Calibration of Advanced Flexible Aircraft Pavement Design Method to S77-1 Method

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Abstract

The US Army Corps of Engineers CBR method (Method S77-1) for the design of flexible aircraft pavements was calibrated against full-scale trafficking tests on unbound pavements conducted 30 years ago. The method used single layer analysis so had no direct mechanism for crediting bound layers for their superior load spreading characteristics. Bound layers were increasingly used, however, and were typically accounted for within the empirical design by using layer equivalency factors.

The layered elastic method was introduced into regular design practice in the mid-1990's, with the release of the computer program LEDFAA by the U.S. Federal Aviation Administration and also the Australian-developed program APSDS (Airport Pavement Structural Design System). These tools facilitated the treatment of bound layers and eliminated the need for the 'layer equivalency' concept. Also, because the effects of the actual aircraft wheel configurations and loads of all aircraft in the design mix could now be quickly computed, the concepts of 'equivalent single wheel load' and 'design aircraft' were no longer needed. In the case of APSDS, its method for dealing with aircraft wander meant that the 'pass-to-coverage ratio' was not required.

Until recently the subgrade performance relationship used by APSDS was appropriate only for large multiwheeled aircraft on low strength subgrades. The relationship was derived by direct calibration against Corps' tests that involved large aircraft loadings (B747, C5A and B36) on low strength subgrades. Test data for higher strength subgrades and lighter aircraft was very limited, making a broader direct calibration of APSDS problematic.

However, S77-1 has been widely used over many years to design pavements for lighter aircraft and for stronger subgrades. The performance of the pavements has generally been satisfactory, and therefore this experience effectively constitutes an extension to the original empirical test data. On this basis, in this study APSDS has been calibrated against S77-1 to produce a layered elastic design tool that is appropriate for all subgrade strengths. This allows the designer to access the full advantages of the layered elastic method, including treatment of wander, to quickly produce designs for complex aircraft mixes and layered structures that are consistent with S77-1.

Introduction

Prior to the introduction of the layered elastic method into airfield design, flexible pavements were usually designed using the US Army Corps of Engineers CBR pavement design method detailed in FAA Instruction Report S-77-1 (Pereira, 1977).

The method (Method S77-1) was calibrated against full-scale trafficking tests on unbound pavements conducted by the Corps 30 years ago. A single layer pavement model was used so there was no direct mechanism for crediting bound layers for their superior load spreading characteristics. In design practice, bound layers were increasingly used, however, and were typically accounted for within the empirical design method by using approximate layer equivalency factors. For example, the US Federal Aviation Administration design method includes recommended ranges of factors for hot mix asphalt, cement treated basecourse, Econocrete and soil cement when these materials replace unbound materials within the pavement structure (FAA, 1995a).

The layered elastic method was introduced into regular airfield design practice in the mid-1990's with the release of the computer program LEDFAA (Layered Elastic Design, Federal Aviation Administration) and also the Australian-developed APSDS (Airport Pavement Structural Design System), (Federal Aviation Administration, 1995b) and (Rickards, 1994, Wardle and Rodway, 1998) respectively. LEDFAA is now an FAA standard design method and is used in parallel with FAA's conventional method. The new tools facilitated the treatment of bound layers and eliminated the need for the 'layer equivalency' concept. Also, because the effects of the actual aircraft wheel configurations and loads of all aircraft in the design mix could now be quickly computed, the concepts of 'equivalent single wheel load' and 'design aircraft' were no longer needed. In the case of APSDS, as described more fully below, its method for dealing with aircraft wander meant that the 'pass-to-coverage ratio' was not required.

Until recently the subgrade performance relationship used by APSDS was appropriate only for large multiwheeled aircraft on low strength subgrades. The relationship was derived by direct calibration against Corps' tests that involved large aircraft loadings (B747, C5A and B36) on low strength subgrades. Test data for higher strength subgrades and lighter aircraft was very limited, making a broader direct calibration of APSDS problematic. However, S77-1 has been widely used over many years to design pavements for lighter aircraft and for stronger subgrades. The performance of the pavements has generally been satisfactory, and therefore this experience effectively constitutes an extension to the original empirical test data.

On this basis, in this study APSDS has been calibrated against S77-1 to produce a layered elastic design tool that is appropriate for all subgrade strengths. This allows the designer to access the full advantages of the layered elastic method, including treatment of wander, to quickly produce designs for complex aircraft mixes and layered structures that are consistent with S77-1.

APSDS Background

APSDS was developed from a road pavement design program, CIRCLY (Wardle, 1999), to include treatment of aircraft wander.

Aircraft do not track consistently along the same path. Field observations have shown that successive passes of aircraft along a pavement are statistically normally distributed about the pavement centreline. The degree of 'wander' can be reasonably characterised by a standard deviation and is found to be significantly different for runways, taxiways and aircraft docking bays. This spreading of aircraft wheel loads across the pavement width to different degrees has a significant effect on the pavement thickness required for different parts of the airport. APSDS computes this effect. Previously, the lateral distribution of aircraft was handled in a simplified fashion using the Pass-to-Coverage Ratio (PCR) concept: a point on the pavement surface was said to receive a `coverage' when any part of a tyre's contact area passed over it. The PCR is defined as the number of passes of a wandering aircraft that is statistically required for the most frequently `covered' point to receive one coverage. The PCR depends upon wheel configuration, tyre width and the degree of aircraft wander. For example the PCRs of a B747, with 16 large main wheels, moving along a taxiway and along a runway are approximately 1.7 and 2.5 respectively. The corresponding PCRs for a Fokker F27, with 4 much smaller wheels, are 3.9 and 7.7. The original PCR concept solely addresses the statistics of load distribution at the pavement surface and, therefore, incorrectly implies that the reduction in pavement damage due to aircraft wander is the same for all pavement thicknesses. APSDS corrects this anomaly.

APSDS uses a concept described by Monismith et al. (1987). The important new and unique feature is that subgrade strains, or alternative indicators of the rate at which deformation develops at the pavement surface, are computed for all points across the pavement in order to capture all damage contributions from all the aircraft wheels in all their wandering positions. This contrasts with previous methods, including S77-1 and LEDFAA, that computed only single maximum values of the damage indicators. It is this feature that eliminates the need for the pass-to-coverage concept and allows the designer to specify any degree of wander.

Layered elastic models are used to compute values of chosen damage indicators, most commonly subgrade strain, which are then related to pavement life (strain repetitions). The strains are converted to damage using a performance relationship of the form:

$$N = \left[\frac{k}{\varepsilon}\right]^{b} \qquad (1)$$

where N is the predicted life (repetitions of ε)
k is a material constant
b is the damage exponent of the material
ε is the load-induced strain (unitless strain)

The pattern of strains at subgrade level experienced during the passage of a multiple axle gear primarily depends on the pavement depth. The two extremes are:

- multiple distinct short pulses resulting from each axle, for shallow depths
- a single longer pulse that reflects the overall loading on the gear, for large depths

Between these two extremes the pulses resulting from each axle overlap making the calculation of damage problematic. Recently the 'reservoir' method, as used in bridge design to handle complex loadings, was implemented to overcome this problem and to ensure a smooth transition between the two extremes.

The Damage Factor for the i-th loading is defined as the number of repetitions (ni) of a given damage indicator divided by the 'allowable' repetitions (Ni) of the damage indicator that would cause failure.

The Cumulative Damage Factor (CDF) is given by summing the damage factors over all the loadings in the traffic spectrum using Miner's hypothesis:

$$\text{Cumulative Damage Factor} = \sum \frac{n_i}{N_i} \tag{2}$$

APSDS calculates the CDF as a function of lateral position across the pavement. The pavement is presumed to have reached its design life when the cumulative damage at any point reaches 1.0.

Calibration

Calibration involves using an iterative procedure to determine the performance parameters, k and b, that best reflect the performance of full-scale test pavements. The procedure used to calibrate APSDS to the Corps' full-scale test data has been detailed previously (Wardle and Rodway, 1998). Six of the Corps' tests, involving B747, C5A and B36 test rigs, trafficking pavements of different thickness to failure over CBR 4 subgrade were used in the calibration process. The subgrade performance relationship obtained was appropriate only for large multiwheeled aircraft on low strength subgrades.

The Corps' test data for higher strength subgrades and lighter aircraft was very limited, making a broader direct calibration of APSDS problematic. However, S77-1 has been widely used over many years to design pavements for lighter aircraft and for stronger subgrades. The performance of the pavements has generally been satisfactory, and therefore this experience effectively constitutes an extension to the original empirical test data. On this basis, in this study APSDS has been calibrated against S77-1 pavement thickness designs to produce a layered elastic design tool that is appropriate for all subgrade strengths. This use of S77-1 as a source of calibration data in effect accepts the S77-1 interpretation of the Corps' full-scale empirical pavement performance data. S77-1 computations were done using the program ACNCOMP which was produced by FAA's Airport Pavement Research and Development Branch. The program is available on the branch web site, www.airtech.tc.faa.gov.

This broader calibration of APSDS now allows the designer to access the full advantages of the layered elastic method, including treatment of wander, to quickly produce designs for complex aircraft mixes and layered structures that are consistent with S77-1.

Aircraft used for Calibration. The commercial aircraft used in the calibration against the S77-1 design method are listed in Table 1. Aircraft masses ranged from 40 to approximately 400 tonnes. To cover a reasonable range of aircraft usage levels, coverages of 10,000 and 100,000 were used.

The calibration process was based on individual aircraft rather than aircraft traffic mixes.

Aircraft Model	Take-off mass (tonnes)	Tyre pressure (Mpa)	Assumed p/c
B747-400	397	1.38	1.73
MD11	285	1.41	1.83
A340-300	270	1.20	1.74
A300-600	170	1.40	1.59
B767-200	140	1.24	1.98
B757-200	110	1.17	1.94
A320-200	70	1.40	3.82
B737-200	60	1.30	3.60
B717-200	52	1.13	3.60
BAe 146	40	0.95	3.30

Table 1. Characteristics of aircraft used in calibration

Pavement Structures. The Multiple Wheel Heavy Gear Load Tests (MWHGLT) conducted at the Waterways Experiment Station, Vicksburg, Mississippi in the late 1960s and early 1970s used test pavement thicknesses ranging from 380 mm to 1040 mm. The pavements consisted of a 75 mm asphalt surfacing layer over a 150 mm thick basecourse of unbound graded crushed rock over uncrushed gravel sub-base of various thicknesses. Consequently in this study the model pavement structure shown in Table 2 was used for the calibration.

Material	Thickness
Asphaltic concrete E = 1400 Mpa, $\nu = 0.4$	75.0 mm
FCR (Unbound basecourse) $\nu = 0.35$	150.0 mm
P154 (Unbound sub-base) $\nu = 0.35$	variable
Subgrade E (MPa) = 10.0 x CBR, $\nu = 0.4$	

Table 2. Model pavement structure used for the calibration.

The unbound basecourse is a standard material designated by FAA as P209, a high quality crushed graded rock basecourse commonly specified for major pavements. The unbound sub-base is a standard material designated by the FAA as P154, a natural, uncrushed gravel commonly used as sub-base.

APSDS, like LEDFAA, automatically assigns moduli to the unbound layers to take account of the stress-dependence of these layers. The method is that described by Barker and Brabston (Barker and Brabston, 1975).

Four representative subgrade CBR values were used in the study: 3, 6, 10 and 15.

Results. For each subgrade CBR value, pavement thicknesses required for each aircraft type at 10,000 and 100,000 coverages were calculated using both APSDS and S77-1. Note that as the S77-1 method assumes a taxiway wander (standard deviation of wander = 773 mm) a standard deviation of 773 mm was also used in all the APSDS computations.

The 20 APSDS computations for each CBR value were run as a batch using trial values of the performance parameters k and b. A 'goodness of fit' measure was calculated for the 20 cases. The parameters k and b were varied by a simple manual bisection process to determine values that maximized the goodness of fit.

Table 3 gives the performance parameters that were obtained:

Subgrade CBR (%)	Subgrade Modulus, E (Mpa)	k	b
3	30	0.0032	9.5
6	60	0.0030	10.9
10	100	0.0024	15.0
15	150	0.0020	23.6

Table 3. Performance parameters obtained from calibration.

As can be seen from the table, the parameters depend on the CBR of the subgrade.

Regression analyses using third order polynomials for the variation of k and b with subgrade modulus (E) in units of MPa give the following:

$$k = 1.64\ 10^{-09}\ E^3 - 4.31\ 10^{-07}\ E^2 + 2.18\ 10^{-05}\ E + 0.00289$$

$$b = -2.12\ 10^{-07}\ E^3 + 8.38\ 10^{-4}\ E^2 - 0.0274\ E + 9.57$$

These functions are plotted on Figure 1.

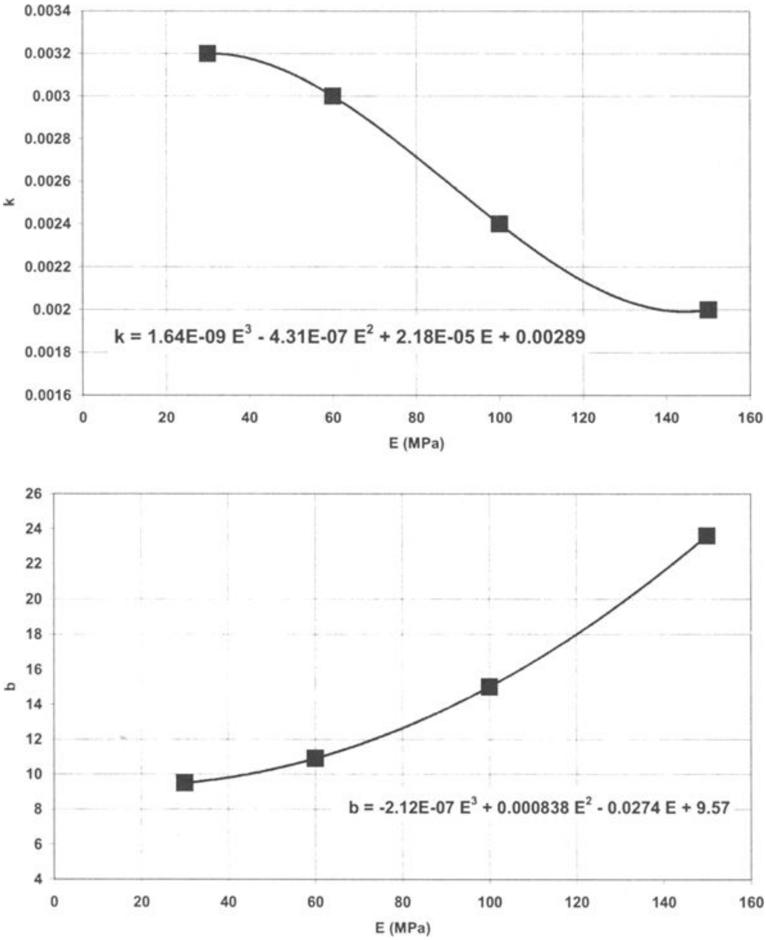

Figure 1. Dependence of performance parameters on subgrade modulus (calibration against S77-1 method)

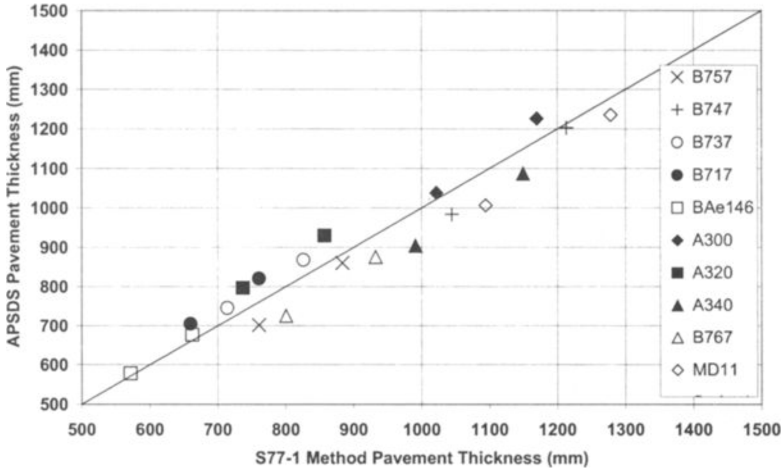

Figure 2. APSDS pavement thickness vs. S77-1 method pavement thickness (subgrade CBR = 6)

Goodness of Fit. To illustrate the degree to which the new APSDS performance relationship produces design thicknesses comparable to the S77-1 method, comparisons have been generated for a subgrade CBR of 6.

Figure 2 compares the pavement thicknesses from the two alternative design methods. The median difference is 57 mm. Similar agreement is obtained for all subgrade CBR values used.

Discussion And Conclusions

The performance parameters for APSDS have been established in this study using an iterative procedure that maximises the 'goodness of fit' between the APSDS models and the calibration data. By using performance relationships with parameters that are dependent on the subgrade modulus it has been possible to obtain pavement thicknesses that agree well with designs generated by the S77-1 method. Although the calibration has only been carried out for CBR values of 3, 6, 10 and 15 the equations given above will give the appropriate parameters for other CBR values by interpolation.

It is believed that the scatter between the S77-1 and APSDS thicknesses is in part because the S77-1 method uses subgrade deflection rather than subgrade strain as the performance indicator. This gives a different spread of results for different aircraft gear configurations.

It should be noted that the pavement thicknesses calculated for some aircraft mixes using APSDS will be somewhat less than those obtained using either LEDFAA or the FAA conventional method. This is because APSDS fully accounts for the fact that the landing gears of the various aircraft in a design traffic mix may track along different paths relative to pavement centreline. By contrast the FAA conventional method combines the effects of a mix of aircraft by converting actual aircraft passes to equivalent passes of a 'design aircraft'. This procedure has the effect of summing the maximum damage caused by each aircraft even though they may track along different parts of the pavement. This is a conservative procedure, to a degree that depends upon the particular composition of each traffic mix.

Unlike the conventional FAA method, LEDFAA allows for the fact that the landing gears of the various aircraft in the design traffic mix may track along different paths. However, this allowance is overridden because LEDFAA has been conditioned by mandating certain input material properties to produce, for typical aircraft traffic mixes, similar pavement thicknesses to those obtained using the conventional method. It produces pavements that are, on average, 3% thicker than the conventional method. They are thicker for CBRs less than 5% and thinner for CBRs higher than 15% (McQueen et al, 1997). Consequently it will give thicknesses that are greater than those obtained using APSDS. Also, as discussed in the LEDFAA user manual, LEDFAA should not be used for single aircraft assessments. The resulting pavement thicknesses are too large. The differences between LEDFAA, the conventional FAA method and APSDS have been discussed in more detail elsewhere (Wardle and Rodway, 1998).

In summary, in this study APSDS has been calibrated against S77-1 to produce a layered elastic design tool that is appropriate for all subgrade strengths. This allows the designer to access the full advantages of the layered elastic method, including treatment of wander, to quickly produce designs for complex aircraft mixes and layered structures that are consistent with S77-1.

The advantages for the designer of the newly calibrated APSDS method compared to the S77-1 CBR design method are:

- Any degree of wander can be specified by the designer, and the effect of wander is more rigorously treated.
- The need for the 'pass-to-coverage ratio' concept is eliminated.
- The different tracking paths of aircraft types relative to pavement centreline are taken into account.
- Pavement thicknesses for combinations of aircraft types and frequencies are quickly and automatically calculated. (Previously manual pavement thickness iteration using Miners Law was needed).
- The effect of different pavement materials, including asphalt and stabilised materials can be quickly explored.

All APSDS inputs, including material moduli, degree of wander, aircraft loadings, and the materials' damage models can be specified by the user. This flexibility is intended to provide the experienced designer with easy access to the full capabilities of a layered elastic-based method and allow scope to give customized treatment to particular pavement situations.

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