DEVELOPMENT OF A ROBUST APPROACH FOR EVALUATION OF AIRPORT PAVEMENT BEARING CAPACITY

Submitted for Presentation and Publication at the
88th Annual Meeting of the
Transportation Research Board

Washington, D.C.
January 11-15, 2009

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Text:	4,807	Words	
Figures:	5*250=1,250	Words	
Tables:	2*250= 500	Words	Originally Submitted on August 1, 2008
Total:	6,557	Words	

Development of a Robust Approach for Evaluation of Airport Pavement Bearing Capacity

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Abstract: The Aircraft Classification Number / Pavement Classification Number (ACN/PCN) method has been adopted by the International Civil Aviation Organization (ICAO) as the standard for reporting airfield pavement bearing strength. Although it has been clearly recommended that the engineer should simultaneously consider the mean and standard deviation in the selection of an evaluation or design input value, many evaluation and design procedures currently only use the mean value in the analysis (AC 150/5370-11A). This study will first illustrate its definitions, possible applications, and potential problems in arriving at a consistent and repeatable value based on the results of nondestructive testing. A goodness study of the existing backcalculation results using the Long-Term Pavement Performance (LTPP) database was conducted. For a more conservative evaluation and design approach, the mean value minus one standard deviation (or the so-called 85% confidence level) may be used for obtaining evaluation or design inputs in general (AC 150/5320-6D). Nevertheless, it was found that this proposed procedure is not based on sound statistical principles especially when its probability distribution function of the population is almost always unknown. In engineering practice, a subset of the population or a random sample is often collected to represent the population characteristics of interest. Consequently, the concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing were adopted. It was proposed that a single representative design input for the entire runway pavement be determined by the lower limit of 95% confidence level (1-tail) to derive a more consistent and repeatable PCN value. A case study was conducted to illustrate the potential problems of the existing ACN/PCN procedures and the benefits of the proposed revisions.

INTRODUCTION

The Aircraft Classification Number / Pavement Classification Number (ACN/PCN) method has been adopted by the International Civil Aviation Organization (ICAO) as the standard for reporting the airfield pavement bearing strength. Although it has been clearly recommended that the engineer should simultaneously consider the mean and standard deviation in the selection of an evaluation or design input value, many evaluation and design procedures currently only use the mean value in the analysis (AC 150/5370-11A) (*1*).

For a more conservative evaluation and design approach, the mean value minus one standard deviation (or the so-called 85% confidence level) may be used for obtaining evaluation or design inputs in general (*2, 3*). This study will first illustrate its definitions, possible applications, and potential problems in arriving at a consistent and repeatable value based on the results of nondestructive testing. To derive a more consistent and repeatable PCN value, the concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing will be proposed for establishing the evaluation or design inputs.

REVIEW OF ACN/PCN METHODOLOGY

The ACN/PCN method is designated by the ICAO as the only approved method for reporting the bearing strength of pavements. Each aircraft is assigned a number expressing the relative structural effect on a pavement for a specified pavement type (R = Rigid pavement and F = Flexible pavement) and a standard subgrade category (A=High, B=Medium, C=Low, D=Ultra low). The concept of a single-wheel load has been employed to define the lading gear and pavement interaction without specifying pavement thickness as an ACN parameter. This is done by equating the thickness derived for a specified airplane landing gear to the thickness derived for a single wheel load at a standard tire pressure of 181 psi (1.25 MPa).

PCN is a number expressing the relative load-carrying capacity of a pavement. A particular PCN value can support an aircraft that has an ACN value equal to or less than the pavement's PCN value for unrestricted operations without weight restrictions. The PCN value is for reporting pavement strength only and cannot be used for pavement design or as a substitute for pavement evaluation. However, ICAO has not specified regulatory guidance on how to determine a PCN value because many member countries are reluctant to agree on an international standardized method for pavement evaluation (*2, 4-8*).

Stet (*6*) further discussed the recent and future developments of this methodology. An alpha-factor is used in the ACN procedure to account for load repetitions and coverages for different loading gears in flexible pavements (*9-10*). Due to the inherent limitations of the existing pavement design and evaluation procedure for some new types of larger airplanes (e.g., B-777 and A380-800), full-scale research projects have been undertaken to develop an alternative mechanistic-empirical procedure using layered elastic design approaches. The ICAO ACN study group (ACNsg) has initiated an investigation study into the impact of revising ACNs on the current ACN/PCN methodology based on the full-scale test results.

PCN assignments are related to design methodologies. Since the current ACN/PCN method does not dictate a specific design method for PCN assignment, the technically derived PCN values are likely to vary to a great extent. Many factors which have a profound influence on PCN assignment include: the PCN method used, the use of empirical or mechanistic based methods, the evaluation method used, the pavement structural life, the method to derive an annual traffic volume, the method to backcalculate material properties, and different transfer functions, etc. Stet (*6*) also demonstrated the PCN values can vary over 200 percent using different theories and evaluation technologies.

GOODNESS STUDY OF EXISTING BACKCALCULATION RESULTS

Since Nondestructive Deflection Testing (NDT) has been recommended to evaluate the overall structural capacity of an existing airport pavement (*1*), a goodness study of the existing backcalculation results using the Long-Term Pavement Performance (LTPP) database was conducted (*11-12*). Starting from 1987, the LTPP program has been monitoring more than 2,400 asphalt and Portland cement concrete pavement test sections across the North America. Very detailed information about original construction, pavement inventory data, materials and testing, historical traffic counts, performance data, maintenance and rehabilitation records, and climatic information have been collected. There are 8 general pavement studies (GPS) and 9 specific pavement studies (SPS) in the LTPP program. Of which, only those GPS (1 to 2 for asphalt concrete and 3 to 5 for portland cement concrete) pavements were used in this study.

Initially, the DataPave 3.0 program was used to prepare the database. However, in order to obtain additional variables and the latest updates of the data, the LTPP DataPave Online (Release 18.0) database (retrieved from http://www.datapave.com) became the main source for this study. The database is currently implemented in an information management system (IMS) which is a relational database structure using the Microsoft Access program (*13*). Automatic summary reports of the pavement information may be generated from different IMS modules, tables, and data elements. The thickness of pavement layers was obtained from the IMS Testing module rather than the IMS Inventory module to be consistent with the results of Section Presentation module in the DataPave 3.0 program.

Comparison of Laboratory Tested and Backcalculated Moduli of AC Pavements

The static (or laboratory tested) elastic modulus data was recorded in the IMS Testing module. In the LTPP database, the dynamic moduli of AC layers were backcalculated using the MODCOMP4 program (*14*) and the data could be retrieved from the IMS Monitoring module. Thus, it would be interesting to compare the laboratory tested layer moduli versus the backcalculated dynamic Young's moduli so as to have a better understanding of their associated variability. As shown in Figure 1, the variability of the relationship between the dynamic and the static (or laboratory tested) moduli could not be ignored (*11*). The average ratios of which are approximately 2.6, 2.7, 7.3, and 3.4 by eliminating some apparent outliers for AC surface, base, subbase, and subgrade layers, respectively. These results also indicated that the recommendation of an adjustment factor (C) of about 0.33 may be appropriate, though more research is needed to reduce the variations.

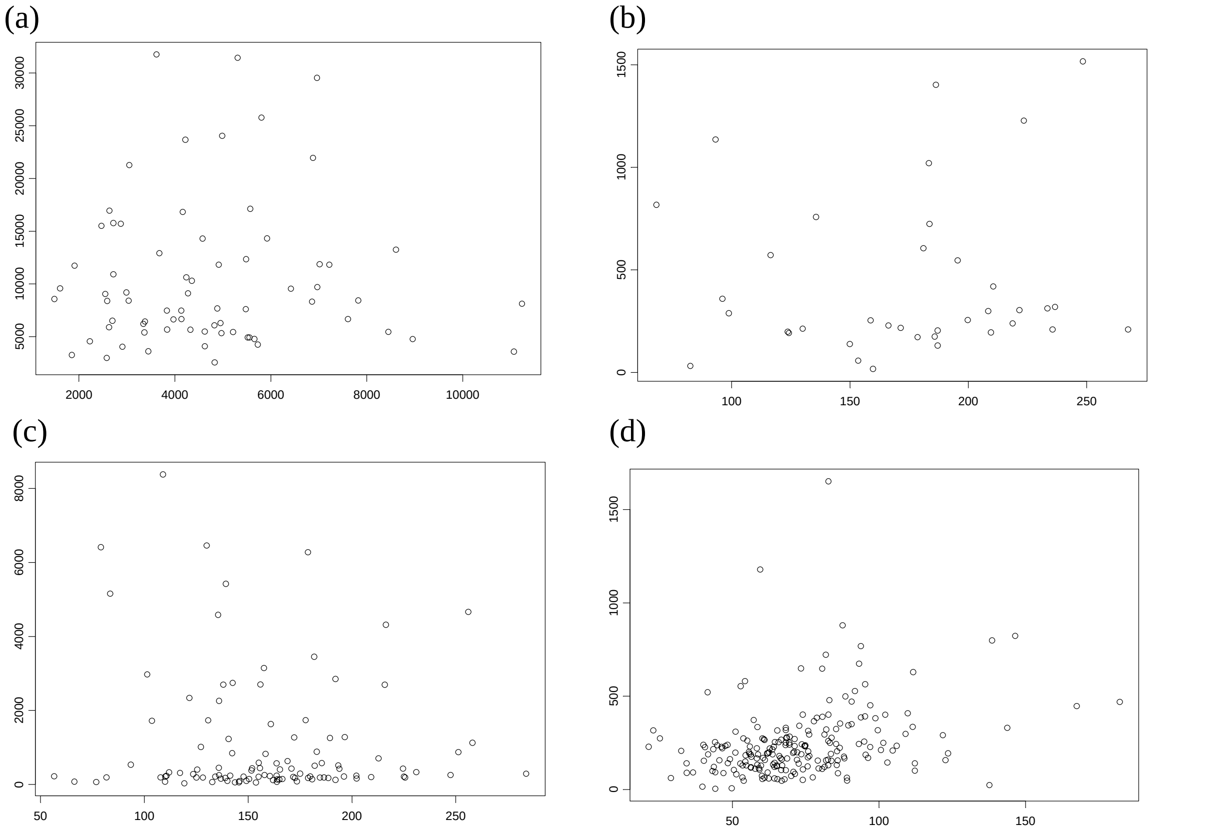


Figure 1 Comparison of layer moduli of (a) AC surface layer; (b) base layer; (c) subbase layer; and (d) subgrade obtained from laboratory testing (x axis, MPa) and backcalculation program (y axis, MPa).

Comparison of Laboratory Tested and Backcalculated Moduli of PCC Pavements

The modulus of each pavement layer backcalculated using the ERESBACK 2.2 program (*15*) was retrieved from the IMS Monitoring module. The laboratory tested layer moduli were compared with the backcalculated moduli so as to have a better understanding of their associated variability in this study. The variability of the relationship between the laboratory tested (or static) and backcalculated (or dynamic) moduli could not be ignored. Figure 2(a)-(c) depicts the average ratios are approximately 1.4, 1.5, and 1.5 for surface, subbase, and subgrade layers for dense liquid foundation, respectively (*12*). Note that very few laboratory tested modulus of subgrade reaction are available in the database. Likewise, Figure 2(d)-(f) depicts the average ratios are roughly 1.0, 1.1, and 3.0 for surface, subbase, and subgrade layers for elastic solid foundation, respectively. It is noted that the recommendation of dividing the backcalculated modulus of subgrade reaction (or k-value) by 2 as the static k-value by AASHTO (*16*) may be a reasonable choice, though more research study is still needed to reduce the variability.

(a) (b)

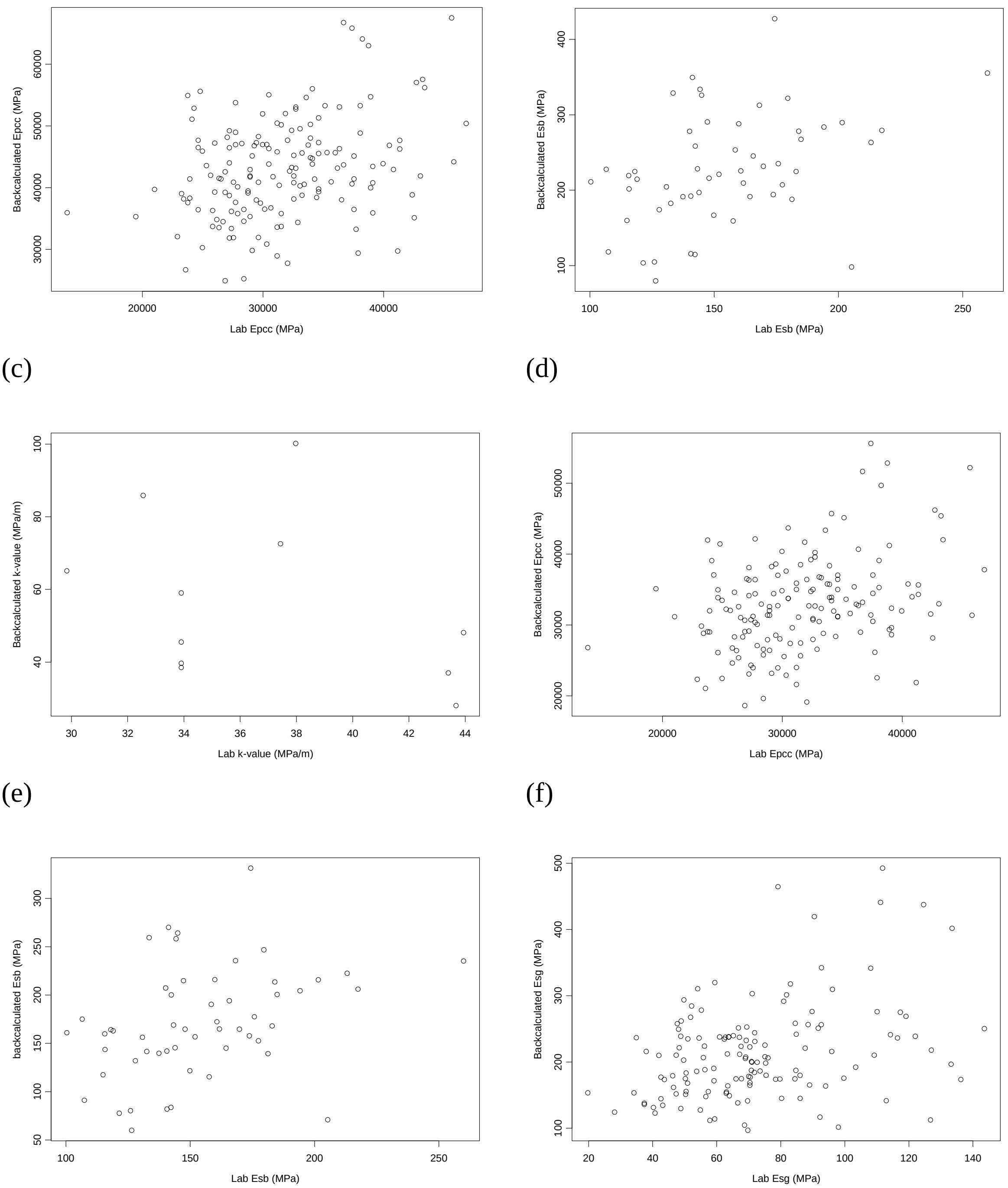


Figure 2 Comparison of laboratory tested and backcalculated layer moduli of (a) surface, (b) subbase, and (c)subgrade for dense liquid foundation; and (d), (e), (f) for elastic solid foundation, respectively.

Relationship between Elastic Modulus and Modulus of Subgrade Reaction

For practical concerns, a relationship between the elastic modulus and the modulus of subgrade reaction is often needed. According to the literature (*15*), the following empirical relationship was developed from the GPS and SPS data analysis:

$$\begin{aligned} &k = 0.296E_s \\ &\text{Statistics}: R^2 = 0.872,\ SEE = 9.37,\ N = 596 \end{aligned} \tag{1}$$

In which, *k* is the modulus of subgrade reaction (MPa/m), E_s is the subgrade elastic modulus (MPa), R^2 is the coefficient of determination, SEE is the standard error of estimates, and N is the number of observations. According the available GPS data, very good agreements have been achieved using the above relationship.

Nevertheless, Barenberg (*17*) has indicated the theoretical difference using elastic solid foundation or dense liquid foundation for having same maximum deflections in backcalculation analysis. Assuming a Poisson ratio of 0.5 for subgrade, a Poisson ratio of 0.15 for concrete slab, and the elastic modulus of the slab is 4 Mpsi (27.6 GPa), the following relationship was derived after some simplification process.

$$E_s^{4/3} = 283.7 * h * k \tag{2}$$

In which, *k* is the modulus of subgrade reaction (pci), E_s is the subgrade elastic modulus (psi), and h is the slab thickness (in). As shown in Figure 3(a), the effect of slab thickness has to be considered in such a relationship.

The aforementioned relationship was further verified by comparing the backcalculated subgrade elastic moduli with the backcalculated modulus of subgrade reaction from the LTPP database. Slab thickness did have significant effects on this relationship as shown in Figure 3(b). Consequently, the following relationship is developed using regression techniques. In which, *k* is the modulus of subgrade reaction (MPa/m), E_s is the subgrade elastic modulus (MPa), and h is the slab thickness (cm).

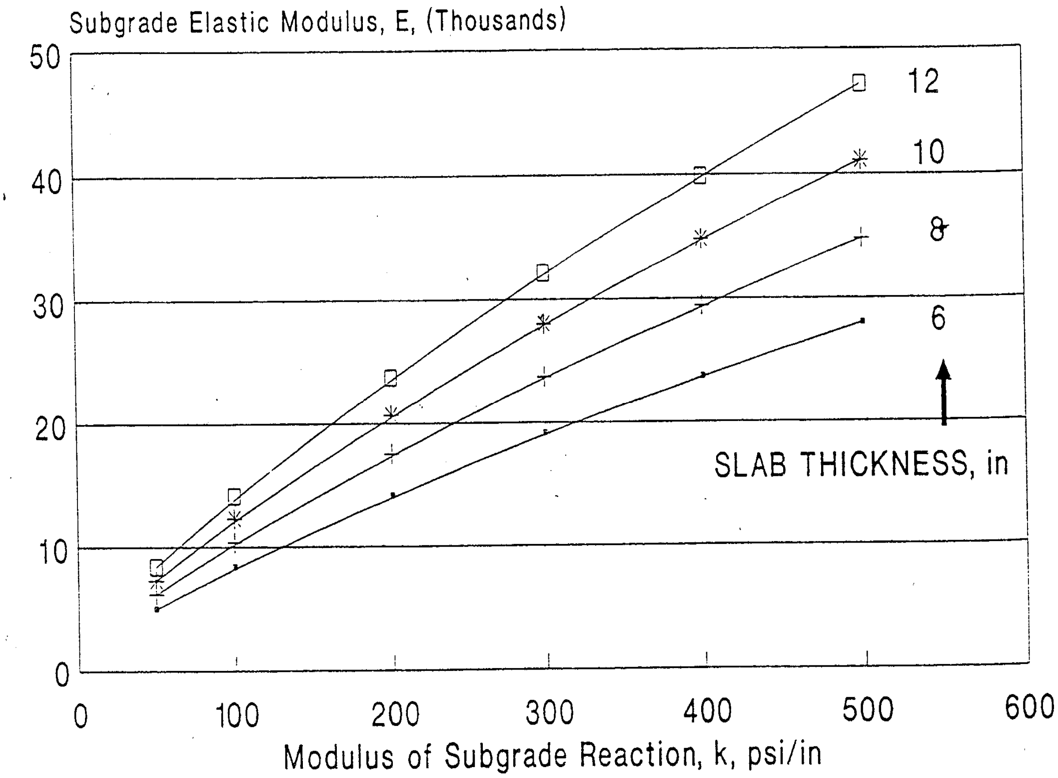
$$\begin{aligned} &E_s = 0.9015(k * h)^{3/4} \\ &\text{Statistics}: R^2 = 0.9524,\ SEE = 15.87,\ N = 138 \end{aligned} \tag{3}$$

TREATMNET AND APPLICATION OF NDT TESTING DATA

Nondestructive deflection testing (NDT) devices have been widely adopted to evaluate existing airport pavement conditions. The elastic moduli of pavement layers representing the material properties or the stiffness of a pavement structure are often backcalculated from various backcalculation procedures. Due to regular pavement maintenance and rehabilitation activities, an existing runway pavement often consists of many homogeneous sub-sections with various lengths and different material properties. Raw NDT data are often sub-divided into several structurally homogeneous sub-sections, followed by back-calculation analysis to obtain the surface and subgrade layer properties in particular.

To arrive at a single representative PCN value for the entire runway pavement, Chou, *et al.* (*18*) proposed a method by taking the length of each sub-section as a weighting factor for analysis of reliability analysis. This approach includes the following three-step procedure: (a) compute the mean values of layer moduli for each sub-section and obtain a mean PCN for each sub-section; (b) order the PCNs from the smallest to the largest and cumulate the corresponding lengths; and (c) choose the PCN value which corresponds to the accumulative 15% of runway length as the representative PCN for the entire runway. The subgrade class is also determined based on the same procedure.

(a)



(b)

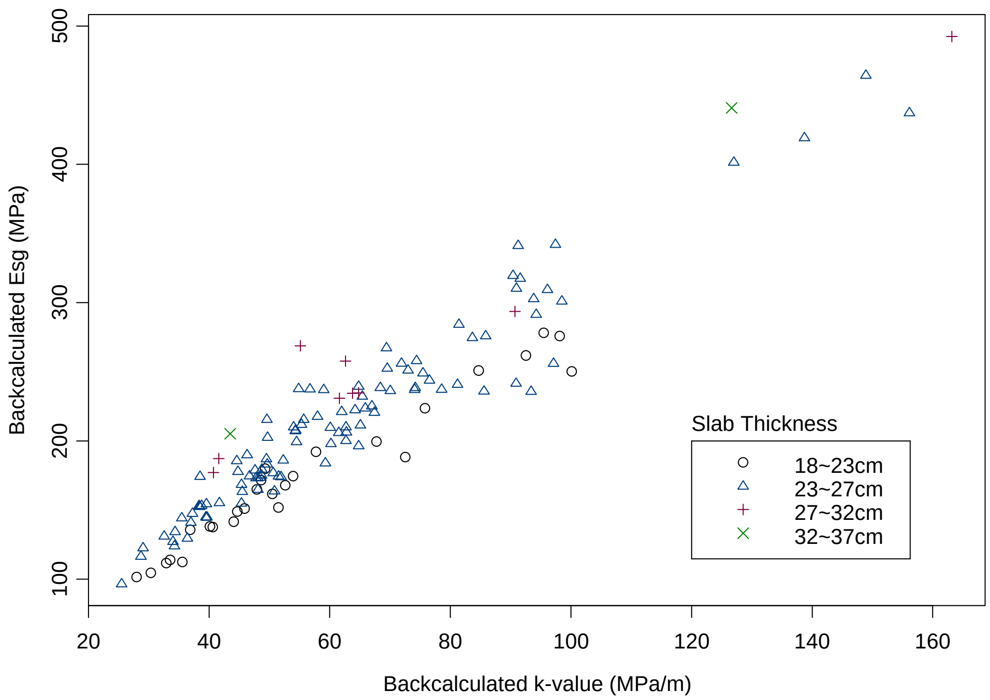


Figure 3 Comparison of elastic solid foundation versus dense liquid foundation based on: (a) theoretical comparison (*17*); and (b) backcalculated results.

The aforementioned approach is based on the recommendation that the mean value minus one standard deviation (or the so-called 85% confidence level) may be used for obtaining a more conservative evaluation or design input (*1, 3*). Nevertheless, it was found that this proposed procedure is not based on sound statistical principles especially when the probability distribution function of the population is almost always unknown and is not always normally distributed.

In engineering practice, a subset of the population or a random sample is often collected to represent the population characteristics of interest. Chebyshev provides the following relationship between the standard deviation and the dispersion of the probability distribution of any random variable. According to Chebyshev's Rule, for any random variable X with mean (μ) and variance (σ^2) the probability that a random variable differs from its mean by at least k standard deviations is less than or equal to $1/k^2$, in which $k > 1$ (*19-20*).

$$P(|X-\mu| \geq k\sigma) \leq \frac{1}{k^2} \tag{4}$$

For example, the probability that *any* random variable differs from its mean by at least two standard deviations is no greater than 1/4, however, this probability is less than 0.05 for a normal random variable. Since the population distribution is unknown and is not necessarily normal in the above approach, the probability that a given random variable differs from its mean by at least one standard deviation is no greater than 1 (using $k = 1$). In other words, the above approach will result in a PCN value in which 0% of the runway length has a value equal to or higher than it. The so-called 85% confidence level (or reliability) is an over-statement and is only true when the population is normal.

DEVELOPMENT OF A PROPOSED ROBUST APPROACH

Consequently, the concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing were proposed for establishing the evaluation or design inputs to derive a more consistent and repeatable PCN value. This proposed robust approach include the following steps: (a) determine the number of sample units to be surveyed; (b) determine a representative design input for the entire runway; (c) obtain a single PCN value as usual.

Determination of the Number of Sample Units to be Surveyed

Let X_1, X_2, ..., X_n be a random sample from a population of any distribution shape with unknown mean μ and known variance σ^2. If the sample size n is large (say $n \geqq 30$), using central limit theorem one can find that the sample mean $\overline{X}$ has an approximate normal distribution with mean μ and variance σ^2/n. Since the standard deviation σ is often unknown and can be estimated from sample standard deviation S, thus the unknown population mean μ can be estimated from the sample mean $\overline{X}$ and the estimation error (e) can be calculated using the following expression. In which, $Z_{\alpha/2}$ is the $100\alpha/2$ percentage point of the standard normal distribution; n is the number of samples; and α is the significance level or the type I error probability (*19-20*).

$$\overline{X}-\mu = Z_{\alpha/2}\frac{S}{\sqrt{n}} \leq e \tag{5}$$

Furthermore, since the sample size n is usually small in most engineering problems and the population may be finite, the estimation error (e) becomes as follows:

$$\overline{X} - \mu = t_{n-1,\alpha/2} \frac{S}{\sqrt{n}} \frac{\sqrt{N-n}}{\sqrt{N-1}} \le e \tag{6}$$

where $t_{n-1,\alpha/2}$ is the upper $100\alpha/2$ percentage point of the *t* distribution with *n-1* degrees of freedom, N is the total number of sample units in the population, and $\sqrt{N-n}/\sqrt{N-1}$ is the finite population correction factor. By rearranging the aforementioned equation and setting $t_{n-1,\alpha/2} = 2$ for 95% confidence level (2-tail), one can obtain the following equation in determining the number of sample units to be inspected:

$$n = \frac{NS^2}{(e^2/4)(N-1) + S^2} \tag{7}$$

Note that the above equation has been adopted by the American Society for Testing and Materials (ASTM) in pavement condition index (PCI) procedure (*21-22*) and is the result of simple statistical inferences.

Determination of a Representative Design Input and a PCN value for the Entire Runway

Since the material properties of an existing runway pavement may vary at different locations, subdividing the entire runway into many homogeneous sub-sections does not automatically solve the issue of random sampling and the need to have a reliable design input. According to the aforementioned statistical concept, a single representative design input for the entire runway pavement may be determined by the lower limit of 95% confidence level (1-tail) using the following expression:

$$\mu = \overline{X} - t_{n-1,\alpha} \frac{S}{\sqrt{n}} \tag{8}$$

Thus, it is recommended that after the raw NDT data has been successfully backcalculated, one can compute the grand mean ($\overline{X}$), sample standard deviation (*S*), sample size (*n*), and the lower 100α percentage point of the *t* distribution with *n-1* degrees of freedom ($t_{n-1,\alpha}$) (normally $\alpha = 0.05$) and then determine the representative design inputs including the layer moduli of the surface and subgrade using the above equation. Subsequently, a PCN value for the entire runway is obtained as usual.

A CASE STUDY FOR TECHNICAL EVALUATION OF RIGID PAVEMENTS

To illustrate the potential problems of the current technical evaluation method and the advantages of the proposed robust approach in determining PCN values for rigid pavements, the following case study was conducted.

Suppose a rigid airfield runway pavement with an effective subgrade k-value of 200 pci and a slab thickness of 14 inches. Assume the concrete has a modulus of rupture of 700 psi, an elastic modulus of 4,000,000 psi, and a Poisson's ratio of 0.15. The runway has a parallel taxiway, and additional fuel is generally obtained at the airport before departure. The pavement life is estimated to be 20 years from the original construction. The traffic data as given in Table 1 was obtained from the Appendix 2, Advisory Circular AC 150/5335-5A (*2*).

Table 1 Rigid Airfield Pavement Traffic Example (*2*)

Airplane	Operating Weight, lbs	Tire Pressure (psi)	ACN (R/C)	** P/C	Annual Departures	Coverages
B727-200	185,000	148	55	2.92	400	2,740
B737-300	130,000	195	38	3.79	6,000	31,662
A319-100	145,000	173	42	3.18	1,200	7,547
B747-400	820,000	200	68	3.46	3,000	17,341
B767-300ER	370,000	190	58	3.60	2,000	11,111
DC8-63	330,000	194	62	3.35	800	4,776
A300-B4	370,000	205	67	3.49	1,500	8,595
B777-200	600,000	215	77	4.25	300	1,412

** Rigid P/C determined at 95 percent of gross load on main gear

Since additional fuel is generally obtained at the airport, and there is a parallel taxiway, thus, passes to traffic cycles (P/TC) = 1; traffic cycles to coverages (TC/C) = pass to coverages (P/C); and coverages (C) = annual departures $*$ 20 years ÷ TC/C. The resulting coverages for each airplane are also listed in Table 1. The required thickness for each airplane at the operating weight and frequency is determined using the COMFAA program (*2, 23*). Based on the required thickness for each airplane, the critical airplane was determined as the B747-400. All departures of the other traffic were converted to the B747-400 equivalent and the total equivalent annual departures of the critical aircraft are 7,424. Since, P/TC = 1; P/C = 3.46; TC/C = 3.46; thus the anticipated total coverages of the critical aircraft = 7,424 $*$ 20 years ÷ 3.46 = 42,913.

By adjusting the gross airplane weight iteratively until the known pavement thickness (14 in.) is obtained, the maximum allowable gross weight of the critical aircraft (B747-400) is determined as 762,000 pounds. In which, the following additional parameters were assumed: percent weight on the main gear = 95 %, tire pressure = 200 psi, and tire contact area = 260.4 in^2. By switching the COMFAA program back to the ACN mode and entering in the allowable gross weight, an ACN of 61.3/R/C is obtained. The final recommended runway rating is PCN 61/R/C/W/T. Note that the tire pressure code for rigid pavement is normally set as W.

Nondestructive Deflection Testing (NDT) was often conducted to determine the overall structural capacity of an existing airport pavement (*1*). Suppose that a total of 57 elastic modulus values of the concrete slab were successfully backcalculated. Based on the current recommended procedures (*1, 18*), one could divide the entire runway into different sets of several structurally homogeneous sub-sections. For example, Figure 4 depicts different evaluation methods using grand mean, the averages of 5 subsections and 10 subsections, all separated data. Figure 5 depicts the cumulative frequency of different evaluation methods and the resulting representative Epcc values.

With random sampling and random variability in mind, the representative elastic moduli of the concrete slab (Epcc) are summarized in Table 2 using grand mean (Method I), 85% confidence of the averages of 5 subsections (Method III) and 10 subsections (Method IV), and 85% confidence of all separated data (Method V) according to the literature (*18*). In addition, Method II uses grand mean minus one standard deviation (or the so-called 85% confidence level) whereas Method VI uses the lower limit of the proposed 95% confidence level method (1-tail). In which, the grand mean $\overline{X}$ = 3,670,764 psi, sample standard deviation

S = 1,272,451 psi, sample size n = 57, $t_{n-1,\alpha} = 2$ for 95% confidence level (1-tail). The slab modulus of rupture (M_r) was estimated using the following equation:

$$M_r = 43.5 \times Epcc / 10^6 + 488.5 \tag{9}$$

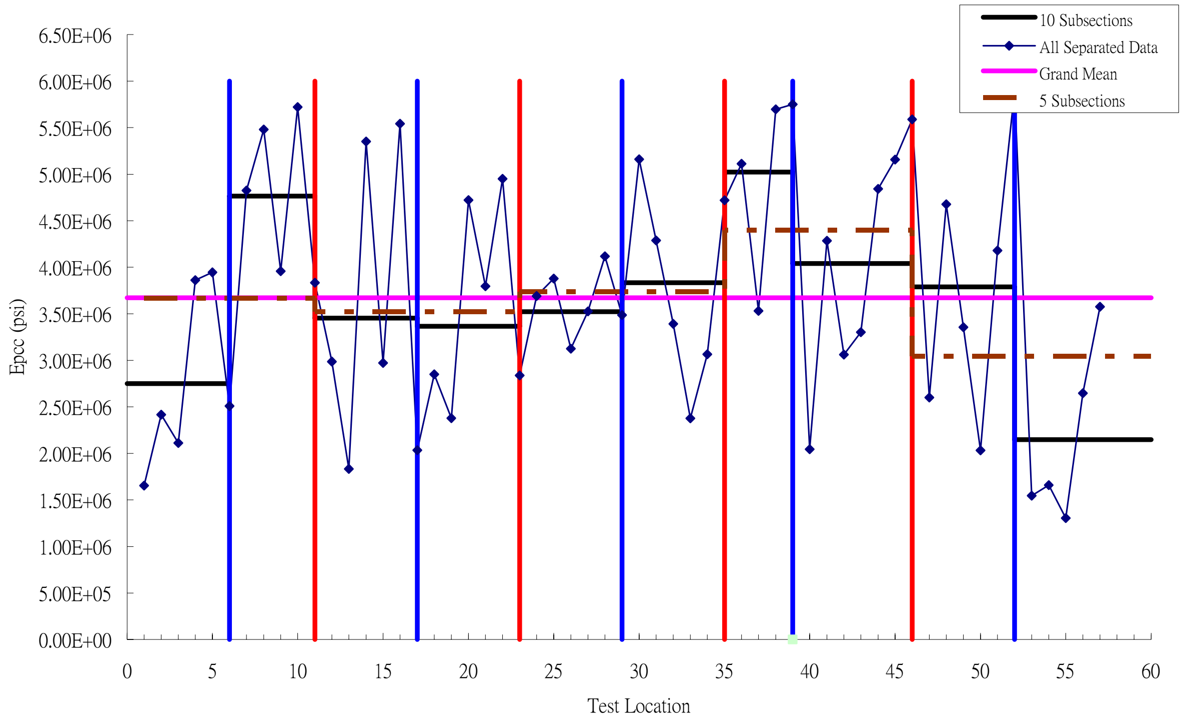


Figure 4 Variation of the backcalculated moduli of the slab.

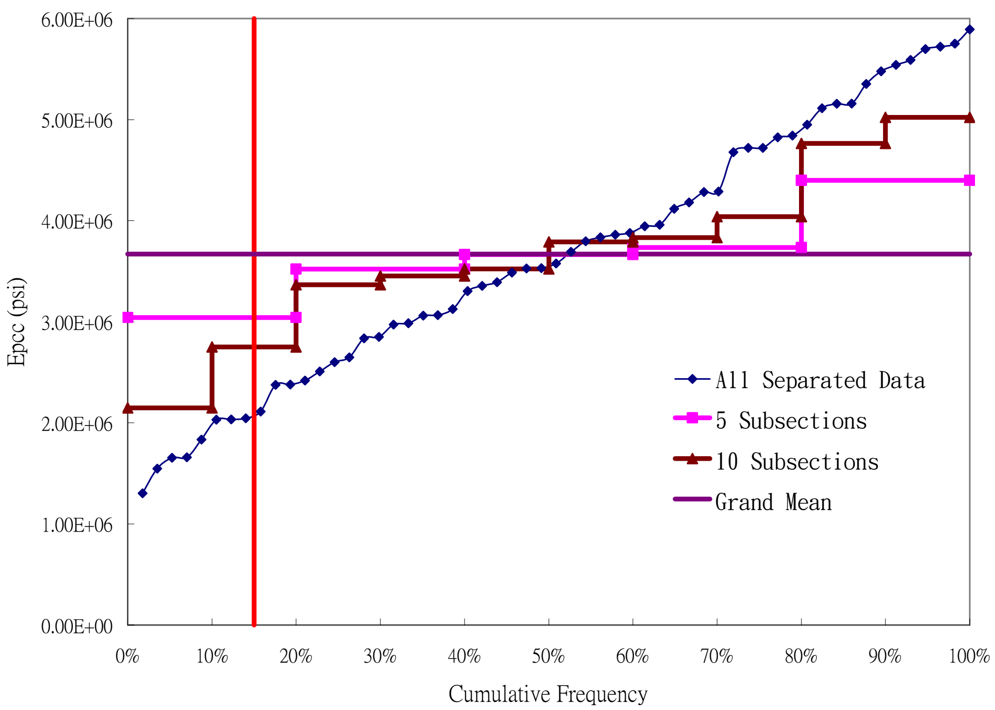


Figure 5 Cumulative frequency of different evaluation methods.

Likewise, the maximum allowable gross weight of the B747-400 aircraft (with 42,913 coverages) for each case is subsequently determined. As expected, the resulting runway PCN ratings range from PCN 47.8/R/C/W/T to 55/R/C/W/T as also shown in Table 2. Based on the ACNs in Table 1, it can be seen that several airplanes would be restricted in their operations on this runway if their respective ACNs are higher than the derived PCN of 48/R/C to 55/R/C. It is apparent that the pavement is inadequate to accommodate the existing traffic or the operating weights have to be restricted.

Knowing that the goodness of existing backcalculation results is still in question for many occasions as previously described, it is desirable to use a robust approach to arrive at a more reliable PCN value for the entire runway. Using the lower limit of the proposed 95% confidence level method (1-tail) results in a PCN rating of 53.3/R/C/W/T.

Table 2 Results of Using Different Evaluation Methods

Method No.	Different Evaluation Methods	Representative Epcc (psi)	Estimated Mr (psi)	Calculated Allowable Gross Weight (lbs)	PCN
I	Grand Mean	3.67×10^6	648.1	700,000	55.0/R/C/W/T
II	Grand Mean - 1 Std.Dev.	2.40×10^6	592.8	640,000	48.6/R/C/W/T
III	5 Subsections (85%)	3.04×10^6	620.7	671,000	51.9/R/C/W/T
IV	10 Subsections (85%)	2.75×10^6	608.1	656,000	50.3/R/C/W/T
V	All Separated Data (85%)	2.05×10^6	585.1	632,000	47.8/R/C/W/T
VI	95% Confidence	3.33×10^6	585.1	684,000	53.3/R/C/W/T

IMPLEMENTATION OF THE PROPOSED APPROACH

The proposed revisions to the existing ACN/PCN calculation procedure (based on the COMFAA program) will be implemented in the existing TKUAPAV airfield pavement design program (*24*) for future practical applications.

CONCLUDING REMARKS

Although it has been clearly recommended that the engineer should simultaneously consider the mean and standard deviation in the selection of an evaluation or design input value, many evaluation and design procedures currently only use the mean value in the analysis. According to the Advisory Circular's recommendation, the mean value minus one standard deviation (or the so-called 85% confidence level) may be used to obtain a more conservative evaluation or design input. Nevertheless, it was found that this proposed procedure is not based on sound statistical principles especially when the probability distribution function of the population is almost always unknown and is not necessarily normal. Consequently, the concepts of random sampling, central limit theorem, and confidence intervals for hypothesis testing were adopted. It was proposed that a single representative design input for the entire runway pavement be determined by the lower limit of 95% confidence level (1-tail) to derive a more consistent and repeatable PCN value. A case study was conducted to illustrate the potential problems of the existing ACN/PCN procedure and the benefits of the proposed revisions. The completion of this study will, hopefully, provide a sound basis for reporting the airfield pavement bearing strength. The proposed approach based on sound statistical principles could be similarly implemented in many engineering practices as well.

ACKNOWLEDGMENTS

This study was sponsored by National Science Council, Taiwan. The authors would like to acknowledge Ms. Chia-Huei Lin and Ms. Pei-Hwa Wu for their hard work in the goodness study of existing backcalculation results.

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