Methodology of Applying Heavy Weight Deflectometer for the Calculation of Runway Pavement Classification Number

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Abstract

The International Civil Aviation Organization requires every airport which serves commercial airline operations to publish its Pavement Classification Number (PCN) in its own Aeronautical Information Publication (AIP). This number is defined as a number expressing the bearing strength of a pavement for unrestricted operations. Likewise, each airline must provide the Aircraft Classification Number (ACN) that corresponds to each type of aircraft it operates. Only when the aircraft's ACN is less than the airport's PCN is the aircraft allowed to land with its maximum landing weight. Otherwise, the aircraft is restricted to a certain weight limit. There are two ways to determine the PCN, the aircraft method and the technical method. Many airports choose to determine the PCN using the aircraft method because of its simplicity. However, the technical method, which can specify the pavement structural bearing capacity more accurately, can give a more precise PCN than using the aircraft method. This paper presents an in-depth description of the establishment of a technical methodology for determining PCNs by applying the Falling Weight Deflectometer field data. A practical case study of a runway with two kinds of slab thickness mixed with two types of subgrade strengths is introduced for calculating the PCN through the established methodology.

Keywords: Airport Runway, Pavement Classification Number (PCN), Aircraft Classification Number (ACN), Heavy Weight Deflectometer

1.Introduction

The International Civil Aviation Organization (ICAO) requires every international airport which serves commercial airline operations to provide the Pavement Classification Number (PCN) to represent the bearing strength of the runway pavement. This PCN must be published in the airport's own Aeronautical Information Publication (AIP). There are two ways to determine a PCN, the empirical U method and the technical T method. Although the concept of PCN is quite clear and easily understood, the computation of the T method is rather complicated and no standard procedure can be followed. Therefore, most international airports chose to determine their PCNs using the U method rather than the T method. While the U method is less complicated and can be achieved without field testing or laboratory experiments, its downside is that the actual pavement damage caused by aircraft loading can not be determined. The objective of this paper is to review and evaluate the current U and T methods and to develop a modified T method which integrates the pre-process of determining the pavement material properties and the post-process of determining the representative runway PCN with the Boeing T method. The Heavy Weight Deflectormer (FWD) is used to obtain the deflection data from the existing runway pavement. Back-calculation and statistical analysis are used to divide the runway length into several homogeneous sub-sections. The PCN of each sub-section is derived based on the modified T method and the integrated PCN of the entire runway is then computed by the post-process.

2. Review of Existing ACN and PCN Methods

(a) Definitions of ACN and PCN [1]

The bearing strength of pavement intended for aircraft with a mass greater than 5,700 kg shall be made available using the ACN-PCN method. ACN is defined as a number expressing the relative effect of an aircraft on a pavement for a specified standard subgrade strength. PCN is defined as a number expressing the bearing strength of a pavement for unrestricted operations. Aircraft can operate in an airport unrestrictedly as long as the ACN value provided by the aircraft manufacturer is less than the PCN value of the airport.

The ACN-PCN method uses a code format to report the PCN. The PCN code shown in Table 1 includes: pavement type, subgrade category, allowable tire pressure, and method used to determine the PCN. There is no need to report the actual subgrade strength or the maximum tire pressure allowable. The subgrade strengths and tire pressures have been grouped into categories as indicated in Table 2, and the subgrade strengths and tire pressures within the range of each category could be represented by the character of that category.

Table 1 PCN Code Format

PCN Value	Pavement Type	Subgrade category	Allowable Tire Pressure	Method Used to Determine the PCN
A Number	R = Rigid F = Flexible	A = High B = Medium C = Low D = Ultra low	W = No limit X = To 1.5 MPa (217 psi) Y = To 1.0 MPa (145 psi) Z = To 0.5 MPa (73 psi)	T = Technical U = Using Aircraft

Source [1]

Table 2 Subgrade Strength Categories

Subgrade Category	Flexible Pavement		Rigid Pavement	
	Characterization	CBR range	Characterization	k-Value Range
A	CBR 15	Above 13	k = 150MN/m^3 (550 pci)	Above 120MN/m^3 (442pci)
B	CBR 10	From 8 to 13	k = 80MN/m^3 (300 pci)	From 60 to 120 MN/m^3 (221 to 442pci)
C	CBR 6	From 4 to 8	k = 40MN/m^3 (150 pci)	From 25 to 60 MN/m^3 (92 to 221pci)
D	CBR 3	Below 4	k = 20MN/m^3 (75 pci)	Below 25 MN/m^3 (92pci)

Source[1]

(b) Calculation Methods of ACN [1, 2]

There are a number of ways to calculate the ACN. A well known calculation method is stated in Aerodrome Design Manual Part 3. Depending on the taxiing condition of the aircraft, two masses are selected for the ACN calculation, i.e. maximum apron mass and a representative operating mass empty (OME). Both are static loads.

The ACN of an aircraft is numerically defined as two times the derived single wheel load (DSWL) expressed in 1,000 kg. The concept of a mathematically DSWL has been employed as a means to define the landing gear/pavement interaction without specifying pavement thickness. The DSWL is obtained by equating the thickness (reference thickness) given by the mathematical model for an aircraft landing gear to the thickness for a single wheel (DSWL) at a standard tire pressure of 1.25 MPa (181psi). For flexible pavements, the extended CBR design method for airfields is used to calculate the reference thickness, and the number of coverage is set at 10,000. For rigid pavements, the reference thickness is the thickness of the concrete slab which will give a maximum flexural working stress of 2.75 MPa (399 psi) by using Westergaard equation when loaded with one main gear at slab center. These calculations are derived using the program developed by Mr. R. G. Packard for rigid pavements, and by the S-77-1 method for flexible pavements [1].

In addition to the method used in the Aerodrome Design Manual Part 3, the aircraft manufacturers also provide charts to obtain the ACN value solely by inputting the aircraft gross weight and subgrade category.

(c) The Calculation Methods of PCN

Table 2 illustrates two ways of obtaining the PCN, the U method and T method. Each method is described below.

i. U Method [2]

The U method adopts the highest ACN value of the aircraft in the mixed traffic as the PCN value. Once the runway adopts this ACN value as the PCN and signs of distress operating are observed, the rating must be adjusted downward in order to maintain normal airport operations. If one or more aircrafts have ACNs that exceed the lowered PCN, then the allowable gross weight for those aircrafts may need to be restricted.

ii. T Method

The T method is based on the measurement of the response of pavement to load. Three different concepts of the T method, the ICAO method, the Boeing method, and the cumulative Damage method, are described next.

(1) ICAO Method [1]

Theories applied to the elastic behavior of pavement indicated the proportionality between load and deflection, thus implying that deflection could indicate capacity of a pavement's capacity to support a load. The conceptual correlation between the deflection of a pavement under a wheel load and the number of repetitions of that wheel load which will result in severe deterioration of the pavement is shown in Figure 1.

However, pavement bearing strength evaluations should address not merely an allowable load but a repetitions use level for that load. Normally, it is necessary to consider a mixture of loading at their respective repetitions use level. There is a strong tendency to rate pavement bearing strength in terms of some selected loading level or the allowable repetitions use level, and to rate each loading in terms of its equivalent number of this basic loading. To do this, a relation between loading and repetitions to produce failure shown in Figure 2 should be established. Similar to Figure 1, Figure 2 is a conceptual diagram that shows the relationship between these two parameters. The linear line equations of Figures 1 and 2 should be derived based on each pavement's structural composition of the runway.

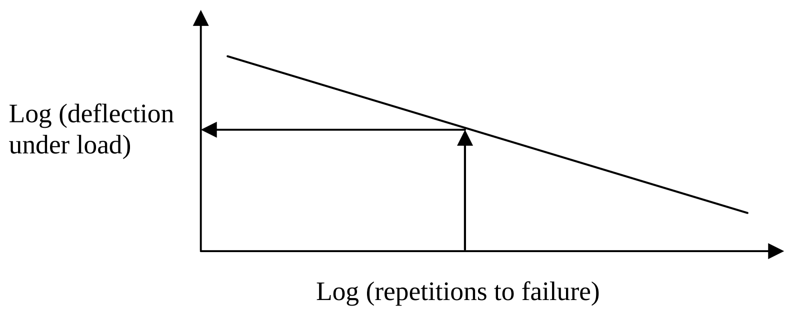


Figure 1 Relation between Deflection and Repetitions [1]

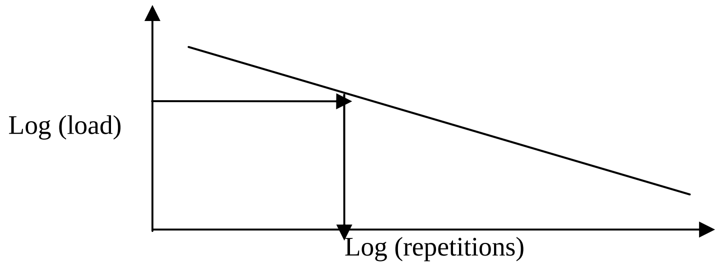


Figure 2 Relation between Load and Repetitions [1]

After obtaining the above information, it is necessary to conduct deflection tests in airports to plot the relationship between the load and maximum deflection as illustrated in Figure 3. The evaluation procedure is as follows:

(1) Choose the critical aircraft and determine the equivalent repetitions of the critical aircraft from other aircraft types in the mixed traffic based on the relation given in Figure 2,

(2) Receive the deflection by inputting the cumulative equivalent repetitions to Figure1; and

(3) Input the deflection to Figure 3 to calculate the corresponding load, and then achieve the PCN value by following the ACN calculation process.

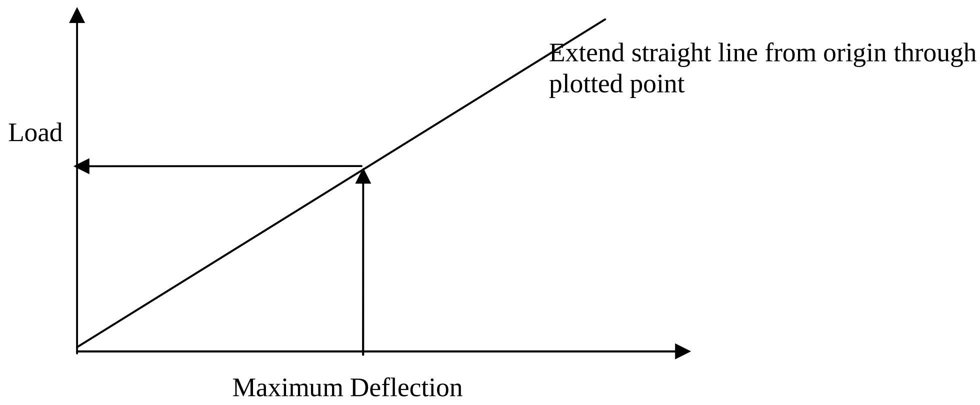


Figure 3 Relation between Load and Deflection [1]

The relationships shown in Figures 1, 2 and 3 are required in order to acquire the pavement condition for each runway. In addition to laboratory tests, field tests are also necessary. Consequently, executing the process addressed by ICAO is time-consuming and labor intensive. Therefore, most airport authorities would rather adopt the U method though even the ICAO's T method has been available for years.

(2) Boeing Method

In 1998, Boeing also proposed a T method which adopts the design concept of the Portland Cement Association (PCA) as the basis of evaluation [3]. The calculation processes are as follows:

a. Determine the traffic volume in terms of traffic cycles for each airplane that has been used, or is planned to be used in the airport during the pavement life period. The aircraft information required for the traffic volume process includes: past, current, and forecasted mix traffic volume; operational or maximum gross weight; typical aircraft weight distribution on the main and nose gear; main gear type; main gear tire pressure; and the pass-to-load repetition (P/LR) ratio as shown in Table 3.

Table 3 Rigid Pavement Pass-to-Load Repetition ratio [3]

Airplane	P/LR Ratio	Airplane	P/LR Ratio	Airplane	P/LR Ratio
707-320C	3.40	DC8-63	3.32	A300 B2	3.54
717-200	3.58	DC9-15	3.63	A300 B4	3.62
727-200	2.89	DC9-51	3.64	A300-600R	3.46
737-200	3.82	DC10-10	3.76	A310-200	3.74
737-300	3.87	DC10-30	3.74	A310-300	3.38
737-400	3.52	MD-11	3.62	A319-100	3.70
737-500	3.85	MD-81	3.39	A320-100	3.78
737-600	3.76	MD-82,-88	3.42	A320-200 Dual	3.72
737-700	3.75	MD-83	3.41	A320-200 DT	2.34
737-800	3.60	MD-87	3.43	A321-100	3.42
747-200	3.48	MD-90	3.47	A321-200	3.45
747-400	3.44	L1011-100	3.42	A330-300	3.68
747SP	3.98	L1011-500	3.44	A340-200	3.72
757-200	3.96	BAC111-500	3.60	A340-300	3.70
757-300	3.94	BAe146-300	3.72	FAA Single	5.18
767-200	4.02	F27	3.86	FAA Dual	3.48
767-200 ER	3.62	F28	3.55	FAA DT	3.68
767-300	3.86	F100	3.58	C130	4.58
767-300 ER	3.84	IL62M	2.94	C141	3.44
777-200	4.17	IL86	3.57	C-5A	3.16
777-200 IGW	4.17	TU-134A	5.80		
777-300	4.05	TU-154B	5.22		

b. Determine the critical aircraft as the design aircraft of the mix traffic. The critical airplane is the one that needs the greatest pavement thickness using the PCA design method.

c. Calculate conversion factors following Equation 1, and determine the equivalent traffic based on gear type. The corresponding conversion factors are shown in Table 4.

$$F = 0.8^{(M-N)} \quad \text{(Eq. 1)}$$

where:

F = conversion factor

M= the number of wheels on the critical airplane main gear

N = the number of wheels on the converted airplane gear

Table 4 Gear Configuration Conversion Factors [3]

To Convert From (N)	To (M)	Multiply Traffic Cycles By
Single	Dual	0.8
Single	Dual tandem (DT)	0.5
Single	Tridem (TD)	0.3
Dual	Single	1.3
Dual	Dual tandem	0.6
Dual	Tridem	0.4
Dual tandem	Single	2.0
Dual tandem	Dual	1.7
Dual tandem	Tridem	0.6
Tridem	Single	3.3
Tridem	Dual	2.5
Tridem	Dual tandem	1.7

d. Example: To convert the traffic of a B737 to the equivalent traffic of a B747, the conversion factor (F) is $0.8^{(4-2)}=0.6$ (B747 is treated as 136,200kg dual tandem gear aircraft with 16,170kg (35,625 lbs) single wheel load). If the repetition of the B737 is 1,000, then the converted equivalent traffic of a B747 is calculated as 1000*0.6=600.

e. Calculate traffic based on load magnitude of Equation 2.

$$R_1 = R_2^{\,A} \qquad \text{(Eq. 2)}$$

where:

$A = (W_2/W_1)^{1/2}$ (Eq. 3)

R_1= Equivalent traffic cycles of the critical airplane

R_2= Traffic cycles of a given airplane expressed in terms of the critical airplane landing gear

W_1= Single wheel load of the critical airplane

W_2= Single wheel load of the airplane in question

Example: follow the calculation in step 3. The single wheel load of a B747 is 16,170kg, and the single wheel load of a B737 is 14,020kg. Thus, A factor is computed as $(14{,}020/16{,}170)^{1/2} = 0.931$, and R_1 is $600^{0.931}=386$.

f. Accumulate equivalent traffic cycles of the critical airplane in traffic mix, and convert it to load repetitions based on Equation 4.

$$TC/LR = (P/LR) \div (P/TC) \qquad \text{(Eq. 4)}$$

Where:

TC= Accumulated equivalent traffic cycles

LR= Load repetitions

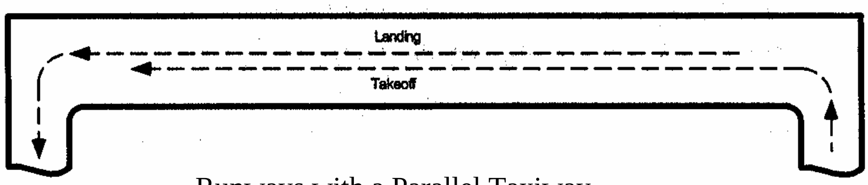
P/LR = Ratios from Table 3

P/TC= Pass-to-traffic cycles ratio. This ratio is determined based on the taxiway type connected with the runway and obtaining fuel at the airport or not as shown in Table 5. The taxiway type connected with the runway is displayed in Figure 4.

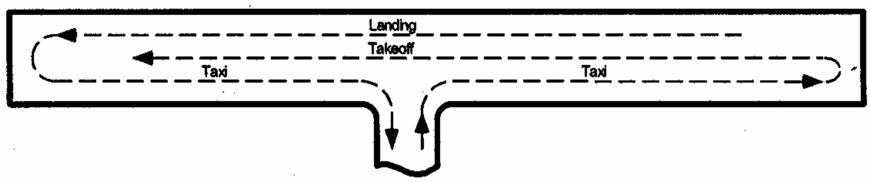
Example: The P/LR ratio of a B747 is 3.44. If the taxiway type connected with the runway is parallel and the B747 obtains fuel at the airport, the TC/LR ratio of the B747 is 3.44/2=1.72 and LR is TC/1.72.

Table 5 Pass-to-Traffic Cycles Ratio [3]

Taxiway \ Obtain fuel	Yes	No
Parallel	1	2
Central	2	3



Runways with a Parallel Taxiway



Runways with a Central Runway

Figure 4 Taxiway Types Connected with Runway [3]

g. Obtain the pavement characteristics, including the concrete slab thickness, the concrete modulus of rupture, and the modulus of the subgrade, k.

h. Convert load repetitions to stress ratio (SR) based on Equation 5. Multiply the concrete modulus of rupture by SR to obtain the working concrete tensile stress.

$$SR= 0.9725-0.03585*\ln(LR) \quad \text{(Eq. 5)}$$

Where LR is load repetitions obtained in step 5.

i. With the allowable working stress, slab thickness, and subgrade modulus, compute the maximum allowable gross weight of the critical airplane using the PCA chart.

j. Assign the subgrade modulus (k-value) to the nearest standard of the ACN/PCN subgrade code.

k. The ACN of the critical airplane may now be determined. Enter the allowable gross weight of the critical airplane from step 8, and calculate the ACN for the standard subgrade code of step 9. The numerical value of the PCN is the same as the numerical value of the ACN of the critical airplane.

l. Assign the tire pressure code based on the highest tire pressure in the mix traffic. Rigid pavements are typically able to handle high tire pressure, and usually code W is assigned.

m. If the allowable gross weight from step 8 is less than the critical aircraft operational gross weight, then the pavement may be assigned a PCN equal to the ACN of the critical aircraft at that gross weight, but with a reduced pavement life.

(3) Cumulative Damage Method

The CROW report also mentioned a PCN evaluation method based on a design method is similar to the one proposed by Boeing [2]. CROW is the Dutch abbreviation for Information and Technology Centre for Transport and Infrastructure. The CROW document presented a PCN evaluation method of concrete pavement founded on fatigue models. The suggested calculation steps are as follows:

a. Collect the traffic information, and determine the critical aircraft with the highest ACN. Convert the traffic volume of each aircraft in the mix traffic to the equivalent traffic volume of the critical airplane.

b. Determine the pavement characteristics, including the subgrade k, pavement thickness and elastic modulus.

c. Calculate the Miner pavement damage due to the mix traffic. Calculate the allowable gross weight of the critical aircraft using the equivalent traffic volume in step1 in the same Miner damage.

d. Determine the ACN that refers to the allowable gross weight of the critical aircraft required in step 3. Assign the pavement PCN to be the ACN of the critical aircraft.

The evaluation method of flexible pavement PCN values is similar to the method mentioned above. This evaluation method could also be performed using the finite element model with consideration of temperature effect.

In general, the U method is the simplest among the above PCN evaluation methods, and can be achieved without any field tests or laboratory experiments. However, the drawback of using the U method is that the actual damage of pavement caused by aircraft loading cannot be determined. The T method is more complicated than the U method, and the PCN values computed by different methods are diverse because of the various concepts used by the different methods [2]. Therefore, establishing a replicable and reliable T method for determining the PCN becomes the main objective of this research study.

A comparison of the three T methods above revealed that material characteristics, such as concrete modulus of rupture and subgrade reaction value, are acquired in order to execute the designated PCN procedures. Both ICAO method and the Cumulative Damage Method need additional laboratory experiments for obtaining the relation as shown in Figure 2. Field testing is also required to obtain the relation displayed in Figure 3. Boeing's method is considered the most comprehensive but the most easily executed among these three methods if the material characteristics are known. In this research study the pre-process procedure of determining the pavement material properties is developed by applying the FWD, and a post-process of determining the representative PCN for a runway with a mixed slab thickness and subgrade classification common in most of in-service runways is presented. By combining the Boeing method as the central part, the modified T method is established.

3. Pre-Process of Determining Runway Pavement Material Properties by Applying Heavy Weight Deflectormeter (HWD)

To understand the present structural condition of the in-use runway, an HWD test was conducted that evaluates the pavement structural strength of the studied case. The test plan and sampling locations were designed based on the suggestions of the network level scales of the FAA AC150/5370-11A[4] and ASTM D 4695-03[5]. The purpose of the HWD test was to analyze the deflection basin at slab center to determine the overall structural strength and back-calculating elastic modulus of each layer for the PCN analysis. In this study, CarlBro PRI2100 HWD was used for the deflection measurement. There are nine geophones aligned in Figure 5 where d_1 indicates the deflection value recorded directly under the loading plate. Raw data are first processed for dividing the entire runway into several structurally homogeneous sub-sections, followed by back-calculation analysis for obtaining the layer properties, particularly the surface layer and the subgrade layer.

(a) Procedure to Determine the Structurally Homogeneous Sub-sections

A three-step procedure analyzes raw data and divides the runway length into several homogeneous sub-sections. In first step, the normalized deflection value, d_{1n}, is derived by multiplying the d_1 with a ratio of the (L_{norm}/ $L_{applied}$) as shown in Equation 4 [6]. A case study of data collected from the runway of one international airport is presented next. Figure 6 shows the normalized deflection (d_{1n}) along the runway.

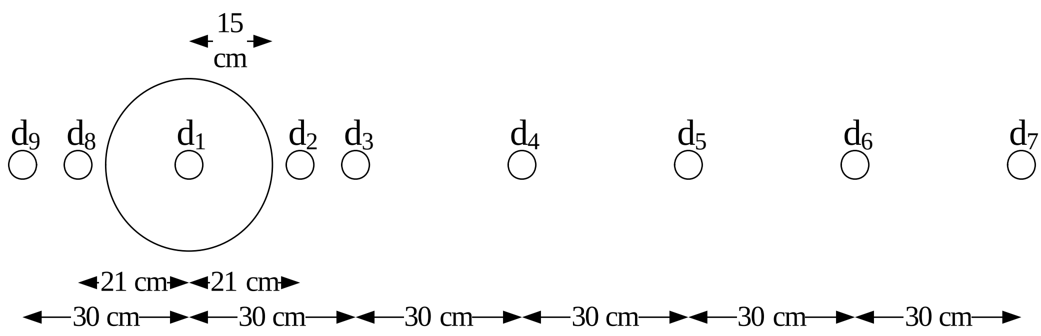


Figure 5 Layout of CarlBro PRI2100 Geophones

$$d_{1n} = \left(\frac{L_{norm}}{L_{applied}} \right) d_1 \qquad \text{(Eq. 6)}$$

Where: d_{1n}=Normalized deflection

L_{norm}=Normalized load, set to be 200 kN

$L_{applied}$=Applied load

d_1=Measured deflection of plate load

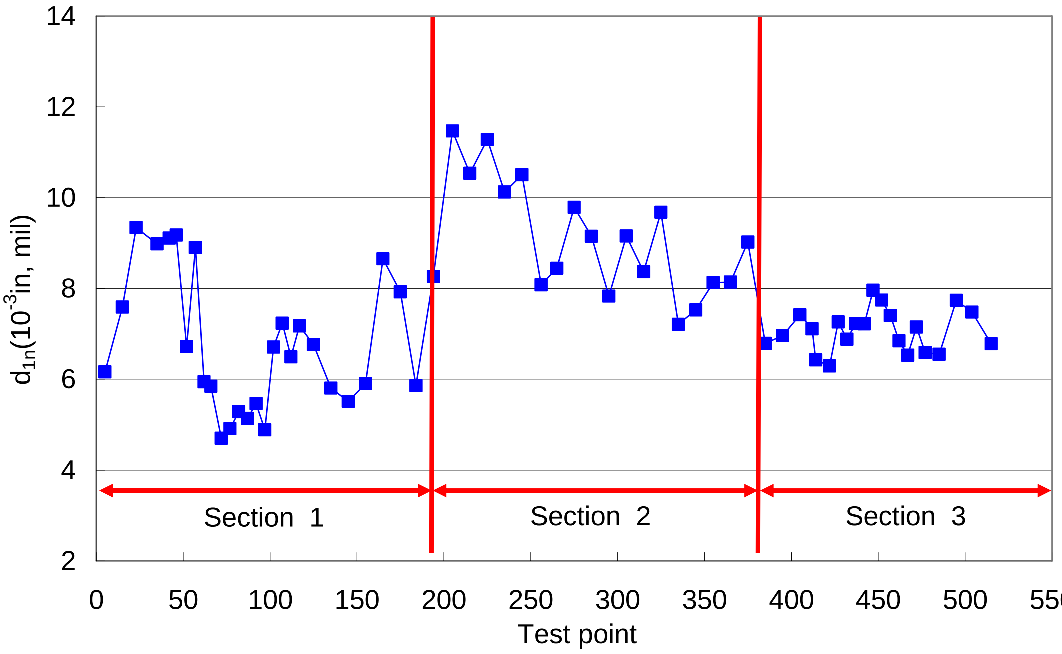


Figure 6 Variation of the Normalized Deflection Data of d_{1n}

The normalized deflection data, d_{1n}, could be treated as the index of overall pavement structural strength. According to the variation of d_{1n} in Figure 6, the overall runway can be divided into three sections which are partitioned at test points 194 and 380. The sections with higher structural strength (smaller d_{ln} values) are at test points 0 to 194 and the section after point 380. The section between test points 194 to 380 has relatively poor structural strength.

The second step is to compute the Impulse Stiffness Modulus (ISM) using Equation 7[4], and plot the variation as shown in Figure 7. The ISM is also called Dynamic Stiffness Modulus (DSM).

$$I(D)SM = L / d_1 \qquad \text{(Eq. 7)}$$

Where: I(D)SM= Impulse and Dynamic Stiffness Modulus (kips/inch)

L= Applied load (kips)

d_1= Maximum deflection of load plate (inches)

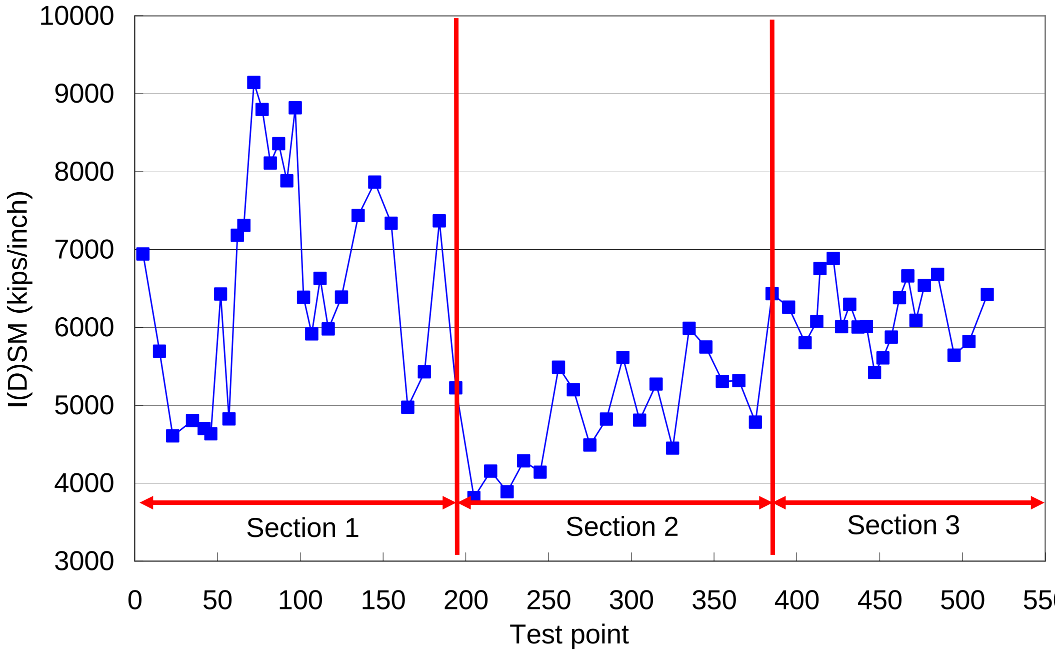


Figure 7 Variation of I (D)SM

The meanings of the magnitude of normalized deflection data and I(D)SM contrast. Smaller normalized deflection data mean higher structural strength, while smaller I(D)SM values represent poorer structural strength. Based on the messages shown in Figure 7, the partition points are the same as those concluded from normalized deflection data. In addition to observing whole pavement structural strength through the normalized deflection data of d_{1n}, FAA AC 150/5370-11A[4] suggests that the variation of subgrade structural strength may be diagnosed based on the normalized deflection data of d_{9n}. Therefore, the third step is to compute the normalized deflection data of d_{9n} as illustrated in Figure 8.

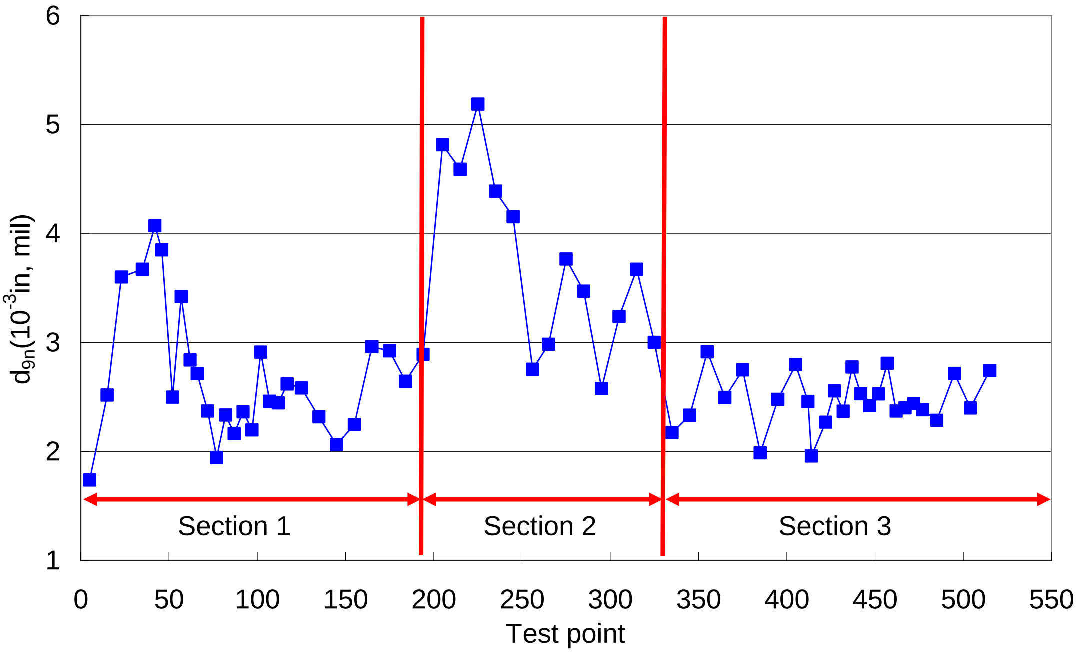


Figure 8 Variation of the Normalized Deflection Data of d_{9n}

Based on the d_{9n} information shown in Figure 8, this runway could again be divided into three sections. However, but the partition points of these three sections are 194 and 330. The section at test points 194 to 330 shows relatively poor subgrade structural strength.

Next, analyzed results of the partition points for the sub-sections can be integrated again with the thickness variation of runway slab (38 cm between test points 64 and 480, 41 cm for the rest of the runway). In t his process, the runway is divided into six sub-sections with five partition points at test points 64, 194, 330, 380, and 480.

(b)Back-calculation of Pavement Layer Properties

Back-calculation is one of the most common methods used to analyze the deflection basin which is collected from HWD. There are quite a few well-known back-calculation programs available from which a suitable software for the case study was selected. In this study, researchers evaluate and compare six back-calculation programs for concrete pavement by utilizing the multiple replicated FWD data collected from the National Taiwan University (NTU) test section., The six programs are BAKFAA[7, 8, 9], DBFWD[10, 11], ILLI-BACK[12], TKUBAK EK[13], MOSULUS 6.0[12], and Rosy DESIGN[14]. The dimension of the NTU test section is 35 m * 3.5 m. The section is sub-divided into two types of pavements, the concrete (rigid) pavement with a dimension of 20 m * 3.5 m and the asphalt concrete (flexible) pavement with a dimension of 15 m * 3.5 m. The rigid pavement sub-section includes 4 slabs, each measuring 5 m*3.5 m. Two slabs are 40 cm in depth with a 20cm aggregate base, while the other two slabs are 25 cm thick over a 35 cm aggregate base. Dowel bars are embedded in the joints. The flexible pavement section is again divided into two sub-sections with the same length (7.5 m) and width (3.5 m) but different thickness, i.e. 25 cm and 40 cm, respectively.

Laboratory tests are conducted for each material layer to acquire the material properties for verifying back-calculation results. This research conducted tests of compressive strength, elastic modulus, third-point tensile strength, and core specimen on rigid pavement, and determined bearing capacity of base and subgrade material by the laboratory California Bearing Ratio (CBR) test and the R value test, respectively. A comparison of the laboratory test results with back-calculation results of the six programs, led to identification of appropriate back-calculation tool(s) for the analysis of runway field deflection data. It was found that the RoSy DESIGN and DBFWD programs functioned better in the back-calculation of elastic modulus of rigid pavement slabs, while the BAKFAA, MODULUS, DBFWD, and TKUBAK EK programs showed better results in the back-calculation of subgrade elastic modulus [12]. It was concluded that the dynamic back-calculation software, DBFWD, performs well both in surface layer and subgrade. Thus, the back-calculation results of DBFWD would be used in the calculation of the PCN value. Figure 9 shows the distribution of back-calculated E and K along the entire runway using the DBFWD program for the given case.

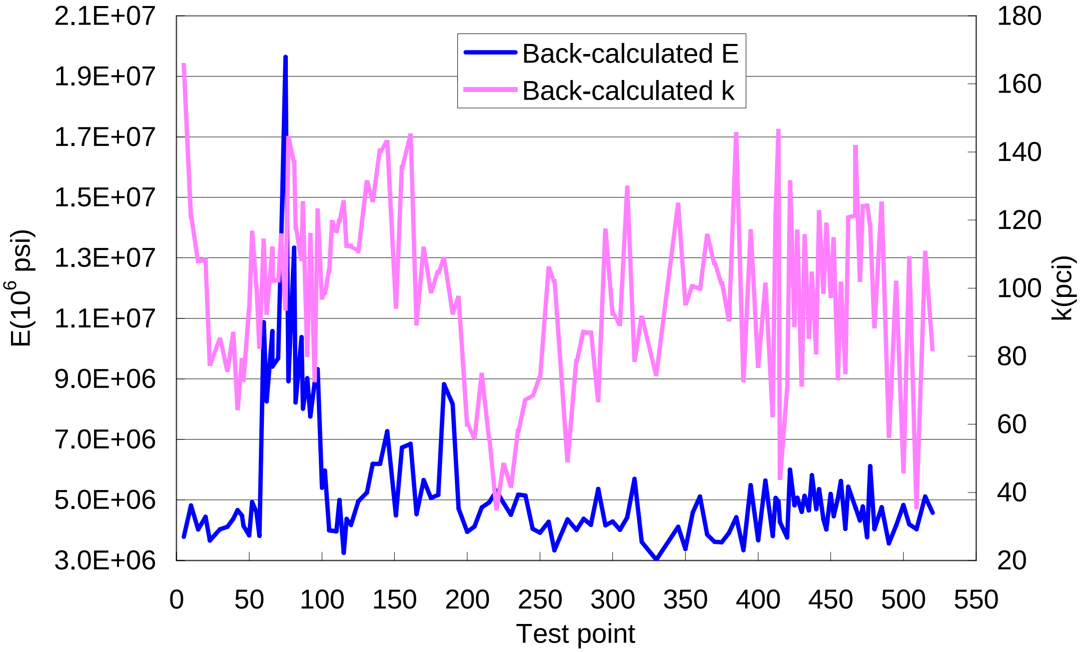


Figure 9 Distribution of Back-calculated E and K along the Entire Runway by Using DBFWD

4. Methodology for Calculating PCN Value

Since the PCN value represents the relationship between the allowable gross weight of a critical aircraft and pavement structural life, the calculation should integrate the analysis of pavement structural strength and air traffic operations. The T method is used to determine pavement bearing capacity by measuring and analyzing the pavement response to loading under existing and projected air traffic, and could be achieved by reversing design process or evaluating the response to loading. Thus, a modified T-method to calculate the PCN is developed by integrating the pre-process of determining the pavement material properties and the post-process of determining the representative runway PCN with the Boeing method. The evaluation procedure is illustrated in Figure 10.

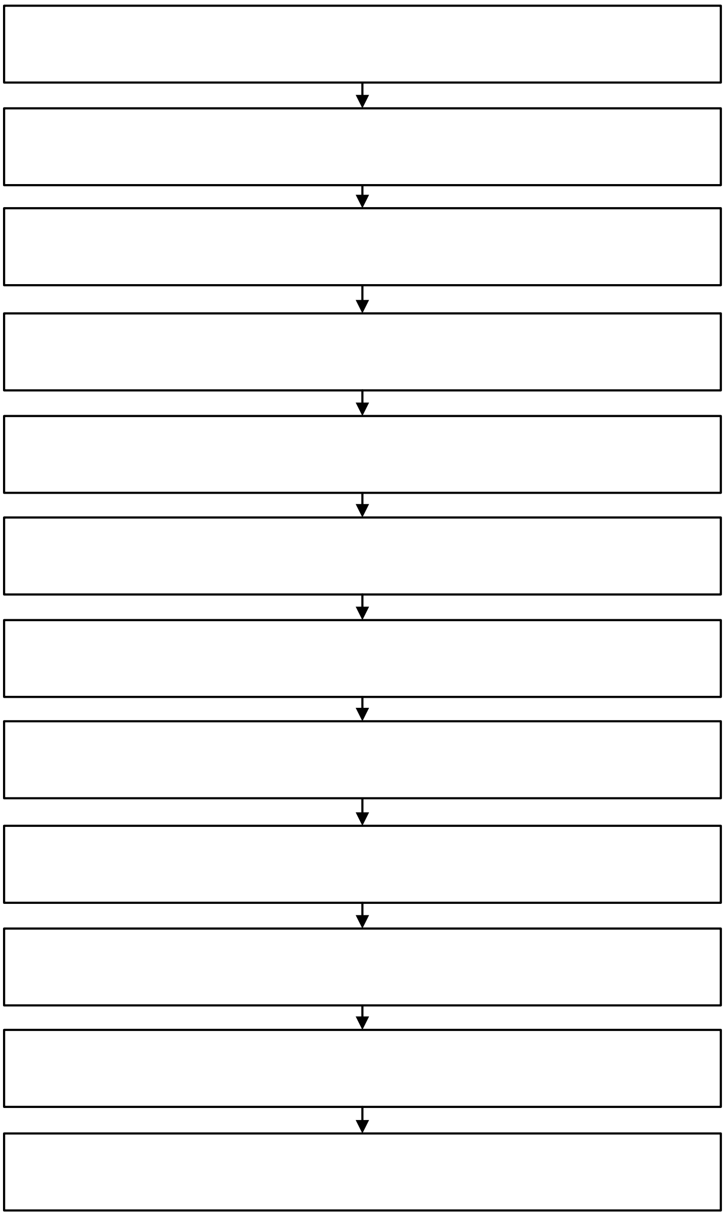


Figure 10 Procedure of Calculating PCN by the Modified T Method

Following the sub-sections classification (steps A to C) and layer properties analysis through the back-calculation program (step D), steps E to L in Figure 10 are presented below.

Although the entire runway has been divided into six homogeneous sub-sections, it is very common that the back-calculated Es and Ks scatter. However, the representative E and K shall be calculated for the sub-section. Based on FAA recommendation, a statistical approach should be used to determine the input values of E and K for each pavement characteristic [4]. It is recommended that coefficients of variation, C_v, of Es and Ks are calculated first. A C_v value of less than 20% is normally acceptable for NDT-based pavement characteristics, and the mean minus one standard deviation is used for establishing evaluation input. If the C_v exceeds 20%, an E value that is less than 85% of all E values is chosen for further analysis of the PCN. The representative K is computed in the same manner. By using this computation, 85% reliability is achieved for the final analyzed result. However, this concept is only applicable to a runway with only one homogeneous section. The reliability of an entire runway can be assured. In most cases there is more than one sub-sections. Each sub-section may reach 85% using the above procedure. Next, the method is presented to integrate the sub-section PCNs into an entire runway with the same degree of reliability.

5. Post-process of Determining Runway PCN

In most cases, sub-sections of runway have various lengths because of the nature of pavement maintenance and rehabilitation history. Therefore, an arithmetic mean of sub-section PCNs cannot provide the 85% reliability for the entire runway. In addition, the subgrade classes also fall into several categories. Computing the average mean of PCNs cannot be used to determine the proper subgrade class. In this study, researchers propose a method to calculate the representative PCN value for the entire runway by taking the length of each sub-section as a weight factor for analysis of reliability analysis. This method conforms to the 85% reliable principles and avoids excessively conservative calculation.

A three-step procedure is developed. First, compute the mean values of E and K for each sub-section and follow Figure 10 for obtaining a mean PCN for each sub-section. Second, order the PCNs from the smallest to the largest and cumulate the corresponding lengths. Third, choose the PCN value which corresponds to the accumulative 15% of runway length as the representative PCN for the entire runway. This will result in a PCN value in which 85% of the runway length has a value equal to or higher than it. More than likely, the subgrade class can be decided by the same procedure, i.e. ordering the subgrade class from the weakest to the strongest, cumulating the corresponding lengths, and choosing the subgrade class which has the accumulative 15% of runway length. Since both the PCN and subgrade class are determined through the same procedure, the selected subgrade class is usually a perfect match with the PCN, i.e. they belong to the same sub-section.

6. Case Study of PCN Determination by the Modified T Method

(a) Determining the Mean E and K of Each Sub-section

Following the studied case presented above, the average values of surface elastic modulus and subgrade k of each sub-section are calculated and shown in Table 6.

Table 6 Average values of E and K of each section

Section	Partition test point	Slab depth	Mean value	
			Concrete elastic modulus	Subgrade k
1	0-64	41cm	30,991 MPa	26,287 kN/m^3
2	64-194	38cm	47,899 MPa	30,623 kN/m^3
3	194-330	38cm	30,661 MPa	20,596 kN/m^3
4	330-380	38cm	27,705 MPa	28,184 kN/m^3
5	380-480	38cm	32,686 MPa	27,913 kN/m^3
6	480-520	41cm	30,350 MPa	22,493 kN/m^3

(b) Determining the Critical Airplane

This process includes three steps. First, estimate the annual traffic by the traffic data. Second, convert concrete elastic modulus into PCC modulus of rupture by Equation 8[4]. Finally, input the PCC modulus of rupture and subgrade k into PCA design chart of each type of aircraft to find the required PCC slab depth as shown in Table 7.

$$M_r = 43.5\left(\frac{E_{pcc}}{10^6}\right) + 488.5 \tag{Eq. 8}$$

Where: M_r = PCC modulus of rupture, psi,

E_{pcc} = Back-calculated PCC elastic modulus values, psi

Table 7 Calculation results of Required PCC Slab Thickness

Type	Max. T/O weight (kg)	Tire pressure (kPa)	ACN	TC/LR	Annual traffic	Load repetition	Stress ratio	Working concrete tensile stress (kPa)	Required PCC slab depth (cm)
B747-400	391,100	1,378	77RC/87RD	3.44	14380	4181	0.6736	3,052	41
A330-300	218,100	1,419	72RC/84RD	1.84	8140	4424	0.6715	3,045	40
A320-200dual	73,400	1,440	48RC/50RD	3.72	5730	1540	0.7094	3,218	31
B737-800	79,300	1,468	54RC/56RD	3.60	4780	1328	0.7147	3,245	33
B767-300	159,500	1,213	54RC/65RD	3.86	4380	1135	0.7203	3,266	35
A300-600R	164,800	1,350	68RC/78RD	3.46	4230	1224	0.7176	3,252	35
MD-11	285,400	1,419	83RC/95RD	3.62	3470	958	0.7264	3,293	40
B777-300	299,600	1,481	88RC/107RD	4.05	3320	820	0.7320	3,321	43
MD-90	71,300	1,378	53RC/55RD	3.47	2410	694	0.7379	3,349	31
B757-200	111,500	1,261	46RC/49RD	3.96	1900	479	0.7512	3,411	29
A340-300	258,100	1,316	64RC/75RD	3.70	1720	464	0.7524	3,416	37

Note: 1. Max. T/O weight, tire pressure, and ACN value are acquired from websites of Boeing and Airbus as well as Aerodrome Design Manual Part 3 [1, 15, 16].

2. The aircraft in the table is representative of each series.

In this case, the type of taxiways connected with this runway is parallel, and it is observed that most aircrafts would fuel in this airport. Therefore, according to Table 5, the P/TC of this runway is 1. Based on this and Equation 4, the P/LR of aircraft operating on this runway is equal to TC/LR, and this ratio could be used to convert annual traffic into load repetitions. Next, convert load repetitions into stress ratio by Equation 5, and multiply the stress ratio by PCC modulus of rupture to derive the concrete tensile stress. Finally, calculate the required PCC slab depth of each aircraft using the PCA design chart. Among the aircrafts listed in Table 7, the B777-300 requires a maximum. PCC slab depth and is chosen as the critical aircraft. The ACN values of each aircraft are also shown in Table 7. The number represents the ACN value, the second code refers to rigid pavement, and the third code refers to subgrade category. The B777-300 is also the aircraft with the maximum ACN value.

(c) Calculate PCN Value

Equivalent traffic cycles are calculated by Equations 1 and 2 and are listed in Table 8. Equivalent traffic cycles of each aircraft, surface elastic modulus, subgrade k, PCC slab depth, and pavement life will be used to calculate the PCN value. It should be emphasized that the PCN is a dynamic value as a function of expected life. The setting of pavement life includes 1, 3, 5, 10, and 20 years in order to examine the relationship between pavement life and allowable gross weight of aircraft.

Table 8 Equivalent Traffic Cycles

Type	Annual traffic	Main gear type	W_2	R_2	W_1	R1
B-747-400	14380	DT	35625	8629	35625	8629
A330-300	8140	DT	35625	4884	35625	4884
A320-200dual	5730	dual	38404	2292	35625	3082
B-737-800	4780	dual	41488	1913	35625	3478
B-767-300	4380	DT	35625	2628	35625	2628
A300-600R	4230	DT	35625	2540	35625	2540
MD-11	3470	DT	35625	2081	35625	2081
B-777-300	3320	TD	35625	3322	35625	3322
MD-90	2410	dual	37288	964	35625	1129
B-757-200	1900	DT	29175	1139	35625	583
A340-300	1720	DT	35625	1029	35625	1029
						33385

Note: 1. W_1 is the single wheel load of the critical aircraft , B777-300.
2. DT means dual tandem; TD means tridem.

The estimated ACN values of the B777-300 for individual sub-sections at each pavement life are shown in Table 9. These numbers are also the proposed PCN values. For example, if the pavement life is set to be 20 years, the PCN value of sub-section 1 is 54 RCWT. “RCWT” is fixed, but the PCN number would vary when the pavement life changes. It is clear that the shorter the pavement life, the smaller the PCN value, and the changing rate (ΔPCN/year) is non-linear. The changing rate of the PCN increases as the pavement life decreases. These phenomena verify the relationship among PCN value, pavement characteristics, and pavement life.

Table 9 ACN/PCN Values of Critical Aircraft of Different Sections

Pave. life (yrs)	ACN/ PCN					
	Sub-sec. 1	Sub-sec. 2	Sub-sec. 3	Sub-sec. 4	Sub-sec. 5	Sub-sec. 6
20	54 RCWT	61 RCWT	50 RDWT	42 RCWT	46 RCWT	61 RDWT
15	57 RCWT	65 RCWT	52 RDWT	44 RCWT	48 RCWT	63 RDWT
10	59 RCWT	69 RCWT	54 RDWT	46 RCWT	50 RCWT	65 RDWT
5	62 RCWT	75 RCWT	59 RDWT	50 RCWT	55 RCWT	72 RDWT
3	69 RCWT	79 RCWT	62 RDWT	52 RCWT	58 RCWT	76 RDWT
1	76 RCWT	88 RCWT	71 RDWT	59 RCWT	65 RCWT	84 RDWT

Table 9 also indicates that subgrade k values are divided into two categories. Sections 1, 2, 4, and 5 belong to category C, while sections 3 and 6 belong to category D. PCN values of sections with category C (low) are discussed first. The PCN value of section 2 is highest among the 4 sections because of the highest surface elastic modulus and subgrade k even if its depth is smaller. The PCN value of the section 1 is the second highest. Next are sections 4 and 5 -- the PCN value of section 4 is the lower of the two. Lastly, two sections with category D (ultra low), sections 3 and 6, are compared. The PCN value of section 6 is higher because of its thicker depth.

In this paper, pavement life of 5 years is selected to demonstrate the determination of PCN for the entire runway. There are two steps involved in this process, First, reorder the PCN of six sections from the smallest value 50 (sub-section 4) to the largest value 75 (sub-section 2). Next, plot the PCN values with the cumulative length percentage of sub-sections as illustrated in Figure 11. The PCN value 55, corresponding to 15% of the cumulative runway length, is then selected as the representative PCN value for the entire runway. Figure 12 displays the subgrade classes versus the cumulative length percentage of the sub-sections. It is found that subgrade category D should be selected to represent the PCN subgrade category. As an integrated result, the PCN value for the entire runway is designated as 55 RDWT for a 5-year pavement life.

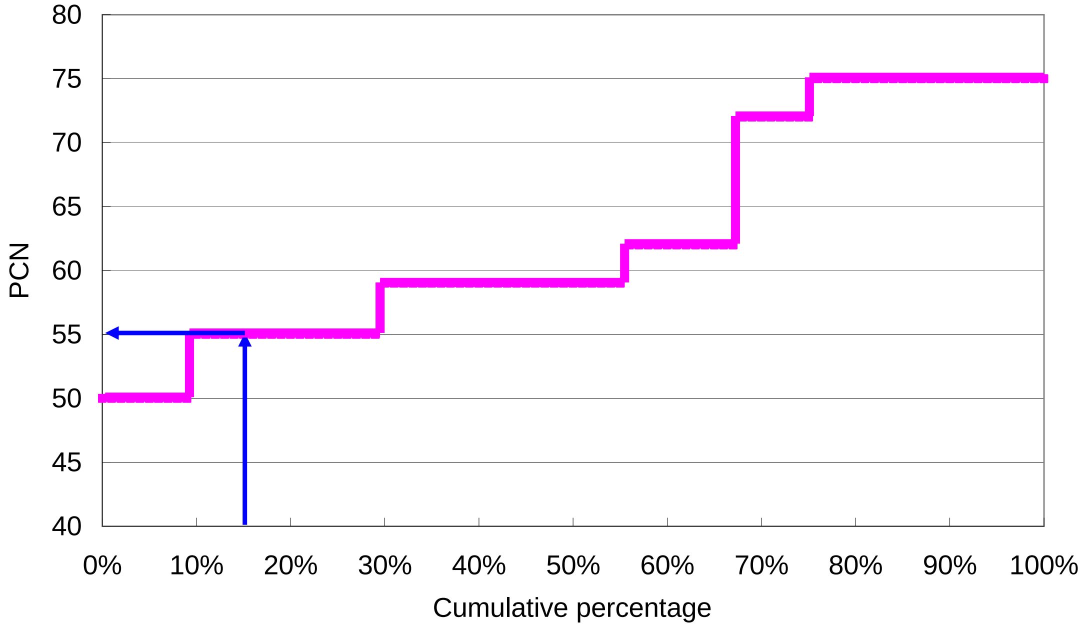


Figure 11 PCN Value with Corresponding Cumulative Runway Length Percentage

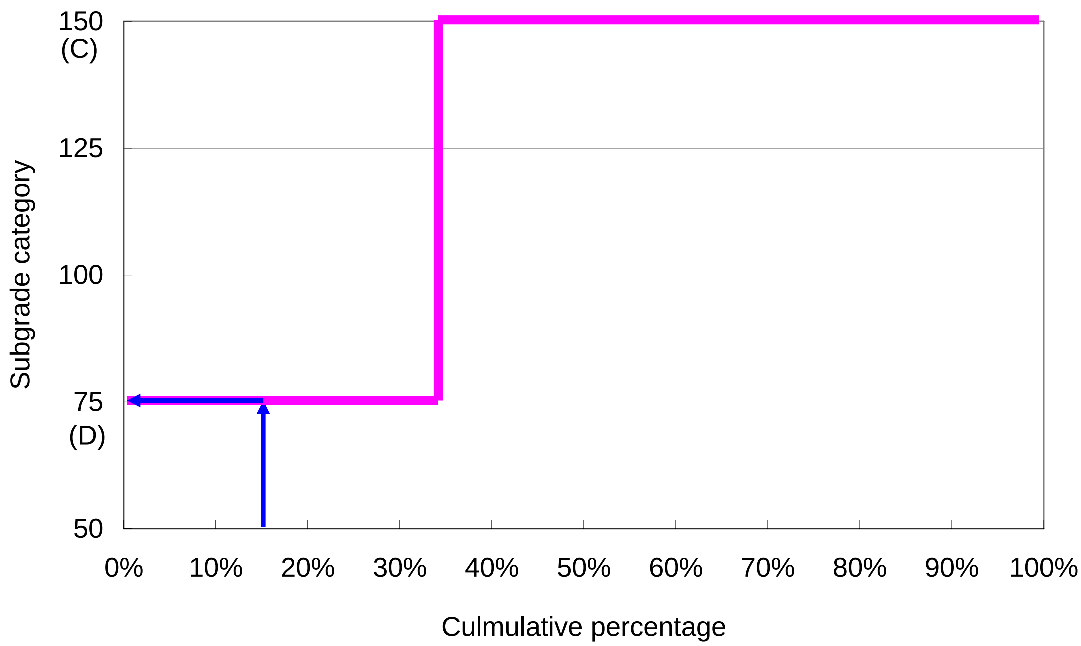


Figure 12 Subgrade Classes with Corresponding Cumulative Runway Length Percentage

7. Conclusion

This research develops a modified T method for calculating a PCN by integrating the pre-process of determining the pavement material properties and the post-process of determining the representative runway PCN with the Boeing T method. This study considers not only the calculation theory of PCN but also the variation of pavement structure. In comparison to any existing T methods, the feature of this modified methodology is unique since it takes into account the reality of non-uniform slab thickness, mixed concrete strengths and various subgrade reactions along the runway. The PCN values of homogeneous sub-sections are calculated first and an integrated PCN value is determined in order to achieve an 85% reliability. In this paper, the procedure of the proposed methodology is clearly illustrated, and the selection of evaluation inputs and representative PCN are presented by case study. The method constructed in this research could assist airport authorities in calculating PCN values efficiently, bearing in mind that PCN is, in fact, the allowable ACN load that consumes the pavement life. Pavements with the same bearing strength can be assigned a large PCN with respective small pavement life, but can also be assigned a small PCN with a higher design life. Since assignment of the PCN is not only a technical but also a policy decision, the airport authority should set the value judiciously. It should not raise the PCN value to cause unexpected damage, nor lower it to restrict the operation of most aircrafts.

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