Selection of Input Parameters for Layered Elastic Design of Flexible Aircraft Pavements

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ABSTRACT: The Australian developed layered elastic tool for flexible aircraft pavement design, Aircraft Pavement Structural Design System (APSDS) is based on the road design program, CIRCLY. One of the advantages of APSDS (and some other layered elastic tools) over purely empirical design methods is that the designer can select and control all input parameters. The operation of this tool is relatively simple. However, unless appropriate input parameters are selected, gross errors can result. The required parameters include subgrade strength, standard deviation of aircraft wander, aircraft masses, tyre pressures and aircraft passes, as well as asphalt modulus and pavement composition. The selection of parameters, including their relative importance, is discussed and indicative values are provided for many input parameters.

KEY WORDS: APSDS, Layered elastic, Flexible aircraft pavement design.

1 INTRODUCTION

Prior to the introduction of computer-based tools for pavement thickness design, aircraft pavements were designed using chart-based methods derived from full scale testing conducted by the US Corps of Engineers between the 1950s the 1970s (Potter, 1985). Charts can be utilised to quickly perform thickness design of pavements for single aircraft types. Where a mix of aircraft are being considered, however, chart based methods lack a simple mechanism for combining the damage caused by different aircraft. Miner's law is normally used to assess the effect of multiple aircraft in traffic mixes on pavement thickness. The use of Miner's Law has been described by Rodway (2000) and has been incorporated into CIRCLY and APSDS to save the pavement designer from having to perform these laborious calculations manually.

Miner's Law does not take into account the effects of aircraft wander or different wheel configurations. Unlike road pavement vehicles, different aircraft have very different wheel configurations and two aircraft (such as the B767 and B737) could traverse the same taxiway and their wheels virtually not interact to damage the same area of pavement. Similarly, two aircraft landing on a runway will not be centered on the same transverse alignment. Therefore, the location of the aircraft wheels and the damage induced would affect different transverse parts of the pavement from one operation of a single aircraft to the next. These effects make the direct application of Miner's Law conservative for aircraft pavement design.

To overcome these deficiencies APSDS was specifically designed to be able to model the wheel configuration of different design aircraft as well as the wander of aircraft across the width of the pavement. The pavement damage is combined for all aircraft in all of their wandering positions through an extension of Miner's Law.

2 AIRCRAFT PAVEMENT STRUCTURAL DESIGN SYSTEM

2.1 Description

APSDS, like most layered elastic tools for flexible pavement thickness design, calculates indicators of damage induced in the modelled pavement by a single load application. This single load damage indicator is then related to an allowable number of load repetitions of the same magnitude. The following comments must be made regarding this seemingly simple statement:

- The indicator of damage varies from design tool to design tool but is commonly either the stress or strain induced at the critical point in the pavement being considered.
- The critical points for damage calculation are usually the top of the subgrade (vertical compressive stress or strain) and the bottom of any bound layers (horizontal tensile stress or strain).
- The relationship between the damage indicator for a single load application and the number of applications to failure remains an empirical relationship based on full scale testing or historical performance. For subgrade deformation (rutting) the empirical relationship is based on the full scale testing conducted by the US Corps of Engineers and reported by Pereira (1977). This relationship is commonly referred to as the S77-1 design curve.

2.2 Layered Elastic Component

The layered elastic component of any design tool is the method for the calculation of the damage (stress or strains at the critical points) induced by a single load application. For APSDS and CIRCLY, this method is based on integral transform methods and Bessel functions and was developed by Gerrard and Harrison (1971) and furthered by Wardle (1976). CIRCLY and APSDS use strains as the indicator of damage.

The use of APSDS is relatively straightforward. One selects and inputs a series of parameters and then the software generates the stresses and strains induced in the pavement. The effects of all aircraft in the traffic mix are determined and a Cumulative Damage Factor (CDF) computed for each nominated transverse distance from the centerline. If the CDF computed is 1.0, then the pavement is modelled to fail at the end of the nominated design life. If the CDF exceeds 1.0, the pavement is modelled to fail before the design life has expired. A typical APSDS damage plot, showing the CDF and superposition of damage effects, is shown in Figure 1.

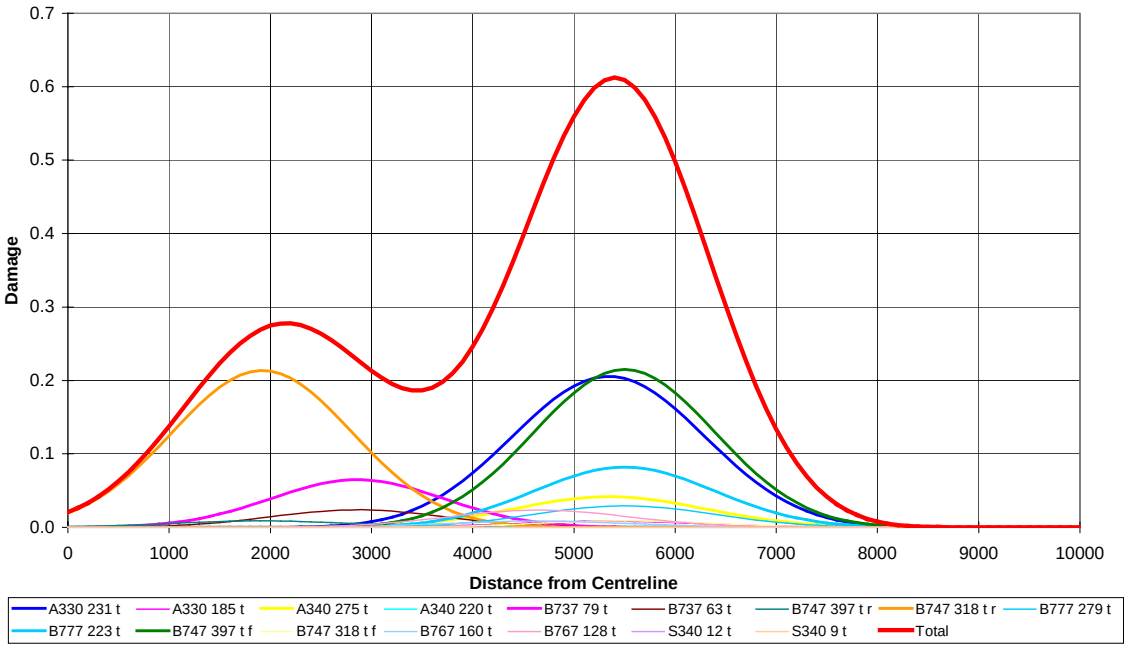

Figure 1: Typical APSDS output.

2.3 Calibration

APSDS is based on the empirical relationships between damage by a single load application and the number of repetitions until failure. The software must therefore be calibrated against the original empirical performance relationships. For traditional flexible pavements the most common governing failure criterion is vertical deformation (rutting) of the subgrade (Rodway and Wardle, 1998). The calibration of the APSDS subgrade failure criteria to the S77-1 design curve is detailed in Wardle, *et al* (2001). Use of these calibrated failure criteria (known as the Chicago criteria) is essential to successful pavement thickness design.

2.4 Factors of Safety

The S77-1 (and therefore the calibrated APSDS) design model is a 'best fit' model, providing a design reliability of 50% unless the designer applies their own factors of safety (such as the overestimation of traffic loading or the conservative assignment of subgrade CBR) (Potter, 1985). There are no built-in factors of safety in either the design tool or model.

2.5 Sensitivities

The sensitivity of pavement thickness to the various APSDS inputs was investigated by White (2005). This investigation used statistical analysis methods to determine the relative influence of each input parameter upon APSDS-computed pavement thicknesses for medium (B737) to large (B747) aircraft. The results clearly showed that the greatest influence on pavement thickness is subgrade strength with aircraft mass the second most influential. Aircraft wander and aircraft passes were shown to be less significant. Tyre pressure, asphalt modulus, base course thickness and asphalt thickness were found to be the least significant input parameters. These relative influences are illustrated in Figure 2 (from White, 2005) which shows total pavement thickness versus standardised (ranging from 1 to 5 to cover the range of practical values) input parameters for a B767 aircraft. The greater the slope of the line, the greater the influence of that input parameter on total pavement thickness.

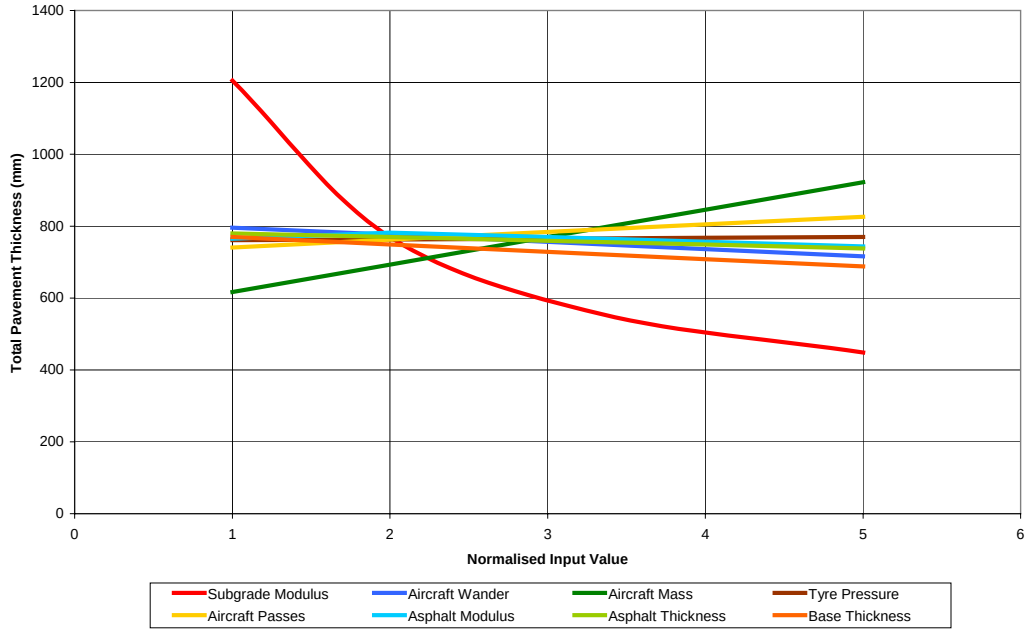

Figure 2: Typical Input Parameter Influence (for B767 aircraft).

It is also noted from Figure 2 that the influence of each input parameter is essentially linear across the standardised values. The only exception is subgrade strength, whose influence is greater at lower subgrade values than at higher values. Appropriate input parameter value selection for any design scenario, should concentrate on the parameters which have the greatest influence on the required pavement thickness. The selection of an appropriate value of each input parameter is described in the following sections.

3 SUBGRADE STRENGTH

The purpose of a pavement is to protect the subgrade from the loads imposed by aircraft and other traffic (Pereira, 1977). The loads are applied to the pavement surface through the aircraft tyres and then the pavement layers spread the load until the stresses and strains induced by the load are small enough to be accommodated by the next lower layer. The deepest portion of the pavement structure is the subgrade and therefore pavement design focuses on the load which can be accommodated by the subgrade material.

The development of the S77-1 design curves by the US Corps of Engineers in the 1960s and 1970s expressed subgrade strength by the California Bearing Ratio (CBR). CBR is a dimensionless unit calculated as being the resistance of a soil to the penetration of a standard piston, as a percentage of the resistance offered by a standard (Californian Limestone) material (DOD, 1964).

The actual field CBR test is cumbersome, expensive and for existing pavements, requires significant disturbance of the insitu structures. Therefore, a number of alternate test methods have been developed in order to simplify the field work whilst maintaining some correlation to the original test method (Holtz and Kovacs, 1981). Alternatives to the insitu field CBR test, commonly available in Australia, include:

- **Laboratory CBR**. Whilst this is a less expensive and relatively simple test, the problem of obtaining a sample which is representative of the moisture conditions, density and soil structure in the field is problematic. Soaked (usually 4 day) and unsoaked tests are available with varying degrees of overpressure.

- **Dynamic Cone Penetrometer**. The Dynamic Cone Penetrometer (DCP) is a device designed for field determination of subgrade stiffness which is measured through resistance to penetration of a standard cone. This cone is dynamically penetrated by the dropping of a standard weight over a standard height. Guidance for the conversion of penetration (blows per mm of penetration) to subgrade CBR is provided but this conversion was derived for fine grained cohesive soils only (AS 1289, 1997). Similar penetrometers are available in other countries under different names.
- **Associated material characteristics**. By measuring associated material characteristics, an indicative CBR can be assigned by comparison to the CBR of materials with similar properties. Commonly used characteristics are the particle size distribution and the plasticity of the fines (Holtz and Kovacs, 1981).

Of these, the laboratory CBR is the most common test for the determination of material CBR on green field sites, where materials will be moistened and compacted and therefore representation of field conditions at the time of sampling is not appropriate. For existing pavement investigations, the remolding of laboratory samples to an appropriate density and moisture content is common and is often supplemented by insitu DCP tests.

It is normal to soak a CBR sample for four days prior to conducting the CBR test (Huang, 1993). Common Australian practice has been to either adopt the four day soaked test result or, where existing pavements are available on the same site, test at the equilibrium moisture content identified under the existing pavements.

US Corps of Engineer practice is to conduct laboratory CBR tests in a soaked state, at a range of densities. The design CBR is then read from a plot of density versus CBR, for a density equivalent to 95% of the maximum density. The US Corps of Engineers also allow an unsoaked CBR determination in arid regions (Ahlvin, 1991). Recent US Federal Aviation Administration (FAA) guidelines stipulate the use of a four-day soaked test for laboratory CBR determination. This is based on the premise that subgrades reach near saturation under pavements within about three years of construction (FAA, 1989). The four-day soaked CBR test does not, however, take into account the pore pressure state of the subgrade under the pavement.

Take two samples of identical subgrade material compacted to the same density at precisely the same moisture content. One sample is retained at zero pore pressure whilst the other has a negative pore pressure applied. The sample with negative pore pressure would behave as a significantly stiffer and stronger subgrade than the zero pore pressure sample. Similarly, a sample with positive pore pressure would perform more poorly than both samples. Pore pressures are generally induced in subgrade materials by the relative height of the water table to the material. No method for incorporating pore pressure into subgrade CBR selection was identified. Engineering judgment and experience must be applied in this regard.

Regardless of the method of selection of subgrade strength in terms of CBR, it must be converted to a modulus for use in APSDS. The conversion from CBR to modulus utilised is a critical part of the S77-1 design model and was formalised by Barker and Brabston (1975). The conversion is:

$$Modulus\ (MPa) = 10 \times CBR\ (\%)$$

Given the high influence of subgrade CBR on thickness required, the selection of an appropriate subgrade CBR is critical to pavement design. This is especially the case for low subgrades where a change of one CBR unit can have a great impact on pavement thickness.

4 AIRCRAFT WANDER

Unlike road and highway pavements, aircraft pavements are subjected to a significant transverse distribution of loads. This distribution of loads is commonly referred to as aircraft wander. An issue related to aircraft wander is that aircraft have significantly different wheel configurations, and therefore, even at zero aircraft wander, the point of load application transversely across the pavement can be significantly different for different aircraft types. The effect of aircraft wheel configuration and aircraft wander combine to distribute damage across the width of the aircraft pavement and effectively increases the service life. APSDS caters for aircraft wander by applying the nominated number of load repetitions across the width of the pavement, based on a nominated standard deviation of aircraft wander, assuming traffic is normally distributed (MINCAD, 2000). The incorporation of aircraft wander into aircraft pavement design tools negates the requirement to utilise Pass to Cover Ratios (PCR). PCRs are necessary to relate passes to coverages for other design tools such as LEDFAA (Layered Elastic Design, Federal Aviation Administration) (FAA, 1995) and the FAA's chart based methods (FAA, 1995a).

A number of studies have been undertaken to measure the actual wander of aircraft on pavements. These studies have concluded that the wander of aircraft changes with the pavement area being considered. For example, aircraft on a runway will land and takeoff with a greater degree of wander across the pavement than aircraft moving slowly along a straight taxiway pavement. Under marshall, aircraft parking on aprons, or at aerobridges, would be expected to have the smallest degree of wander.

Table 1 provides the findings of two studies regarding the degree of aircraft wander on different areas of aircraft pavement. They are considered appropriate where site or project specific information is not available, which it rarely is.

Table 1: Aircraft Wander Standard Deviation.

Pavement Area	**HoSang (1975)**	**US Army/Air Force (1988)**
Runway	1800 mm – 3400 mm	1550 mm
Taxiway	800 mm – 1800 mm	770 mm

Whilst no specific literature was located, MINCAD (2000) suggests that 200 mm may be an appropriate standard deviation of wander for parking positions. The following wander standard deviations are commonly used in Australia:

- Runway. 1550 mm
- Taxiway. 773 mm
- Apron. 200 mm

5 AIRCRAFT MASS

Each aircraft has a measurable and exact mass at which it operates on any given area of aircraft pavement. In addition, all aircraft have published, certified, maximum operating masses, referred to as the Maximum All Up Mass (MAUM). Aircraft rarely operate at their MAUM and therefore, to utilise their MAUM in pavement design is an overly conservative approach, especially given their high influence on pavement thickness. Mass can vary significantly for any given aircraft make, type and variant. In commercial operations, additional weight implies greater fuel burn and therefore more expensive operations. Also, at many airfields, large aircraft cannot operate at their MAUM due to runway length requirements on takeoff.

APSDS allows the input of any aircraft mass. Therefore the effect of different assumed operating masses can be readily assessed. The mass should be selected to be within the range of operating masses for the design aircraft and should be based on some sensible estimate of the likely mass for the majority of operations. Aircraft operators record aircraft masses for each and every flight and therefore the actual information is available but may need to be summarised or combined into a number of operations of aircraft at one or two typical or characteristic masses.

6 AIRCRAFT TYRE PRESSURE

Just as each aircraft is certified to operate at a published MAUM, it is also published with a standard operating tyre pressure. However, in practice, aircraft maintainers will adjust the tyre pressure to provide an appropriate mass/tyre pressure combination. This is done to limit the amount by which a tyre deforms during operations. APSDS allows the input of any tyre pressure for each aircraft being designed for. However, it is common practice to adopt the standard operating tyre pressure at all operating weights of the aircraft. This is a slightly conservative approach to pavement design but is almost always adopted. Tyre pressures generally have little effect on pavement thickness required.

7 NUMBER OF PASSES

The number of aircraft passes is the number of times the design aircraft travels past any given cross section of aircraft pavement during the design life. This is distinctly different from coverages, operations, movements and departures. The number of passes of each of the design aircraft must be determined based on:

- **Design life of the pavement**. Typically 10 or 15 years is adopted for flexible aircraft pavements based on the time between asphalt overlays.
- **Configuration of the pavement**. The ratio between departures and passes will be affected by the airfield layout, including the number of runways, parallel taxiway and parking arrangements.
- **Traffic growth**. Like road traffic, aircraft traffic is assumed to grow over time with an annual growth rate of 3% being a reasonable approximation in the absence of project specific information.

APSDS allows any number of passes to be assigned for each aircraft considered in the design traffic.

8 ASPHALT MODULUS

As for all materials used to model aircraft pavements in APSDS, asphalt is assigned a modulus. This modulus is considered to be an elastic resilient modulus. The measurement of asphalt modulus is an inexact science which is expensive and time consuming to determine on a project by project basis (Sukumaran, *et al*, 2002). Unlike base and sub-base materials, which have an automated method for modulus assignment within APSDS (based on Barker and Brabston (1975)), asphalt moduli are assigned by the designer for each design scenario.

Asphalt modulus varies with pavement temperature, load duration, asphalt age and induced confining stress. Therefore, any particular asphalt mix will exhibit a large range of moduli

during its life. However, a constant asphalt modulus (per design scenario) is required by APSDS.

Procedures are available which relate air temperature to pavement temperature, and in conjunction with bitumen penetration data, to asphalt modulus. One method was developed by Heukelom and Klomp (1964) and described in Brabston, *et al* (1975). Due to the cost associated with such methods, it is normal for designers to assume a typical value of asphalt modulus. Table 2 provides some guidance on typical asphalt moduli values in various Australian environmental conditions. Given the low influence of asphalt modulus on pavement thickness, adoption of presumptive or typical values is generally appropriate.

Table 2: Typical asphalt moduli.

Environment	**Moduli**
Asphalt in northern and tropical regions. Young asphalt in moderate regions.	1000 MPa
Mature asphalt in moderate regions. Young asphalt in southern and alpine regions.	2000 MPa
Mature asphalt in southern and alpine regions.	3000 MPa

9 OTHER INPUTS

There are a number of addition items, which are also input into APSDS by the designer. Their selection, however, is an integral part of the design solution rather than the selection of an appropriate input parameter. Therefore, only general guidance can be provided. These additional inputs are as follows.

9.1 Aircraft Traffic Mix

Aircraft traffic is specific to each and every design scenario and guidance for its selection can only be made generally. The elements required to develop an aircraft traffic scenario include:

- **Aircraft types**. Each aircraft type and its variant are required for the aircraft to be modelled. The wheel spacing and operating mass are the most critical characteristics.
- **Passes**. The number of operations, departures of movements must be determined and converted to aircraft passes.
- **Design life**. For flexible pavements this is generally taken to be 10 or 15 years.

9.2 Asphalt thickness

The thickness of asphalt surfacing in Australian aircraft pavement design practice is generally 40 mm to 50 mm. In the USA and other countries, thicker asphalt layers are common. However, a significant number of Australian pavements that have been subject to multiple overlays have 200 mm or more of asphalt.

9.3 Base course thickness

Base course materials are commonly utilised in thicknesses of between 100 mm and 400 mm, depending on the size of the aircraft. The larger the aircraft the thicker the base course required to protect to sub-base material from over stressing.

10 CONCLUSIONS

APSDS is a layered elastic tool for the design of flexible aircraft pavements. It is based on the road pavement design tool CIRCLY. As is generally the case with layered elastic design tools, APSDS relates modelled single load event damage indicators to the number of allowable load repetitions by an empirical relationship.

The use of APSDS is relatively simple but if the input parameters are not appropriately selected, gross errors in the resulting design thickness can occur. Therefore, the following input parameters should be appropriately selected based on the design scenario and experience:

- Subgrade Strength.
- Aircraft Wander.
- Aircraft Mass.
- Aircraft Tyre Pressure.
- Number of Passes.
- Asphalt Modulus.

The aircraft traffic mix and pavement composition (base course thickness and asphalt thickness) must also be determined. When a designer selects these input parameters, effort should be concentrated on subgrade strength, aircraft mass and number of passes, as these have the greatest influence on pavement thickness required. Less effort or conservative estimates are generally acceptable for the less influential input parameters.

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