were never directly implemented as an FAA standard. Hence, the current FAA requirements in figure 1 are generally inconsistent with the CI-derived criteria. A major source of inconsistency identified in the 1989 report is that depths of compaction as given in the AC are referenced from the top of the subgrade, whereas CI is computed for a given depth measured from the surface.

One of the goals of the current work is to implement the CI-derived criteria in a theoretically correct manner. However, this requires some means of generating approximate CI values from the thickness design program for a series of depths below the surface. In fact, there is no exact means of doing this, since the FAARFIELD program implements a layered elastic-based response model (LEAF), and, as stated above, the CI is essentially a reverse application of the CBR design method. A solution was found in the reformulation of the CBR equation proposed by Barker and Gonzalez (2008) and refined by Gonzalez, Barker and Bianchini (2012). Barker et al. re-derived the CBR equation from first principles:

$$t = \sqrt{\frac{P}{\beta \times CBR} - \frac{A}{\pi}} \tag{1}$$

where t is the pavement thickness, P is a single wheel load of area A, and β is a function of coverages only. In this paper, the design form of the reformulated CBR equation is not used. However, Barker and Gonzalez also emphasized that β directly relates vertical stress to CBR:

$$\beta = \frac{\pi \times \sigma_z}{CBR}. \tag{2}$$

In equation (2), vertical stress σ_z is given by Froelich's formula (Tschebotarioff, 1951) for stress in a homogeneous half-space with a stress concentration value n=2 (Barker and Gonzalez, 2008):

$$\sigma_z = \frac{nP}{2\pi R^2} \cos^n \phi \tag{3}$$

where R is the distance from the point of application of the load to the point being evaluated, and φ is the angle the line makes with the vertical. Note that substituting n=3 in equation (3) leads to Boussinesq's equation, of which elastic layer theory is a generalization to multiple layers and distributed loads. Thus, σ_z in equation (2) is not the layered elastic stress as returned by LEAF. Rather, equation (2) assumes a different (narrower) stress distribution than LEAF. The difference in assumed stress distributions within the soil mass accounts for a large part of the difficulty in relating the CBR method to layered elastic analysis.

TABLE 3-4. SUBGRADE COMPACTION REQUIREMENTS FOR FLEXIBLE PAVEMENTS

GEAR TYPE	GROSS WEIGHT Lb.	NON-COHESIVE SOILS Depth of Compaction, inch				COHESIVE SOILS Depth of Compaction, inch			
		100%	95%	90%	85%	95%	90%	85%	80%
S	30,000	8	8-18	18-32	32-44	6	6-9	9-12	12-17
	50,000	10	10-24	24-36	36-48	6	6-9	9-16	16-20
	75,000	12	12-30	30-40	40-52	6	6-12	12-19	19-25
D (incls. 2S)	50,000	12	12-28	28-38	38-50	6	6-10	10-17	17-22
	100,000	17	17-30	30-42	42-55	6	6-12	12-19	19-25
	150,000	19	19-32	32-46	46-60	7	7-14	14-21	21-28
	200,000	21	21-37	37-53	53-69	9	9-16	16-24	24-32
2D (incls. B757, B767, A-300, DC-10-10, L1011)	100,000	14	14-26	26-38	38-49	5	6-10	10-17	17-22
	200,000	17	17-30	30-43	43-56	5	6-12	12-18	18-26
	300,000	20	20-34	34-48	48-63	7	7-14	14-22	22-29
	400,000 – 600,000	23	23-41	41-59	59-76	9	9-18	18-27	27-36
2D/D1, 2D/2D1 (incls. MD11, A340, DC10-30/40)	500,000 – 800,000	23	23-41	41-59	59-76	9	9-18	18-27	27-36
2D/2D2 (incls. B747 series)	800,000	23	23-41	41-59	59-76	9	9-18	18-27	27-36
	975,000	24	24-44	44-62	62-78	10	10-20	20-28	28-37
3D (incls. B777 series)	550,000	20	20-36	36-52	52-67	6	6-14	14-21	21-29
	650,000	22	22-39	39-56	56-70	7	7-16	16-22	22-30
	750,000	24	24-42	42-57	57-71	8	8-17	17-23	23-30
2D/3D2 (incls. A380 series)	1,250,000	24	24-42	42-61	61-78	9	9-18	18-27	27-36
	1,350,000	25	25-44	44-64	64-81	10	10-20	20-29	29-38

Figure 1: Compaction requirements from AC 150/5320-6E (FAA, 2009). Tabulated values denote depths in inches below the finished subgrade above which densities should equal or exceed the indicated percentage of the maximum dry density. 1 inch = 2.54 cm.

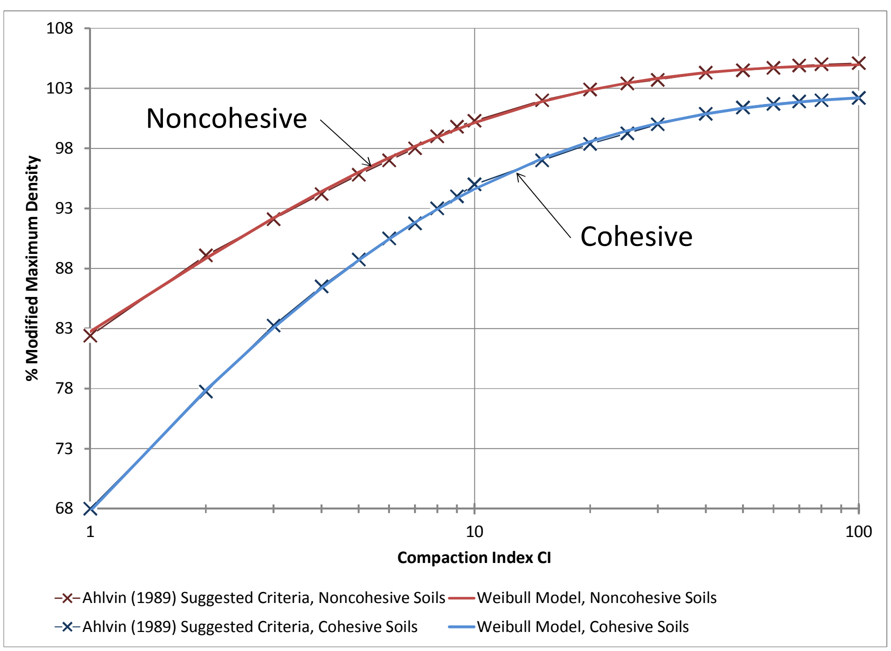

Figure 2: Suggested criteria for percent modified maximum density as a function of CI, based on Ahlvin (1989).

3 GENERAL DESCRIPTION OF THE PROCEDURE

A procedure was developed for computing compaction requirements based on three major assumptions:

1. At any depth below the surface, the *ratio* of the vertical stress computed for a layered elastic structure with n=3 (the LEAF case) to the stress for the same structure with n=2 is equal to the ratio $S_{3:2}$ of the stresses computed using equation (3) with the same values of n. For a uniformly loaded circular area of radius r, the stress ratio $S_{3:2}$ as a function of depth z directly under the load center is given by:

$$S_{3:2}(z) = \frac{u - \dfrac{1}{\sqrt{u}}}{u - 1}, \text{ where } u = 1 + \left(\frac{r}{z}\right)^2 \tag{4}$$

   Equation (4) converges to 1.5 for large depths, and at shallow depths the value of $S_{3:2}$ depends on the load radius r. Thus, at typical depths within the subgrade, the stress used to compute CI should be approximately 1.5 times the maximum vertical stress computed by LEAF.
2. For any level of coverages, the value of β is given by the regression equation reported by Gonzalez et al. (2012). Thus, β does not depend on the aircraft type.
3. For computed values of CI, the corresponding percentages of required compaction for cohesive and non-cohesive soils are given directly by the curves in figure 2.

In addition, based on the recommendations in Ahlvin (1989), 6000 annual departures of a given aircraft was taken as the standard level of traffic for determining compaction requirements. Combining assumptions 1 through 3 above suggested the following procedure:

1. For 6000 annual departures of a given aircraft, use FAARFIELD (LEAF) to compute vertical stress $\sigma_z^{(n=3)}$ and the pass-to-coverage ratio (P/C) at each depth of interest. (Note that in the FAARFIELD flexible design procedure, P/C varies with depth.)
2. At each depth z of interest, compute coverages C = 6000 departures / (P/C).
3. At each depth z of interest, compute $S_{3:2}(z)$ using equation (4), where radius r is the radius of one wheel known from the gear geometry. Compute equivalent $\sigma_z^{(n=2)}$ from: $\sigma_z^{(n=2)} = S_{3:2}(z) \times \sigma_z^{(n=3)}$.
4. For the coverages in step 2, compute β from the following formula (Gonzalez et al, 2012):

$$\log(\beta) = \frac{1.7782 + 0.2397 \log(C)}{1 + 0.5031 \log(C)} \tag{5}$$

5. Compute CI by solving equation (2) for CBR, using $\sigma_z = \sigma_z^{(n=2)}$ from step 3 and β from step 4:

$$\text{CI} = \frac{\sigma_z^{(n=2)} \times \pi}{\beta} \tag{6}$$

6. Enter the appropriate curve in figure 2 with CI to obtain the compaction requirement.

Steps 1 through 6 assume that all layer thicknesses have already been determined by the appropriate thickness design method. The FAA thickness design method assumes that all soil layers will be compacted to the specified minimum density; therefore, the subgrade failure model parameters do not compensate for field densities higher or lower than the requirement.

4 IMPLEMENTATION OF THE PROCEDURE IN FAARFIELD

The following paragraphs describe the implementation of the automated compaction procedure in FAARFIELD for single aircraft traffic, and for mixed aircraft traffic. For single aircraft traffic, the implementation was relatively straightforward, following the six steps listed above. The main programming changes involved modifying the program so that P/C is computed at levels other than the top of the subgrade or bottom of the HMA layer (step 2), and encoding the information contained in the curves in Figure 2. It was also necessary to output the computed compaction information in a form that is usable to the engineer and comparable to Figure 1.

Although Ahlvin's original compaction curves were drawn by hand on semilog graph paper, these curves were found to be well represented by a mathematical model of the Weibull form:

$$\%\text{ Maximum Density} = a - be^{-c(CI)^d} \tag{7}$$

where *a*, *b*, *c* and *d* are curve fitting parameters that take on different values for cohesive and non-cohesive soils. The values in Table 1 were determined for the parameters in equation (7) using the commercial curve-fitting program CurveExpert.

The criteria of figure 2 and equation (7) are expressed as continuous curves of percent density with respect to CI. To be practical for specifying construction, the criteria must be given in terms of the minimum percent density that should be obtained over a given depth interval. For example, in figure 1, depth ranges are listed for fixed percentages of minimum compaction that increase in 5% steps up to a maximum requirement of 100% maximum dry

Table 1: Values of Weibull model parameters for compaction curves

Parameter	Value, Non-cohesive soils	Value, Cohesive Soils
a	1.05076×10^{2}	1.02631×10^{2}
b	6.07679×10^{1}	1.52974×10^{2}
c	1.00105×10^{0}	1.47964×10^{0}
d	3.98940×10^{-1}	2.99569×10^{-1}

density for non-cohesive soils and 95% for cohesive soils. The tabulated values represent the range of depths (in inches) below the finished subgrade level within which the density must exceed the stated percentage. This standard is convenient from the point of view of the subgrade contractor, but as noted above, it cannot be reconciled with a theory of compaction throughout the full range of pavements covered by figure 1.

Because FAARFIELD computes CI values for a specific combination of gear load and structural layers, it is possible to output a design-specific schedule of minimum compaction percentages and associated depth ranges referenced to any desired vertical datum, e.g., the top of subgrade. Practically, this means that the range of depths below the top of the subgrade for, say, 90% minimum compaction will vary for different design subgrade CBR values. This subgrade dependence is one of the main differences between the existing tabulated requirements and the FAARFIELD-based requirements.

The conversion from continuous curves to compaction control points is done in the following way. First, the pavement thickness design is performed, which yields the total pavement thickness. Starting from the top of the pavement, and at 25.4 cm (10 in.) intervals, FAARFIELD computes CI values at each depth. Percent maximum densities for both cohesive and non-cohesive soils are computed using equation (7) and stored along with the corresponding CI values. Next, the depths from the surface corresponding to the 100%, 95%, 90%, etc., compaction levels are determined by simple linear interpolation of the depth-compaction curves. The depths computed in this step correspond to the lower limits of the ranges for each compaction level, with the upper limit equal to the depth for the next higher compaction level (see figure 3). While this method is not the most conservative approach, it generally gives the best agreement with current standards and was therefore adopted. However, alternative rules are possible. Note that the depths must first be shifted by subtracting the pavement thickness to obtain the depth below the finished subgrade. Finally, all values are rounded to the nearest 2.54 cm (1 inch) and displayed in a table as part of the design output. Table 2 shows an example for a single aircraft design. In this case, the traffic consists of 6000 annual departures of a generic dual-tandem (2D) airplane of 90.72 tonnes (200,000 lbs.) gross weight. The pavement, designed using FAARFIELD 1.305, consists of 125 mm (4.9 in) P-401 hot-mix asphalt (HMA) surface, on 150 mm (5.9 in.) P-403 HMA base, on 460 mm (18.1 in.) P-209 crushed aggregate subbase, on a CBR 6 subgrade. Since the subgrade plasticity index (PI) is not known, FAARFIELD reports the compaction requirements for both non-cohesive ($PI < 3$) and cohesive ($PI \geq 3$) soils, listing depths measured from both the pavement surface and the top of the subgrade. (In theory, the compaction depth measured from the top of the subgrade can be found simply by subtracting the total pavement thickness (825 mm in this example) from the surface-referenced compaction depth, but in fact there is some error from rounding and metric-to-U.S. unit conversion.) Figure 3 shows how the compaction requirements were determined from the computed depth vs. percent maximum density curve for non-cohesive soils. For comparison to FAARFIELD, table 2 also lists the applicable compaction requirements for the 2D-200 airplane from AC 150/53200-6E.

Table 2: Computed compaction requirements for single aircraft (2D-200) example

% Max. Density	FAARFIELD 1.305 with automated compaction				AC 150/5320-6E	
	Depth of compaction measured from pavement surface, cm (in.)		Depth of compaction measured from top of subgrade, cm (in.)		Depth of compaction measured from top of subgrade, cm (in.)	
	Noncohesive	Cohesive	Noncohesive	Cohesive	Noncohesive	Cohesive
100	0 - 51 (0 - 20)	Not applicable	Not applicable	Not applicable	0 - 43 (0 - 17)	Not applicable
95	51 - 119 (20 - 47)	0 - 48 (0 - 19)	0 - 46 (0 - 18)	Not applicable	43 - 76 (17 - 30)	0 - 15 (0 - 6)
90	119 - 211 (47 - 83)	48 - 86 (19 - 34)	46 - 137 (18 - 54)	0 - 13 (0 - 5)	76 - 109 (30 - 43)	0 - 31 (0 - 12)
85	211 - 315 (83 - 124)	86 - 145 (34 - 57)	137 - 241 (54 - 95)	13 - 71 (5 - 28)	109 - 142 (43 - 56)	31 - 46 (12 - 18)
80	Not applicable	145 - 206 (57 - 81)	Not applicable	71 - 132 (28 - 52)	Not applicable	46 - 66 (18 - 26)

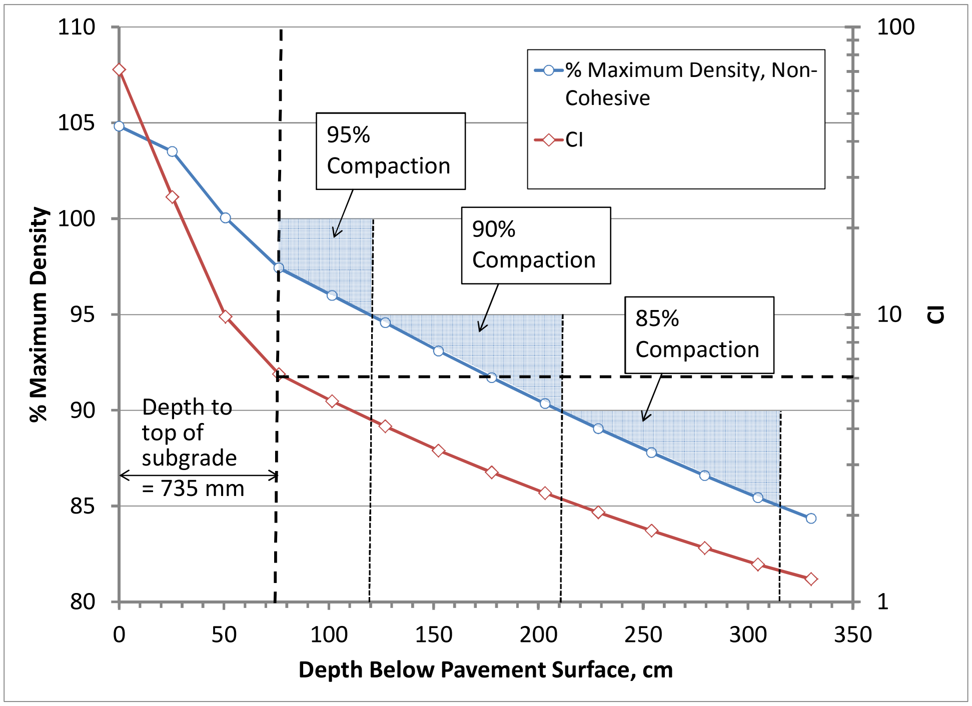

Figure 3: Computation of compaction requirements for non-cohesive soil, single aircraft (2D-200) example.

In Figure 3, the CI computed at the top of the subgrade depth is approximately 6.0, which agrees closely with the design subgrade CBR value in the example. Note that the number of annual departures is fixed at 6000 in step 1 of the compaction computation procedure. This is done for the sake of standardization; however as a practical matter the effect is quite small. As an example, if the compaction requirements in table 2 were recomputed assuming 4000 annual departures instead of 6000, the required depth for 85% maximum density would only change from 315 to 310 cm (non-cohesive), and from 145 to 142 cm (cohesive).

For mixed aircraft traffic, the procedure is similar but in addition it is necessary to implement programming rules that determine which subset of airplanes in the mix controls the compaction requirement. These are not necessarily the same airplanes that control the thickness design. In AC 150/5320-6E, the standard employed is that "The airplane in the mix that should be used to determine compaction requirements is the airplane requiring the maximum compaction depth from table 3-4, regardless of the anticipated number of operations." FAARFIELD implements a similar approach, except that the critical airplane compaction requirement is determined automatically at each depth rather than for the section as a whole. Thus, the procedure in section 2 is modified so that for each depth z, CI is computed for 6000 annual departures of each airplane in the mix, and only the maximum CI for that depth is stored. The flowchart for the mixed aircraft procedure is shown in Figure 4. In the current implementation, depth increment Δz = 25.4 cm (10 in.) and terminal z (the lower limit of computations) is equal to 6.096 m (240 in.).

5 COMPARISON WITH EXISTING STANDARDS

The following example compares the new automated FAARFIELD method to existing compaction standards in AC 150/5320-6E. Consider the three-aircraft mix in table 3. For a

CBR 6 subgrade, the 20-year FAARFIELD 1.305 thickness design for this mix is: 125 mm (4.92 in.) P-401 HMA surface, on 225 mm (8.86 in) P-403 HMA stabilized base, on 560 mm (22.05 in.) P-209 crushed aggregate subbase. For CBR 3 the surface and base thicknesses are the same as above, but the P-209 design thickness increases to 1,082 mm (42.6 in.). Figure 5 graphically compares the FAARFIELD-generated density requirements with the equivalent requirements based on AC 150/5320-6E (figure 1). For both CBR 3 and CBR 6 designs, FAARFIELD correctly identified the B777-200 ER gear as the critical gear generating maximum CI values at each depth. Based on figure 1, the B777-200 ER also controls the AC 150/5320-6E compaction criteria.

Table 3: Aircraft mix for compaction example

Airplane	Gear Type	Gross Weight, kg (lbs.)	Annual Departures
B767-200	2D	154,221 (340,000)	1200
B777-200 ER	3D	298,464 (658,000)	365
A310-200	2D	142,900 (315,041)	4000

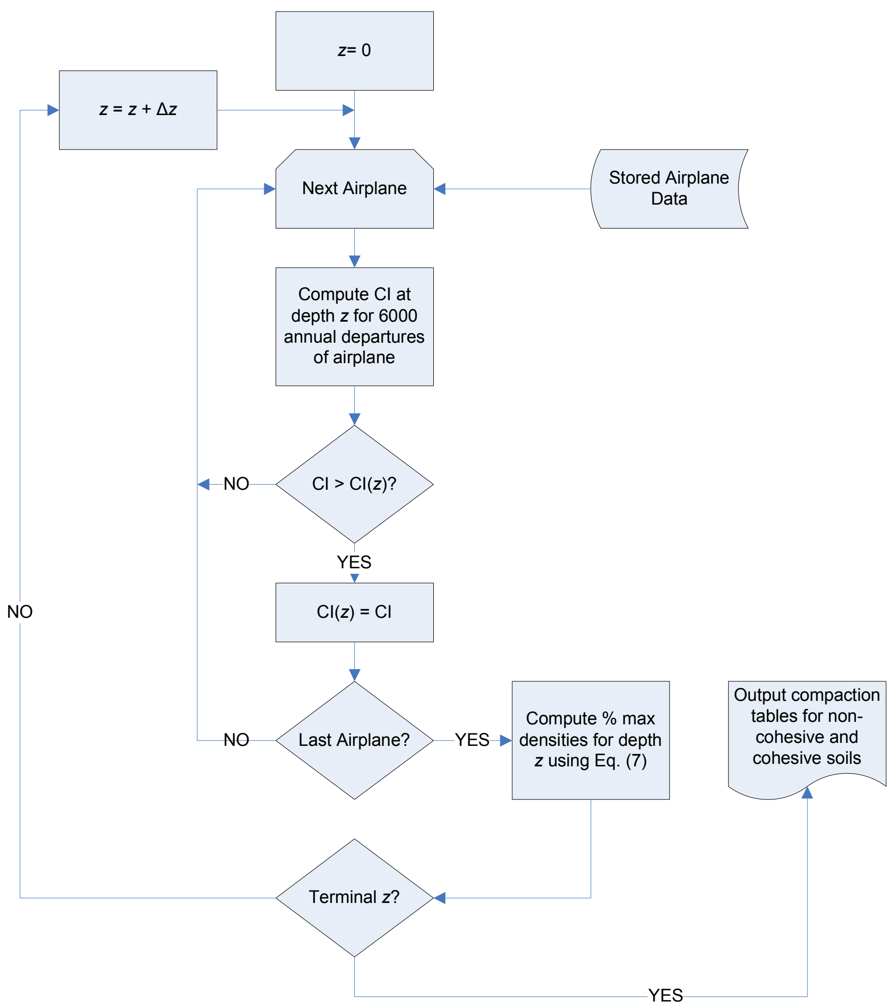

Figure 4: Flowchart for computation of compaction requirements with mixed airplane traffic.

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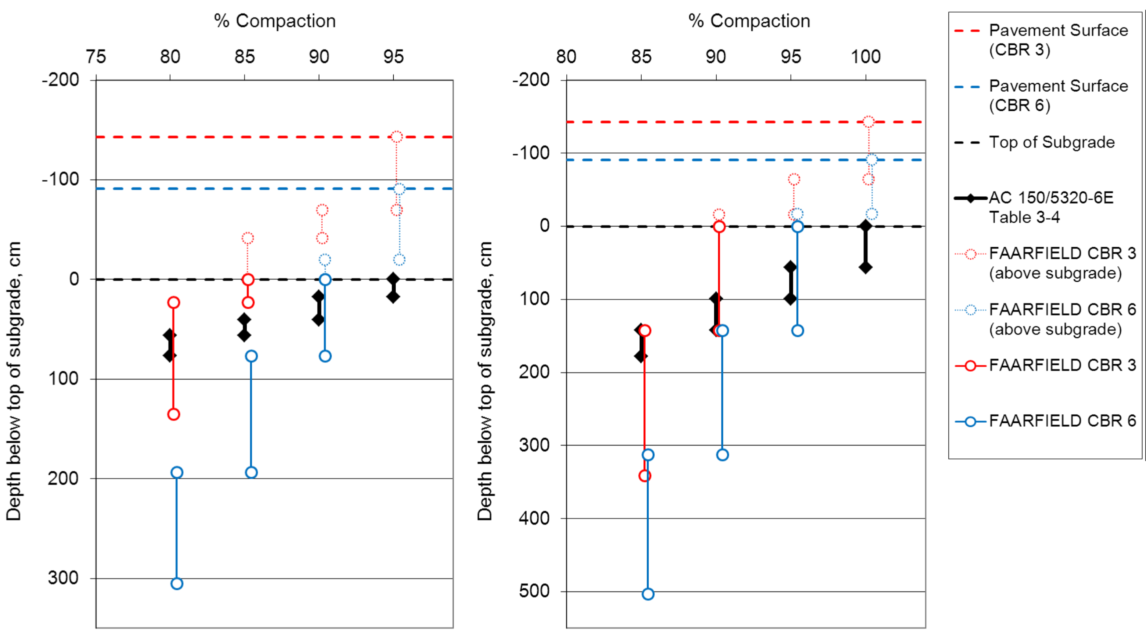
Figure 5 demonstrates how FAARFIELD computes different compaction requirements depending on the design CBR value. This is a direct consequence of the compaction theory, since in a properly designed pavement the CI at the top of a CBR 6 subgrade (and hence the density requirement at that depth) is necessarily higher than for CBR 3. It also reflects the fact that lower CBR materials are more likely to be loosely compacted in the field or to fall into the cohesive category. Figure 5 also illustrates the greater range of depths for which the new method may require compaction to medium densities, in particular for higher strength subgrades. In the current example, for CBR 6 and non-cohesive soils (see fig. 5b), FAARFIELD requires 85% of maximum dry density to 503 cm (198 in.) below the top of subgrade level, and 90% to 312 cm (123 in.). This compares to only 178 cm (70 in.) and 142 cm (56 in.) respectively based on current standards. Of course, whether additional compaction at lower depths would actually be required in a particular case depends on the natural densities of the soils in place. Assuming, for example, that the in-place density of the CBR 6 subgrade soil 1 m (3.3 ft.) below the surface is 90% of maximum dry density, then based on figure 5(b) for non-cohesive soils, additional compaction would be needed to a depth of approximately 140 cm (55 in.) at most.



(a) Cohesive Soils (b) Non-Cohesive Soils

Figure 5: Graphical representation of computed compaction criteria for mixed traffic example.

On the other hand, the design-based criteria require significantly less compaction effort in the higher density ranges closer to the surface as compared to existing standards. While the existing criteria for non-cohesive soils require compaction to 100% maximum dry density to 56 cm (22 in.) below top of subgrade, the new design-based criteria do not require any compaction to 100% (or more precisely, the 100% limits apply only to the higher quality base and subbase materials above the subgrade level, where more stringent material specifications presumably ensure that they meet that requirement). Similarly for cohesive soils, the existing standard calls for compaction of cohesive materials to 95% to a depth of 18 cm (7 in) below finished subgrade. By contrast, the FAARFIELD design-based criteria require a maximum of 90% compaction of CBR 6 subgrade materials and 85% compaction of CBR 3.

6 CONCLUSIONS

The FAA has developed a computational procedure for determining soil compaction requirements for airport pavements. The procedure is intended to be run in conjunction with the thickness design in the FAARFIELD program. By incorporating an approximate theoretical relationship between CBR and computed stress, the FAARFIELD-generated results are consistent with the field-validated, CI-based compaction criteria originally proposed for FAA use by Ahlvin. Moreover, the new compaction limits are computed with reference to the pavement surface, thus eliminating a major theoretical shortcoming of the current published standards in AC 150/5320-6E.

Due to the theoretical limitations of the current table-based standards, it is not possible to state definitively whether the new procedure is more or less conservative than the current standard. Examples using mixed airplane traffic suggest that, as implemented, the proposed procedure would relax the current requirement for compaction of subgrades to 100% of maximum dry density for non-cohesive soils and to 95% for cohesive soils. However, lower densities may be required to be enforced to greater depths than is currently the case. Additional comparisons are needed to fully evaluate the effect of the new design-based criteria.

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