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Aircraft - Runway Interaction and an Insight into Evolving Civil Aviation Regulations

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This thesis is presented for the Degree of
Doctor of Philosophy
of
Curtin University

January 2013

ACKNOWLEDGEMENTS

This interesting topic was suggested by my principle supervisor Professor Hamid Nikraz, head of civil engineering at Curtin University. We had many useful discussions during the course of this research. The author acknowledges Professor Nikraz's able guidance. Completing this work would not have been possible without the steadfast dedication to research of Professor Nikraz. His passion for innovative engineering and the research process are evident in not only his own publications, but those of his previous students as well. I am greatly indebted to his help and encouragement.

Many thanks are also extended to my aviation industry colleagues, whose insightful advice and comments have helped in completing this academic journey. I also thank all staff of the School of Civil and Mechanical Engineering, especially Ms Liz Field providing administrative assistance that helped in successfully completing my study at Curtin University.

ABSTRACT

Runway is an essential element of any airport and it significantly influences the safety of an aircraft that uses it. A typical flight includes various phases, but landing is considered as the most crucial phase of the flight. An improper landing may results in serious implications for safety of the aircraft and its occupants, if the runway condition is compromised. An aircraft imposes a tremendous load on a runway pavement during landing phase that causes deflection of the pavement. Consequently, the runway design and performance requirements are largely affected by the potential deflection. A critical review of the relevant literature indicates that the study of aircraft-runway interaction has been a challenging problem for runway designers, airport operators, and researchers. As a result, the design, evaluation, and performance reporting of a runway pavement is still based on semi-empirical approaches. A review of international civil aviation regulatory framework also reveals that prescriptive and empirical procedures dominate the field practices. This study analyses an aircraft-runway interaction as a structure-foundation interaction problem using basic principles of engineering mechanics. It is based on idealisation of various characteristics of a runway by mechanical elements, such as Winkler springs, stretched elastic membranes, shear beam, and dashpot concepts while considering the forces applied by an aircraft on a runway pavement during landing. As a result, an analytically derived deflection model has been developed to examine the runway deflection profiles. Besides, a parametric study has also been carried out to examine the relationship between deflection, impact pressure, and vertical velocity of an aircraft during landing. Consequently, the developed analytical expression to estimate runway deflection is expected to be useful in designing, technical evaluation, and strength reporting of a runway pavement. Additionally, considering aviation operations as risky and safety sensitive activities, the impact of changing civil aviation regulatory system from prescriptive regime to an outcome based legislative framework on aviation safety is also investigated in this research.

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NOTATION

Basic SI units are given in parentheses.

a	Radius of the equivalent circular area (m)
A	Equivalent area of contact between the landing gear wheels and the runway (m^2).
g	Acceleration due to gravity (m/s^2)
h	Equivalent free fall height (m)
k	Subgrade coefficient
k_s	Modulus of subgrade reaction of the pavement system (N/m^3)
m	Mass of the aircraft associated with a main landing gear leg load (kg)
M	All-up mass (kg)
p	Equivalent static contact pressure exerted by landing gear wheels on the runway pavement surface (N/m^2)
p^*	Non-dimensional equivalent static contact pressure exerted by landing gear wheels on the runway pavement surface (= $p/k_s a$) (dimensionless)
P	Landing gear leg load (= mg)
v	Total velocity of the aircraft at runway touchdown point during landing (m/s)
v_h	Horizontal velocity of the aircraft at runway touchdown point during landing (m/s)
v_v	Vertical velocity of the aircraft at runway touchdown point during landing (m/s)
v_v^*	Non-dimensional vertical velocity of the aircraft at runway touchdown point during landing (= v_v/ga) (dimensionless)
w	Dynamic deflection of the runway pavement (m)
w^*	Non-dimensional dynamic deflection (= w/a) (dimensionless)
w_s	Static deflection of the runway pavement (m)

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CHAPTER 1

INTRODUCTION

1.1 General

Air transportation is an integral part of our lives. Thousands of flights take place around the world every day, including commercial, military, and general aviation. Assuring aviation safety has become one of the foremost engineering challenges of the 21st Century in present era of increasing air traffic. Various national organizations are responsible for aerodrome management tasks together through the International Civil Aviation Organisation (ICAO)[1] to develop global aerodrome regulations and standards.

Fig.1.1. A view of an aircraft landing

[1] International Civil Aviation Organisation (ICAO) was formed in 1944 as a specialized agency of the United Nations to promote the safe and orderly development of civil aviation. The ICAO develops international civil aviation standards, practices, and procedures for its 189 member countries known as the Contracting States.

A runway plays a vital role in aviation safety by providing safe and efficient landing and takeoff of an aircraft (Fig. 1.1). Therefore, it is imperative that while designing the runways a serious consideration should be given to operational and physical characteristics of the aircraft, which is expected to use the runway. Generally, the runways for takeoff and landing of aircraft suffer from sinking due to ground settling, which is not a sought after situation. It is also desirable that the surface of the runways remain significantly flat throughout its length. However, it is noticed that the runways loose their flatness due to static and dynamic loads exerted by operations of the aircraft. This surface depression in the aircraft wheel path on the runway is known as rut or deflection. Rutting stems from a permanent deformation in any of the pavement layers or subgrade normally caused by movement of the materials due to aircraft landing loads. It is governed by amount of the loads, characteristics of runway materials, and strength and consolidation behaviour of subgrade soil. Besides, water accumulation in the sunken areas during rainy season further increases the depth of ruts.

Runway pavement is one of the most important aspects of an airport facilities related to the aircraft operation. Generally, the runway pavements used in aerodromes are classified as flexible pavements and rigid pavements. A flexible pavement is made of an asphalt concrete surface layer over a granular base layer, a subbase layer, and a subgrade. The rigid pavements consist of a cement concrete surface layer over a chemically treated base layer, a subbase layer, and a subgrade (Whiteley, 2006). Certain military operations also use the unsurfaced runways, occasionally. These runways are not provided with surface layers and they are normally built in remote areas such as, war zones or natural disaster locations (Tingle and Grogan, 1999). However, it is always a demanding task to design unsurfaced runways for the heavy aircraft categories considering the substantial surface rutting as a result of tremendous landing loads and soil subgrade deformation.

Airport operations are heavily dependent on runway pavement infrastructure and its ability to withstand aircraft takeoff, landing, and taxi loads. Since rutting is a primary failure criterion when determining functional capabilities of an airfield, the concept of total rutting plays a significant role in development of a performance prediction model. An increasing demand for heavier loads and higher speeds has necessitated more realistic modelling of the interaction of the aircraft and runway pavements.

Primarily, the methods used for reporting load-bearing capacity of an airfield pavement have put emphasis on development of a procedure for measuring and classifying the load ratings of different aircraft. The allowable bearing pressure on a pavement known as pavement strength, is usually defined as the load rating of the heaviest aircraft that can use the pavement on unrestricted basis without exceeding the permissible rutting (Loizos and Charonitis, 2001). Criteria recommended by the ICAO for pavement strength considers the aircraft mass and allowable tyre pressure (International Civil Aviation Organisation, 2004). The ICAO further recommends that the strength of a runway pavement shall be reported using aircraft classification number (ACN) and pavement classification number (PCN) method by indicating information about the pavement type for ACN-PCN determination, subgrade strength category, and maximum allowable tire pressure category. ACN is a number that expresses the relative effect of an aircraft on the pavement for a specified standard subgrade strength. Similarly, the PCN is to express the strength of a pavement for unrestricted operations. A pavement is classified as flexible or rigid for a given standard aircraft gear loading to determine the ACN. However, the ACN-PCN method is meant only for the publication of the pavement strength data in the aeronautical information publications (AIPs), and it is not intended for design of the pavements (International Civil Aviation Organisation, 1983).

Though some prior analyses of aircraft-runway interaction recognise the importance of runway rutting in providing safe designs of the runways, much attention has not been given to present a simplified runway deflection model for routine design practices. The literature review presented in chapter 2 identifies that there is not much research work available on the aircraft-runway interaction area that could address the evaluation of runway deflection or rutting, analytically. Consequently, the runway designs are still based on semi-empirical approaches (Thom, 2008; Yoder and Witczak, 1975). In view of the importance of the runway rutting, this project makes an attempt to develop a runway deflection model in accordance with the principles of structure-foundation interaction. Therefore, this study is aimed at developing such a model for determination of deflection considering the aircraft-runway interaction as a structure-foundation interaction problem. The runway pavement is idealised as a mechanical model using Winkler springs model for the purpose of this project. Furthermore, this research suggests that the proposed analytical deflection model can be used for runway pavement evaluation. Additionally, considering aviation as a highly regulated industry, this project also investigates the runway pavement regulatory standards, practices, and evolution of civil aviation regulatory regime.

1.2 Objectives and scope of thesis

Most critical loads on a runway occur due to gross weight of the aircraft and its high rate of descend (ROD) at touchdown point on a runway pavement during landing. A significant function of the landing gears and runway is to absorb vertical energy of the aircraft at touchdown during landing phase. An aircraft of a given weight and ROD at touchdown has a certain kinetic energy that must be dissipated by the landing gears and the runway. Therefore, a safe landing is highly influenced by the runway characteristics, especially the strength and deflection behaviour of pavement layers. Since, rutting (Fig.1.2) is a primary failure criterion when determining the functional capabilities of an airfield; the concept of total rutting plays a significant role in the study of aircraft-runway interaction for development of a deflection prediction model. The primary objectives of the research work reported in this thesis were to study the aircraft landing forces that causes deflection in the runway pavement, idealise the behaviour of runway layers, develop a simplified runway deflection model and examine deflection profiles, and suggest the use of deflection model for a runway pavement evaluation and strength reporting.

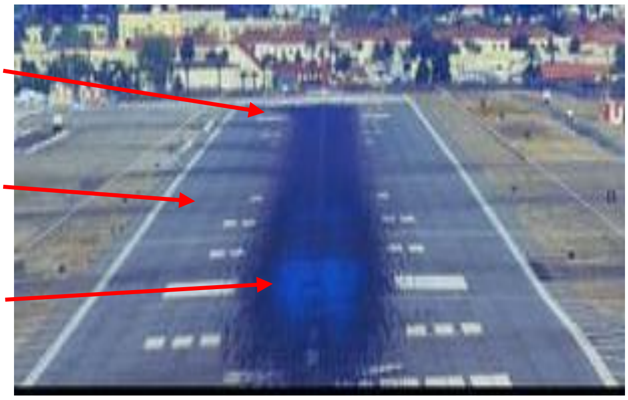

Fig.1.2. Rutting at a runway touchdown zone (adapted from Fotosearch, 2010)

The earlier studies on the pavement behaviour indicate a relationship between load and the deflection in empirical forms. This implies that the deflection is an indicator of load supporting capacity of a pavement. As a result, this can also be established that the pavement deflection determined for a particular applied load could be adjusted proportionately to predict the deflection caused by other loads. The aircraft weight is transmitted to the runway pavement through its undercarriage during landing. The factors such as, number of wheels, their spacing and size, and the tyre pressure determine the distribution of the aircraft load to pavement. The effects of distributed loads from adjacent wheels of dual, dual-tandem, and adjacent legs of the complex aircraft undercarriages overlap at the subgrade and intermediate levels. In these cases, the effective forces combined from two or more wheels exert on the pavement structure. Falling weights on the pavement generates dynamic stresses that diminish away from the point of impact. Attenuation of the dynamic stress from the point of impact has been studied by various researchers and the studies have concluded that elastic theory gave reasonable predictions of stress attenuation when compared with measured values in granular soils (Mayne and Jones, 1983). Since the distribution of loads by a pavement structure is over a much narrower area on a high strength soil subgrade than on a low strength soil subgrade, the combining effects of adjacent wheels is much less for the pavements on a high strength subgrade than a low strength subgrade. According to Boeing Commercial Airplanes (2002), the subgrade conforming to California Bearing Ratio (CBR) 15 and subgrade modulus (*k*)

150 MN/m^3 is classified as high strength subgrade. Likewise, the subgrade with CBR 6 and value of k as 40 MN/m^3 is known as low strength subgrade.

For a rational analysis and design of runway, all the above mentioned aspects must be considered while estimating the landing load. Consequently, the key issues and challenges facing runway bearing strength and deflection have been identified in this study by a wide review of research resources. This research has been developed using mechanical modeling to derive an analytical expression to estimate deflection and study deflection profiles. Furthermore, a detailed parametric study has also been carried out to investigate the effects of various parameters governing the runway deflection model. These results may be useful in design, evaluations, and load bearing strength of a runway pavement. The underlying philosophy is that, if the model could accurately predict the deflection analytically, then it can be used in field applications. Subsequently, the civil aviation regulatory issues have also been investigated in this study. Various characteristics and landing profiles of the modern transport aircraft are included in this thesis to provide an understanding about the details and operational parameters of the aircraft during landing.

1.3 Thesis Outline

Chapter 1 provides an overview of this research project and it introduces the statement of research problem. A brief background for the research, the scope, and the research objectives are also mentioned in this chapter.

Background information and literature review on runway pavement, regulatory issues, and foundation models are presented in chapter 2. Major factors influencing runway pavement life in view of deflection are reviewed. Observations of various researchers from runway pavement tests and studies are described in context of deflection and technical evaluation of the pavement. This chapter also reviews relevant civil aviation regulatory framework covering aviation operations and airports.

An analytical expression to estimate runway pavement deflection caused by an aircraft landing load is derived in chapter 3. A simple deflection model based on mathematical analysis using mechanical modelling has been developed. The runway pavement is idealised with Winkler spring model to develop the expression.

In chapter 4, a parametric study has been carried out using the deflection model to analyse a relationship between deflection, impact pressure, and vertical velocity of an aircraft at touchdown point on a runway surface during landing phase. Likewise, some charts are also developed to study the deflection profiles based on the model. An illustrative example is also used as a part of the parametric study.

Chapter 5 deals with runway pavement evaluation methods and practices. Results of the developed deflection model suggest that a runway pavement evaluation can be carried out using the analytically developed expression instead of the current semi-empirical practices. In view of justifying the use of the deflection model for pavement evaluation purpose, the aircraft landing forces and standards are also discussed. Moreover, some current runway pavement evaluation practices of major countries and international recommendations of the ICAO on this issue are deliberated in this chapter.

Influences of recent fundamental shifts of civil aviation safety regulatory framework related to airport and aircraft operations are discussed in chapter 6. Primarily, it focuses on associated effects of prescriptive and performance based civil aviation safety regulations related to airports and aircraft on aviation safety. Impact and potential risks of commercial pressure on aviation safety as a consequence of outsourcing and privatisation of safety sensitive activities related to airfield and aircraft are also investigated in this chapter.

Extending the discussion on evolution of civil aviation safety regulations, chapter 7 explores the role and necessity to expand the competency standards of aeronautical personnel involve in tasks associated with airworthiness of an aircraft and aviation safety. It investigates the possibilities of bringing various categories of aeronautical engineering personnel under state licensing and registration system in view of enhancing the aviation safety.

Chapter 8 examines the prospective advanced applications of the deflection model in the runway pavement load bearing strength reporting practices of airport operators under civil aviation safety regulations. An argument to use potential deflection for the bearing strength reporting of a runway pavement is presented in this chapter.

Chapter 9 summarises the main research findings, investigation outcomes, and conclusions of this research. It also includes some recommendations for future research directions based on findings of this project.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Aircraft-runway interaction analysis has been a complex issue in field applications and the research literature is scarce in this area. This chapter provides review of methods of analysis based on mathematical and experimental studies on aircraft-runway interaction as reported in the literature. This literature review also summarises the concepts of the available foundation models in the area of foundation-structure interaction that may be used for the study of the aircraft-runway interaction. The pavement responses from test studies and observations by other researchers are also included in this chapter. In view of strict regulatory nature of the aviation industry, a review of civil aviation regulatory framework has also been presented in this chapter.

2.2 Aircraft-runway interaction analysis

Chou (1983) suggested a stress factor for assessing the subgrade rutting potential of flexible pavements for aircraft load. It has been ascertained that the rutting of the pavement is directly proportional to the computed stress factor in the subgrade. Therefore, if several different types of pavements are designed for a given subgrade soil and for a given aircraft load at the same performance level, the pavement with the largest stress factor will most probably have the greatest potential of subgrade rutting. Similarly, for a given subgrade soil, if two pavements are designed for two different aircraft loads at the same performance level, the heavier aircraft load will have a greater stress factor in the subgrade.

Vajarasathira, Yener and Ting (1984) presented a dynamic analysis of stresses and deflections induced by moving vehicles and by linear temperature variations in airport pavements, which lie on visco-elastic foundations. This analysis had used a direct numerical method that was derived from the structural impedance approach and the algorithm was extended to a simple model developed to sufficiently describe the behaviour of airport pavements. An ideal beam supported by springs and dampers simulating subgrade was chosen as a tool. The beam is subjected to temperature differentials that cause uplift and warping. Based on this model, several numerical examples were solved in order to identify the factors, which influence the pattern and magnitude of deflections and stresses in the pavement.

Tingle and Grogan (1999) evaluated the functional failure of unsurfaced airfields supporting operations of C-17 aircraft. The report described that the airfields failed prematurely despite displaying sufficient structural strength in terms of California Bearing ratio (CBR). The rutting observed in the field was actually a measure of the displaced loose material generated by the shearing action of a braking aircraft. Furthermore, the researchers found that the rutting noticed in the field was not the same as the traditional rutting (plastic deformation) documented in the literature. The areas of the airfield exhibiting the greatest rutting were the braking zones and the turnaround sections. The developed prediction model can be used to estimate the number of aircraft operations required to produce a specific loose till depth for a particular site.

Using field test data, Fang (1999) plotted the variation of pavement deflections and strains with time as the aircraft wheels passed by. It was established that the deflection versus time curve had one peak for the inner loading case, and the peaks for the edge loading case were found to be directly proportional to the number of axles on the main landing gear. The peaks were located for the inner loading case and the transverse edge loading case that were at the geometric centre of the semi-gear and between any pair of dual wheels respectively. Similarly, the peak for the transverse loading edge case depends upon the load transfer characteristics of the joint. The analysis demonstrates that the maximum deflections occur between the dual wheels, whereas the maximum strains happen beneath one of the wheels. Likewise, the plots indicate the clear reversals in the longitudinal strain-versus-time curves. Correspondingly, the computation further shows that the load transfer efficiency for dummy joints is direction dependent, and that the load transfer efficiency decreases significantly during the first year the pavement is in service.

Lee, Daniel and Kim (2000) evaluated the fatigue and rutting characteristics of various modified and unmodified mixtures using uni-axial tension and tri-axial compression cyclic tests, respectively. The researchers examined the fatigue and healing behaviour of the mixes by using the viscoelastic continuum damage (VCD) model and investigated the effects of the material properties on the fatigue life and micro damage healing potential of asphalt concrete. The structural analysis based on the multi-layered elastic theory to compare the fatigue lives of the various mixes in pavement systems demonstrated that the modified mixtures have a better rutting resistance as expected. However, the ranking among the modified mixtures changes depending on the confining pressure. Furthermore, it was also found that the rutting performance of the mixtures have a linear relationship between the vertical permanent deformation and number of applied loads in a logarithmic scale. Similarly, the vertical permanent deformation increases with an increase in shear stress invariant.

Ramsamooj (2000) denotes a rational method of design for the thickness of concrete runways and taxiways against the fatigue mode of distress based on multilayered elastic theory combined with fracture mechanics (EFM). The material properties used for the design are the tensile strength, the fracture toughness, the Young's modulus, Poisson's ratio, and the lower threshold stress intensity factor corresponding to the endurance limit. The stresses in the jointed pavements produced by the gear loads and thermal curl stress were analysed. Alike the effect of the combined thermal and aircraft gear load stresses including the lateral wander of the gear loads is handled rationally. It was found that the effect of the thermal curl stress merely increases the minimum level of stress resulting from the aircraft and thermal loading. This type of stress is less severe than an increase in the aircraft gear load stress of the same amount. Stresses and fracture mechanics were used to compute the fatigue life for several concrete thicknesses and for 500,000 applications of Boeing 777 loading. Additionally, a computer program was utilised to consider the lateral distribution of the traffic that may consist of a number of dual axle load in single or tandem or tridem configuration. As a result, it was stated that the design was developed for Boeing 777 only, but a mixture of aircraft types would not pose any difficulty. The program provides output in the form of design stresses, deflection, and the fatigue life.

Gopalakrishnan (2004) compared subgrade moduli back-calculated HWD test data with the laboratory test results. The post-traffic subgrade characterization test results from subgrade trench sections were evaluated and compared with the pre-traffic test pit data. The evaluation of the correlations amongst subgrade soil properties was carried out by using the combined data. The regression analyses revealed that the subgrade resilient modulus is significantly related to the unconfined compressive strength. Therefore, it was suggested that their results could be used in the mechanistic-based analysis and design of airport flexible pavements for the use of the NGA. The subgrade resilient modulus (MR) is a required input for a priori mechanistic-based analysis and design of flexible pavements. This was also noted that the several previous studies had investigated the relationship between laboratory-based MR and the non destructive testing (NDT) based back-calculated MR.

The study of material properties such as, field density, maximum theoretical density, asphalt content, and aggregate gradation of airfield pavements was carried out by Shoenberger and DeMoss (2005). The recovered asphalt cement was also evaluated for penetration, viscosity, and the specific gravity. The results show that the majority of distresses found in the recycled asphalt concrete (RAC) pavements, as with virgin mixtures, were from environmental or climatic causes with very few load related distresses even in the parking and taxiway areas. Therefore, the use of RAC can be an economical solution while being beneficial to our environmentally conscious society.

Gopalakrishnan and Thompson (2006) characterized the rutting behaviour of flexible test pavements subjected to multiple-wheel heavy aircraft gear loading at the National Airport Pavement Test Facility (NAPTF). Two series of traffic tests were conducted. During the first series, a Boeing 777 (B777) aircraft gear and a Boeing 747 (B747) gear were trafficked on two low-strength subgrade and two medium-strength subgrade flexible test sections until the test sections were deemed failed. The second series of traffic tests involved repeated loading of six-wheel aircraft gear (the same as B777 gear) and four-wheel gear on low-strength subgrade test sections with variable granular subbase thicknesses. The results established that the mean rut depths (RD) accumulated under B777 loading and B747 loading were similar. For a similar number of load repetitions, low-strength subgrade test sections with reduced subbase thicknesses yielded larger rut depth.

Gopalakrishnan (2006) presented the results from airport traffic load testing using B777 gear and B747 gear on a low-strength subgrade flexible pavement section with a substantially thick unbound granular subbase layer. Data from in-situ instrumentation and heavy weight deflectometer (HWD) testing were analysed at different stages of trafficking to evaluate the pavement structural deterioration imposed by the tests gears. At the end of traffic testing failure mechanism of pavement structures were also studied. The results showed that the maximum HWD deflections, the back-calculated moduli, and the mean rut depths were similar for both test gears throughout the traffic testing.

Sawant (2009) derived a solution algorithm based on the finite-element method to analyse rigid pavements under moving aircraft loads. The concrete pavement was made distinctive by thick plate elements that account for the transverse shear deformation and bending. The underlying soil medium was also modelled by elastic spring and dashpot systems. Similarly, the dynamic interaction between aircraft and pavement was modelled by a spring-dashpot unit. As a result, it was established that the maximum deflection decreased with increasing slab thickness, the time period of vibration increased with slab thickness, the maximum deflection decreased with increasing soil modulus and the velocity of moving load significantly influenced the pavement responses. Additionally, two clear peaks in the maximum deflection-velocity response curve indicated that the maximum deflections at the time of the first peak were higher than those of the second peak for lower soil modulus, whereas maximum deflections at the second peak were higher than the first peak for higher soil modulus.

Safwat et al. (2011) had evaluated an analytical approach for predicting rutting in a pavement and they found that under a moving wheel load, the pavement material moves vertically and horizontally. Therefore, it is important to consider the effects of lateral wandering of the traffic when calculating rutting under wheel load. The lateral movement of the material is induced by repeated shear stresses and the initial deformation zone is primarily caused by an increase in density from repeated traffic loading. However the researchers had established that the lateral wandering of traffic results in significantly less rut depth as compared with that if the wheel passages loaded only the rut centre. The predictive model was based on a number of passages of wheel loads, the pavement structure and the material properties at various temperatures.

2.2 Review of foundation models

The real foundation soils are complex in their load-carrying capacity and load-settlement behaviour. Therefore, the early researchers had developed the various elastic subgrade models of foundation soil behaviour. These subgrade models are known as mechanical models and they use the mechanical elements, such as springs, membrane, shear layer, and dashpot (Selvadurai, 1979). Though the subgrade models do not possess the ability to duplicate complete soil behaviour, it is expected that they will be useful in predicting the soil behaviour along-with the soil-structure interface in acceptable agreement with observed behaviour. Kerr (1964, 1965), Selvadurai (1979), Horvath (1989), Winkler (1867), Hetenyi (1946), Pasternak (1954), and Rhines (1969) presented excellent surveys of the subgrade models for unreinforced soils. These models were developed incorporating various aspects of the soil behaviour to represent its load-settlement response as accurately as possible.

2.2.1 Winkler model

Idealizing the behaviour of the foundation soils by mechanical models for dealing with the soil-structure interaction problems is a common practice. The earliest and simplest model, proposed by Winkler (1867) is a one-parameter model consisting of closely spaced, independent linear springs (Fig. 2.1). This model assumes that the deflection, w, of the foundation soil at any point on the surface is directly proportional to the stress, q, applied at that point and independent of stresses applied to other locations, that is,

$$q(x) = k_s \, w(x) \tag{2.1}$$

for two-dimensional problems, where k_s is termed as the modulus of subgrade reaction. An important feature of the Winkler subgrade model is that the displacement occurs immediately under the loaded area and outside this area the displacements are zero. Additionally, the displacements of a loaded region for this model are constant whether the foundation soil is subjected to an infinitely rigid load or a uniform flexible load. Eq. (2.1) is usually the response function for the Winkler model. Selvadurai (1979) has reported that the Winkler model represents a very accurate idealization of the actual operating conditions in many engineering problems, quite apart from foundation soil - structure interaction. Idealizing the ground by Winkler springs is frequently used in the design of highway and airfield pavements for representing the behaviour of soil subgrades (Ashford and Wright 1992; Mallick and El-Korchi 2009).

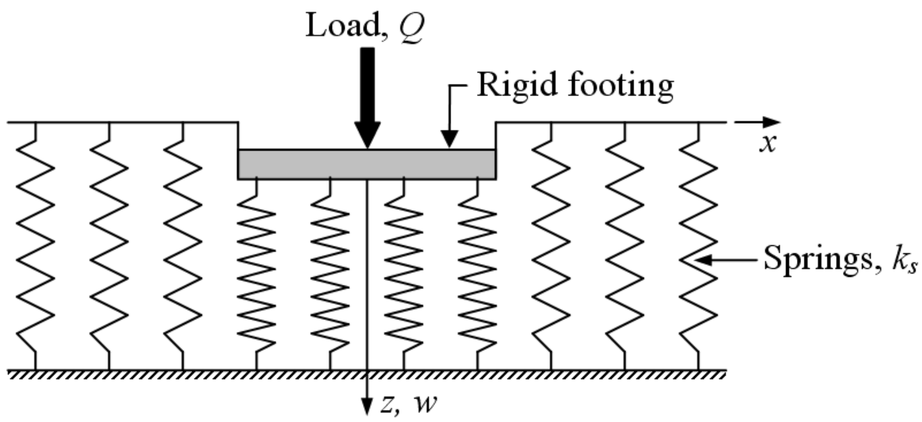

Fig.2.1. Winkler subgrade model (Winkler, 1867)

2.2.2 Filonenko-Borodich model

The model proposed by Filonenko-Borodich (1940) achieves continuity between the individual springs in the Winkler model through a thin smooth elastic membrane under a constant tension in all horizontal directions. In case of the three dimensional problems; for example a rectangular of circular foundations, the response function for this model is given by:

$$q(x,y) = k_s w(x,y) - T\Delta^2 w(x,y) \tag{2.2}$$

where, q is applied vertical surface pressure, T is constant membrane tension, and $\Delta^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$. In case of two dimensional problems, for example, a strip foundation, Eq. (2.2) reduces to:

$$q(x) = k_s w(x) - T \frac{d^2 w(x)}{dx^2} \qquad (2.3)$$

2.2.3 Hetenyi Model

In addition to extensive work with Winkler model, Hetenyi (1946) proposed a model, which assumes that the interaction between the independent spring elements is accomplished by incorporating a structural member, for example, an elastic beam in one dimensional bending problems and an elastic plate in two dimensional bending problems that deforms in bending only. For three dimensional problems, the response function for this model is given by:

$$q(x, y) = k_s w(x, y) - D\Delta^4 w(x, y) \qquad (2.4)$$

where, D [$=E_p h^3/(12(1 - \nu_p^2))$] is the flexural rigidity of the plate, E_p is the Young's modulus of the plate, ν_p is the Poisson's ratio of the material of the plate, h is the thickness of the plate, and $\Delta^4 = \Delta^2\Delta^2 = \frac{\partial^4}{\partial x^4} + 2\frac{\partial^4}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4}$. For two dimensional problems, the Eq. (2.4) reduces to:

$$q(x) = k_s w(x) - D \frac{d^4 w(x)}{dx^4} \qquad (2.5)$$

where D (=EI) is the flexural rigidity of the beam, I is the moment of inertia of the beam cross-section.

2.2.4 Pasternak model

The model proposed by Pasternak (1954) assumes the existence of shear forces between the springs of the Winkler model. These forces produce a coupling effect as a result. Originally no mechanism was postulated that could produce these forces. Kerr (1964) suggested a model that could produce these shear interaction would consist of an incompressible plate or layer that deforms in transverse shear only. This implies that there is no bending effect on top of Winkler model.

$$q(x,y) = k_s w(x,y) - G_p H \nabla^2 w(x,y) \tag{2.6}$$

where G_p is the shear modulus and H is the thickness of the shear layer. It can be observed that the response function for the Pasternak model given by Eq. (2.6) is identical with the response function for the Filoneko-Borodich model given by Eq. (2.2), if T is replaced by $G_p H$. Thus the surface deflection profiles for this model are very similar to those obtained for the Filonenko Borodich model. Again, for the two-dimensional problems, the Eq. (2.6) reduces to:

$$q(x) = k_s w(x) - G_p H \frac{d^2 w(x)}{dx} \tag{2.7}$$

with the models considered so far, the Winkler model can be considered as a limiting case, as the T, D and G_p tend to zero.

2.2.5 Kerr model

Kerr (1965) modified the Pasternak model with another spring layer on top of the shear layer. The response function for this model is given by:

$$(1 + \frac{k_s}{k})q - \frac{G_p H}{k} \nabla^2 q = k_s w - G_p H \nabla^2 w \tag{2.8}$$

where, k is the spring constant of the upper spring layer and all other parameters are as defined previously.

2.2.6 Continuum models

The soil media have often been idealized as three dimensional continuous elastic solids or elastic continua to account for the continuous behaviour. Generally, the distribution of displacements and stress in such media remains continuous under the action of external force systems. The response function for the three dimensional elastic soil medium is generally obtained by using the theory of elasticity solution by Boussinesq (1985), who analysed the problem of a semi-infinite homogeneous isotropic linear elastic solid subjected to a concentrated force that acts normal to the plane boundary.

This indicates that the elastic continuum model predictions are closer to the real soil behaviour than those predicted by the mechanical models. These models have the added benefit of providing body stresses as part of the solutions, which is not possible by the mechanical models. However, it appears that the elastic continuum models have limited uses particularly for the plate, mat or raft analysis for various reasons. Mathematical complexity of the elastic continuum is considered as one of the important reasons that limit its uses. Additionally, the determination of the elastic parameters, Young's modulus E_s and Poisson's ratio v_s (or shear modulus G_s and Bulk modulus K_s) of soil deposits in field situations is difficult. These parameters vary with confining pressure and so is the depth of the soil deposit. Several researchers, such as Reissner (1958), and Vlazov and Leontiev (1966) have imposed constraints or simplifying assumptions with respect to the possible distribution of displacements and stresses upon the basic equations for a liner elastic isotropic continuum. Hence, these models are considered as the simplified elastic continuum models.

2.2.7 Reissner model

The model proposed by Reissner (1958) imposes certain possible displacement and stress constraints upon the basic equations for a linear elastic isotropic continuum. Therefore, by assuming that the in-plane stresses (in the *x-y* plane) throughout a soil layer of thickness *H* are negligibly small ($\sigma_{xx} = \sigma yy = \boldsymbol{\tau}_{xy} = 0$) and that the displacement components *u*, *v* and *w* in the rectangular Cartesian coordinates' directions *x*, *y*, *z*, respectively satisfy the conditions:

$$u = v = w = 0 \text{ on } z = H;\ u = v = 0 \text{ on } z = 0 \tag{2.9}$$

It can be seen that the response function for the soil model is given by:

$$c_1 w - c_2 \nabla^2 \mathrm{w} = q - \frac{c_2}{4c_1} \nabla^2 q \tag{2.10}$$

where, constants c_1 and c_2 characterising the soil response are related to E_s and G_s by $c_1 = E_s/H$ and $c_2 = G_s H/3$ in which E_s and G_s are respectively the Young's modulus and shear modulus of the soil layer. It can be seen that the Eq. (2.8) and (2.10) are identical. For a constant or linearly varying stress, after redefining $c_1 = k_s$ and $c_2 = G_p$, Eq. (2.10) also becomes identical to the Eq. (2.2) or (2.6).

2.2.8 Vlazov model

The model proposed by Vlazov (1949a, 1949b) also imposes certain possible displacement constraints upon the basic equations for a linear elastic continuum. Vlazov's approach to the formation of the soil model is based on the application of a variational method. The details of the application of general methods of analysis to the theory of elasticity solutions have been given by Vlazov and Leontiev (1966) in addition to the following assumptions for the horizontal displacement.

$$u(x, z) = 0 \tag{2.11}$$

The vertical displacements are expressed as

$$w(x, z) = (x)\, h\, (z) \tag{2.12}$$

where, u and w are the corresponding displacement in x and z directions. The function $h\ (z)$ describes the variation of displacement $w(x,\ z)$ in the z direction. Several such variations have been proposed including the linear and exponential variations.

$$h(z) = (1 - \eta); h(z) = \ sinh \left[\frac{\gamma(H-z)}{L}\right] / \sinh[\frac{\gamma H}{L}] \tag{2.13}$$

where, $\eta = \frac{z}{h}$ and ν *and* L are constants. The response function for this model is given by:

$$q(x) = cw\,(x) - 2t\,\frac{d^2\,w\,(x)}{dx^2} \tag{2.14}$$

where

$$c = \frac{E_0}{1-\nu_0^2}\int_0^H\left[\frac{dh}{dz}\right]^2 dz; \quad t = \frac{E_0}{4(1+\nu_0)}\int_0^H (h)^2\,dz \tag{2.15}$$

$E_0 = \frac{E_s}{1-\nu_0^2}$, $\nu_0 = \frac{\nu_s}{1-\nu_s}$ are respectively the elastic modulus and Poisson's ratio for the elastic material.

By comparing the Eq. (2.14) with (2.2) and (2.7), it is apparent that the shear modulus G_p, the membrane tension T, and the spring constant k_s, are directly related to the elastic constant E_s and ν_s of the soil layer. Therefore, it represents a physical interpretation of the modulus of subgrade reaction k_s.

Vallabhan and Das (1991) presented a modified Vlazov's model and they had developed a unique iterative technique based on variational principles to determine a consistent value of the γ parameter that controls the decay of stresses in the continuum. The model automatically gives a consistent value of γ whereas the Vlazov model did not give a precise value of γ; instead, it had recommended the values between 1 and 2 for γ. An additional feature of this new model is that the computer code is very small, and using even IBM PC-XT- compatible computers, the results can be obtained quickly.

2.2.9 Elastic - Plastic models

The elastic soil models do not take into account any elastic-plastic or irreversible behaviour of the soil medium. Therefore, the analysis of elastic-plastic soil behaviour can be carried out using either purely mechanical models or continuum models. The basic distinction between purely elastic and elastic-plastic model is that the stresses or forces that can be induced in the soil medium are limited owing to the introduction of a yield or failure criterion in the latter case (Selvadurai, 1979).

An example of a purely mechanical type elastic-plastic model is the soil model proposed by Rhines (1969) to account for punching shear failure in the highly compressible soil. This particular model uses modified Pasternak model, which is also called as Kerr model and it assumes that the shear layer interconnecting the springs is capable of sustaining finite shearing stress. The shear stress to shear strain relationship for the elastic layer is of an elastic-rigid plastic type. Selvadurai (1976) has also used modified Pasternak model in connection with the axi-symmetric loading of a rigid circular plate resting on an elastic-plastic Pasternak foundation. The analysis indicated that the yielding occurs at edges of the footing and the load displacement curve is bilinear. Likewise, the break that corresponds to the onset of yielding in the shear layer and slop of the post yield portion of the curve is less than the slop of the elastic portion. Further to that the maximum contact pressure for the given applied load after yielding is less than that it would have been, if the foundation under the same load remained realistic.

2.3 Regulatory overview

Since the beginning, the aviation industry has been highly regulated under national and international regulations, because of the instinctive safety risks associated with the operations of an aircraft. Therefore, the safety sensitive aviation activities are regulated under prescriptive standards and regulatory regimes. Most legal frameworks have a history of establishing on national basis before entering the international scene, but the peculiarity of aviation law is that it has been both international and national from the very beginning. Since the establishment of the International Civil Aviation Organisation (ICAO) in 1944 as a specialized agency of the United Nations to develop aviation standards and recommended practices (SARPS), the civil aviation industry has been regulated significantly by the national aviation authorities (Department of Infrastructure Transport Regional Development and Local

Government, (2008). The safety objectives are being achieved by various regulatory tools, such as licensing and certification of activities and infrastructure.

Annex 14 contains SARPS of the ICAO as a minimum standard for aerodromes that includes the physical characteristics of runways (International Civil Aviation Organisation (2004). According to the International Civil Aviation Organisation (2006a), these standards apply to all contracting states under the Chicago convention. The ICAO also recommends that the contracting states are expected to use the precise wordings and phrases of ICAO regulatory standards in their national regulations. Therefore, the provisions of the ICAO Annexes have been written in a manner to facilitate incorporation without major textual changes into national legislation of the contracting States for harmonisation purpose. For example, the expression ‘licence’ used throughout the ICAO Annexes has the same meaning as the expressions ‘certificate of competency or license’, which is used in Chicago convention documents. Similarly the expression ‘flight crew member’ has the same meaning as the expressions ‘member of the operating crew of an aircraft’. Therefore, the ICAO expects that the Contracting States should use these terminologies in their national legislations. Furthermore, under Article 38 of the convention, the contracting states are required to notify the ICAO of any differences between their national regulations and the International Standards set by the annex (International Civil Aviation Organisation, 2006a).

Many other documents and annexes published by the ICAO cover standards and recommended practices related to various activities of the aviation industry. For example, the annex 1 encompasses the recommended competency standards for aeronautical personnel involve in airworthiness of aircraft and flight operations (International Civil Aviation Organisation, 2006c). According to the Chicago Convention, the contracting states of the ICAO are required to adopt these standards into their national legislations (International Civil Aviation Organisation, 2006a). Primary purpose of developing the standards and incorporating them into the national legislations as civil aviation regulations is to ensure safety of aviation operations throughout the world, consistently. However, these standards do not address the competency requirements related to engineering personnel who work in aircraft manufacturing or airport industry. A consistent international standard covering competency requirements for aeronautical personnel in these segments of the aviation industry may further enhance aviation safety. Therefore, the developments of future civil aviation regulatory framework may also need to investigate the possibilities to include this.

According to Herrera et al. (2009), a number of safety indicators are generally considered as a part of safety management systems. These indicators can be divided in two broad categories known as outcome-based indicators, which are categorised as reactive and activity indicators as proactive. However, the researchers have found that the aviation industry has focused on measuring reactive indicators as a safety measure. Furthermore, it has been recognized that these indicators do not provide a full overview of the safety level and accident and incident rate is not an excellent tool to measure the health of a system. Therefore, a balance between prescriptive and performance based regulatory framework may be required to ensure safety in the ever changing aviation industry.

The ICAO was given the ongoing task of adopting safety-relevant SARPS in a form of Annexes to the Convention (International Civil Aviation Organisation, 2009a). While implementation of these standards is the surest way to advance safety globally, the SARPS are not enforceable by ICAO. Consequently, the implementation task was entrusted to the contracting states. Since ratification of the Chicago convention back in 1947, it has become increasingly difficult to know the extent to which the SARPS are being implemented by the contracting states. Therefore, ICAO has established the universal safety oversight audit programme (USOAP) to ensure compliance and harmonisation of aeronautical practices in national legislations of the contracting states to that of SARPS mentioned in the annexes. The USOAP comprises of regular, mandatory, systematic, and harmonized aviation safety audits of all contracting states (International Civil Aviation Organisation, 2009b). The objective of the ICAO safety oversight programme is to identify whether the Contracting States are adequately discharging their responsibility for the aviation safety oversight or not. The primary function of the safety oversight programme is to carry out safety oversight assessments at state’s request. Nevertheless, the ultimate responsibility for the safety oversight rests with the contracting states.

According to International Civil Aviation Organisation (2004), the contracting states should certify aerodromes open to public use in accordance with the relevant ICAO specifications and standards through an appropriate regulatory framework. As part of the certification process, the states are required to ensure that the physical characteristics of the runway, such as pavement categories, runway strip design, and the pavement bearing strength (PBS) reporting procedure meets the ICAO standard prior to granting the aerodrome certificate to an applicant. Similarly, the legislation also requires that a maintenance programme for runways and related infrastructure should be established by the aerodrome license holder to maintain facilities in a condition that does not impair the safety of the aircraft.

2.3.1 Technical evaluation and strength reporting of a runway pavement

Health monitoring and reporting of load bearing strength of a runway pavement is an important part of an airport operation in the chain of flight operations. This task plays a significant role in ensuring safe operation of an aircraft during takeoff and landing. According to Stet and Verbeek (2005), the evaluation of a pavement performance requires an accurate site testing system that can precisely predict deterioration of the pavement with time and it can also ensure that any deterioration of the pavements is identified as early as possible, so as to minimise the requirement of any major reconstruction work. They also indicate that the current methods cannot adequately compute pavement damage caused by new large aircraft. The researchers also believe that some more advanced structural models may be capable of better representing the response interaction from landing gears of new generation aircraft (NGA). Currently, many studied are being carried out by various civil aviation regulatory authorizes in the world to address this issue. The data collected by these studies will be used to develop advanced failure models that are capable to the NGA.

Stet and Verbeek (2005) further state that an accurate analysis of the pavement response to a given aircraft load is necessary, but it is not sufficient for a pavement design. Additionally, reliable predictions of failure of a pavement are essential. For example, some failure models are indicated in the form of regression functions relating level of strain produced by a passing aircraft landing gear to the number of coverage to failure. The strain response is normally based on a mechanistic analysis, such as a three dimensional finite element method, while the failure models are suggested by traffic tests of full scale pavement structures. Consequently, it is considered as one of the mechanistic empirical design methods.

The International Civil Aviation Organisation (2004) has recommended that the bearing strength of a runway pavement shall be reported using the aircraft classification number - pavement classification number (ACN-PCN). The bearing strength is the ability of a runway pavement to accept the loads imposed by an aircraft while maintaining its structural integrity (International Civil Aviation Organisation, 1983). The ACN-PCN system reports a unique PCN, which indicates that an aircraft with an ACN equal to or less than the PCN can operate on the runway pavement subject to any limitation on the tyre pressure. The bearing strength of the pavement is reported by indicating the PCN, pavement type, subgrade category, allowable tyre pressure, and the basis of the evaluation. Horonjeff and McKelvey (1994) have reported that the ACN can be found from the runway pavement design charts or analytical equations. A ratio between the pavement thickness required for the aircraft and that required for a standard single-wheel load of 500 kg at a standard tyre pressure of 1.25 MPa defines the ACN. The PCN can be determined either by carrying out a technical evaluation of the pavement or on the basis of the aircraft load rating experience.

The ACN is a number expressing the relative structural effect of an aircraft on runway pavement for specified subgrade strength in terms of a standard single-wheel load (Fig. 2.2 and Fig. 2.3). Similarly, the PCN is a number, which expresses the relative load carrying capacity of a pavement in terms of a standard single-wheel load (Horonjeff and McKelvey, 1994). The International Civil Aviation Organisation (1983) mentions that the ACN of an aircraft is numerically defined as two times the derived single wheel load (DSWL), where the DSWL is expressed in thousands of kilograms and, the single wheel tire pressure is standardized at 1.25 MPa. Additionally, the DSWL is a function of the subgrade strength. The ACN) is also defined for four subgrade categories known as *k.* The maximum ACN of an aircraft is calculated at the mass and centre of gravity (CG) that produces the highest main gear loading on the pavement and the relative aircraft ACN charts show ACN as a function of aircraft gross mass (Table. 2.1).

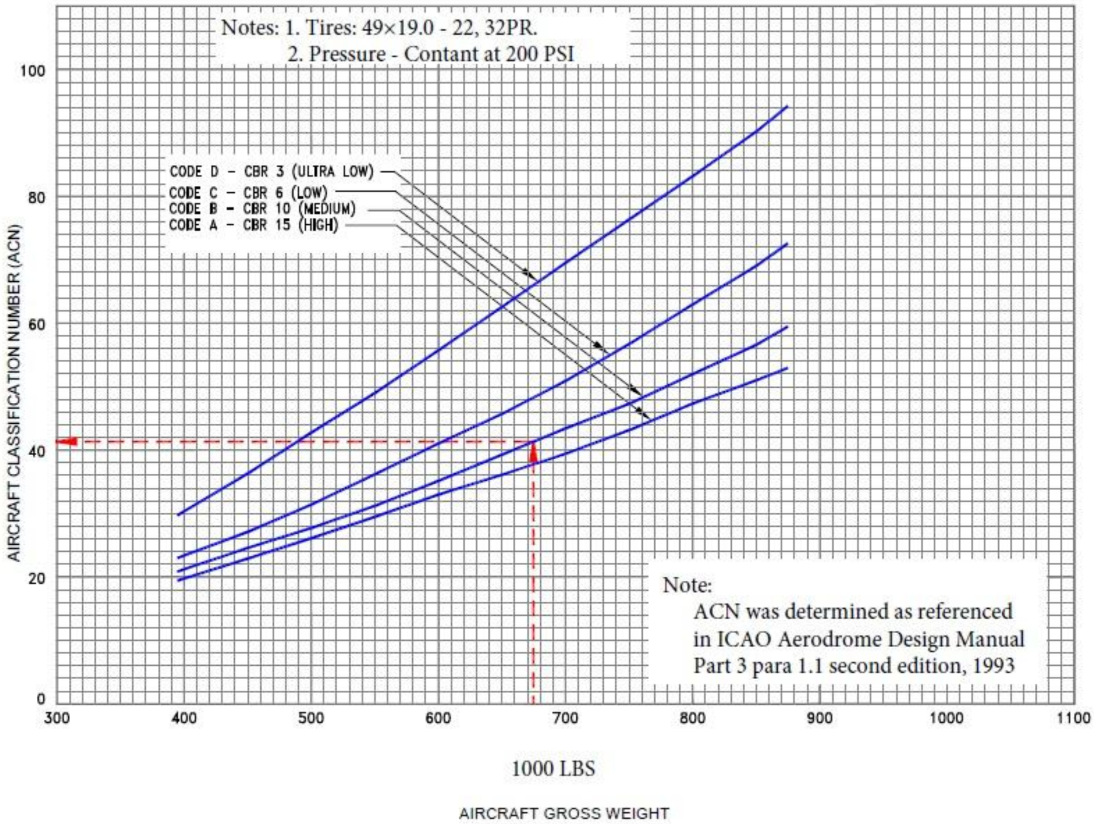

Fig.2.2. Boeing 747-400 Aircraft classification number - Flexible pavement (After Boeing Commercial Airplanes, 2002)

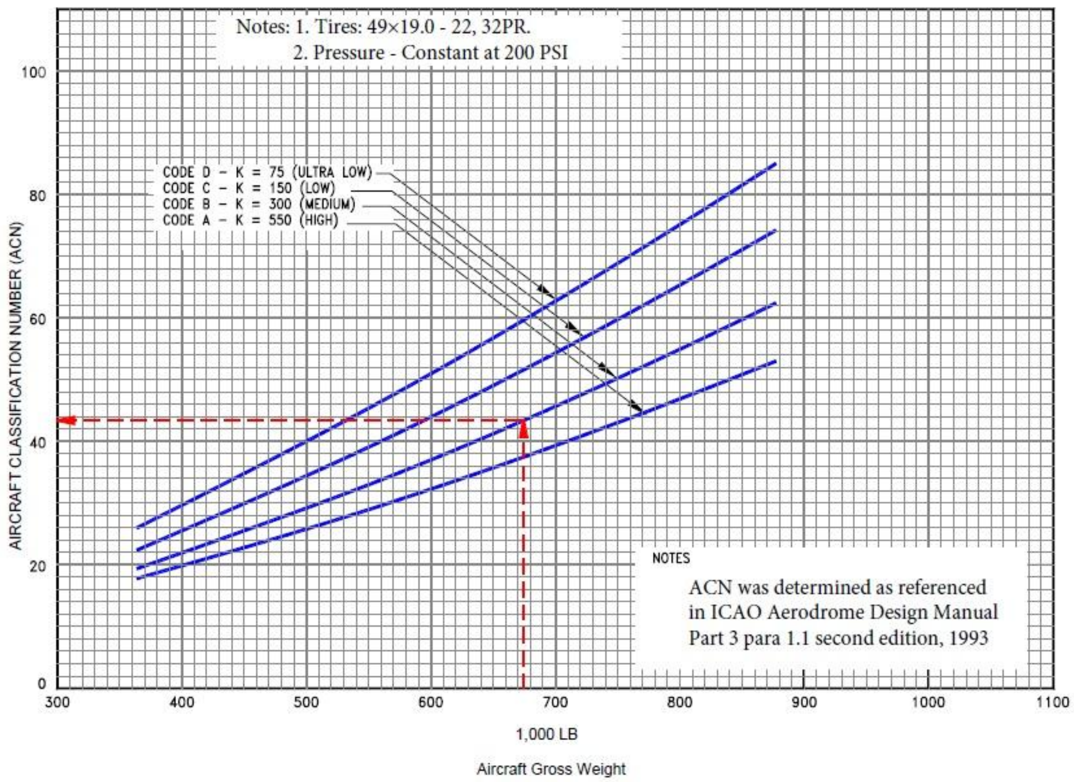

Fig.2.3. Boeing 747-400 Aircraft classification number - Rigid pavement (After Boeing Commercial Airplanes, 2002)

According to the International Civil Aviation Organisation (1983), the concept of a mathematically derived single wheel load has been employed in ACN-PCN method as a means to define the landing gear-runway pavement interaction without specifying pavement thickness as an ACN parameter. This is done by equating the thickness given by the mathematical model for an aircraft landing gear to the thickness for a single wheel at a standard tire pressure of 1.25 MPa. The single wheel load so obtained is then used without further reference to thickness (Fig. 2.4). This is consistent with the objective of the ACN-PCN method to evaluate the relative loading effect of an aircraft on a pavement.

The International Civil Aviation Organisation (1983) further elaborates that the ACN/PCN method uses eight standard subgrade values, which are four rigid pavement *k* values and four flexible pavement California Bearing Ratios (CBRs), rather than a continuous scale of subgrade strengths. The grouping of subgrades with a standard value at the mid-range of each group is considered to be entirely adequate for reporting. The subgrade strength categories *k* are identified as high, medium, low and ultra-low and assigned the numerical values of *k* (determined using a 75 cms diameter plate) is 150 MN/m^3, 80 MN/m^3, 40 MN/m^3, 20 MN/m^3, respectively. A standard stress of σ = 2.75 MPa for reporting purposes has been stipulated.

Table.2.1. ACN of various types of Airbus aircraft (After Civil Aviation Safety Authority, 2011a)

Aircraft Type	MTOW (kg) OWE (kg) TP (kPa)	Flexible Pavement Subgrade CBR%				Rigid Pavement Subgrade K in MN/m3			
		A 15	B 10	C 6	D 3	A K150	B K80	C K40	D K20
A319-100	75865 38952 1380	39 18	40 18	44 20	50 22	44 20	46 21	48 22	50 23
A320-100	68013 39768 1210	35 19	36 19	40 21	46 24	38 20	41 22	43 23	45 24
A320-200	77395 44968 1440	41 22	42 22	47 24	53 28	46 24	49 26	51 27	53 28
A321-100	78414 47000 1280	42 23	44 24	49 25	55 30	47 25	50 27	52 29	54 30
A330–300	212000 121870 580	55 29	60 30	69 33	94 41	47 28	54 27	64 31	75 36
A340–300	271000 129300 1380	59 24	64 25	74 28	100 34	50 25	58 24	69 26	80 30
A340- 500,600	366072 178448 1420	70 29	76 31	90 34	121 42	60 29	70 28	83 32	97 37
A380-800	562262 281233	56 23	62 25	75 28	106 36	55 26	67 27	88 31	110 38

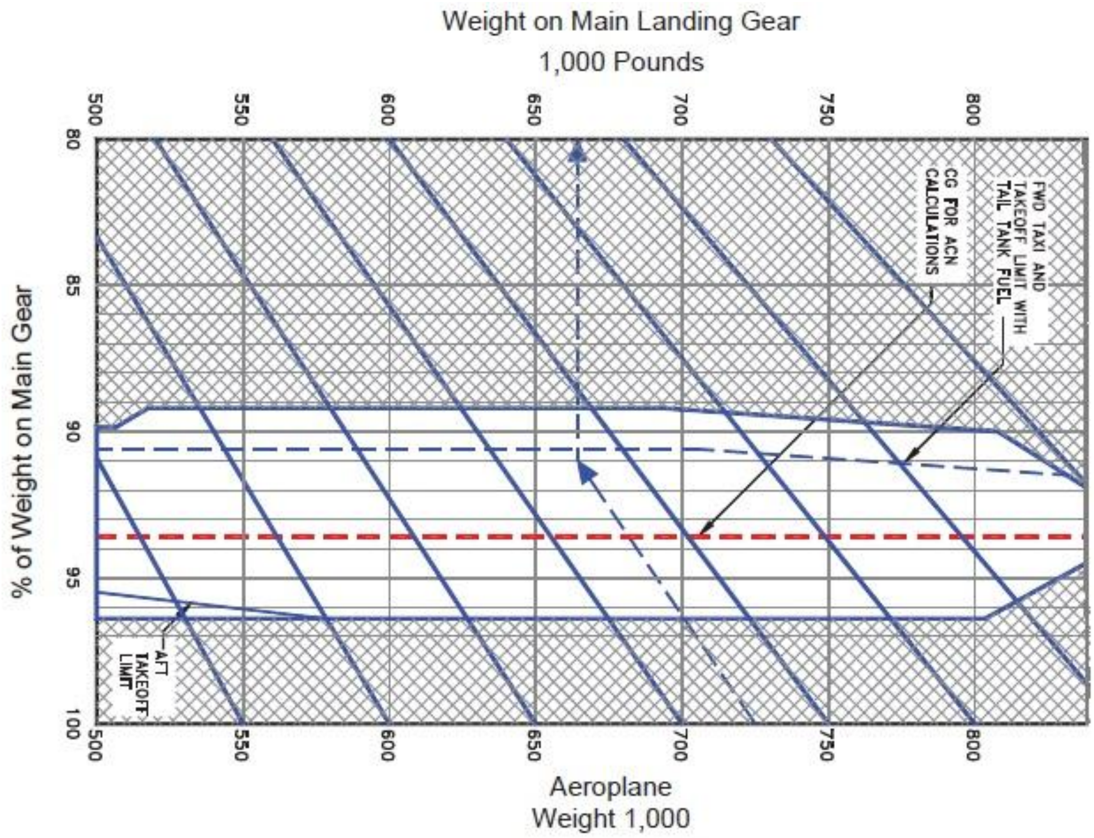

Fig.2.4. Landing gear loading on a runway pavement (adapted from Boeing Commercial Airplanes, 2002)

2.3.2 Aircraft landing gear configurations

Landing gear or undercarriage forms the principle support for an airplane on ground. Several types of aircraft with various loading configurations are being used in aviation industry to transport passengers and cargo. The aircraft can be characterised by their undercarriage type and wheel arrangements. Most airplanes are equipped with a tricycle type of landing gear arrangement, which consists of a nose gear leg and two main gear legs (Federal Aviation Administration, 2012a). The number and location on main gear vary and some main gear legs have more than one wheel. Multiple wheels spread the aircraft weight over a large area in addition to providing a safety margin if one wheel should fail. The heavier aircraft uses four or more wheels on one main gear leg. Federal Aviation Administration (2012a) specifies that the mechanism is called as a bogie when more than two wheels are attached to one leg (Fig. 3.4). The most common types of gear configurations are single, dual, and the dual tandem. However, the new generation large aircraft typically have a triple dual tandem wheel configuration (Whiteley, 2006). The number wheels required on a bogie are determined by the gross weight of the aircraft and the runway pavement on which the aircraft is intended to land.

2.4. Conclusions

Several studies deal with the design aspects of aircraft-runway interaction, but much attention has not been given to present a simplified runway deflection model for the routine design practices. Despite significant volumes of research existing in the areas of runway to aircraft interaction including pavement strength requirements for light aircraft and the new generation aircraft (NGA), the deliberation given to the runway deflection caused by the aircraft landing forces still remains limited. Similarly, the information and research findings regarding the runways are scarce.

In conclusion, the research literature suggests that the problem of subgrade rutting is an important factor in the overall structural design system of the runway pavements. In recent years, the method of controlling the magnitude of the vertical compressive strain at the surface of the subgrade to a tolerable amount associated with a specific number of load repetitions has been proposed and adopted in some design procedures. Previous analyses of aircraft-runway interaction have been combined with empirical studies in order to provide safe designs of the runways. However, much attention has not been given to present a simplified runway deflection model for the routine design and runway pavement evaluation practices. The ACN/PCN method enables the evaluation of interaction between the aircraft landing gear and the runway pavement without a reference to the pavement thickness and the runway deflection (Stet and Verbeek, 2005; International Civil Aviation Organisation, 1983). Additionally, these prescriptive standards and procedures are mandatory in aviation industry to ensure safety of the aircraft and its occupants.

CHAPTER 3

DEVELOPMENT OF RUNWAY DEFLECTION MODEL

3.1 General

Landing is the most crucial phase of a typical flight and the process of landing applies a tremendous load on the runway. The literature review shows that the estimation of the dynamic deflection of the runway pavement at the touchdown point caused by aircraft landing has not been given due attention in the past. This chapter aims at presenting an analytical expression for calculating the deflection of the pavement at the touchdown point caused by a landing gear load during aircraft landing. The expression may be useful for analysis and design of the runway pavements considering impact loads. An aeroplane is assumed to contact the pavement with a limit descent velocity of 10 feet/sec at design landing weight[2] of the aeroplane (Federal Aviation Administration, 2012c). This imposes impact loads on the runway pavement, which may cause deflection and deterioration of the pavement at touchdown zone. The deflection of the runway pavement can be predicted using values of the impact load.

3.2. Aircraft landing and deflections

The art of landing an aeroplane consists of bringing it in contact with ground at the lowest possible vertical velocity and at the same time somewhere near the lowest possible horizontal velocity relative to the ground (Barnard and Philpott, 2006). The vertical velocity of the aircraft causes an impact over a finite area in touchdown zone (Fig. 3.1) known as touchdown point of the runway resulting in a significant deflection of the runway pavement. Movement of material in the runway pavement layers is considered as one of the principal reasons for the deflection in a runway pavement. The movement is manifested as strain or deflection, and it is established

[2] Design landing weight is the maximum weight of an aeroplane for landing conditions at maximum permitted descent velocity of the aeroplane during landing (Federal Aviation Administration, 2012c).

that an acceptable criterion of runway failure would be deflection (Horonjeff and McKelvey, 1994). Consequent to the difficulties in estimating the deflection, most pavement designs are still based on empirical knowledge and experiences (Mallick and El-Korchi, 2009). Normally, the pavements do not fail disastrously; instead they gradually wear out, deflect, and suffer a loss of serviceability over time. Consequently, the evaluation of pavement performance becomes difficult and no single analytical equation can be provided as a solution (Ashford and Wright, 1992). Hence, the deflection analysis of the pavement during landing can be done by various methods, such as analytical and numerical approaches generally used in highway pavement analysis.

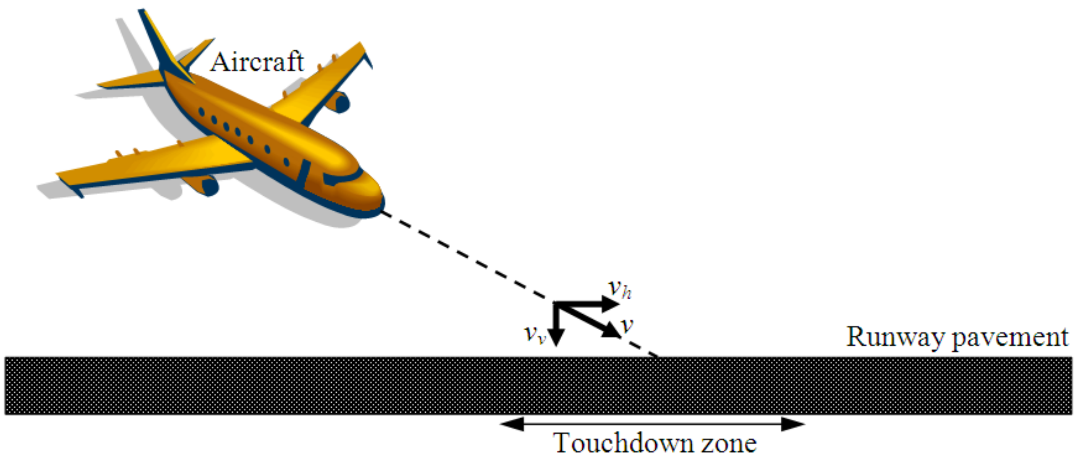

Fig.3.1. Landing of an aircraft on a runway

In the simplest case, the stresses and deflections in the pavement system caused by the moving landing gear wheel load is analyzed by Boussinesq theory (Boussinesq, 1885) assuming the load to be a point load on a single layer system (Mannering et al. 2009). Considering a circular load, Ahlvin and Ulery (1962) presented solutions for the evaluation of stresses, strains, and deflections at any point in a homogeneous half space. Their work makes it easier to analyze a more complex pavement system than that considered in the Boussinesq theory. Likewise, Vajarasathira, Yener, and Ting (1984) presented a dynamic numerical analysis of stresses and deflections induced by moving vehicles in airport pavements considering inertial effects of moving vehicles in order to investigate the pattern and magnitude of stresses and deflections in the pavement. On the basis of finite element algorithms, the dynamic analyses of rigid pavements to moving aircraft loads were presented by including some aspects of aircraft-pavement-subgrade interaction by Alvappillai et al. (1992, 1993) and Taheri and Zaman (1995). Taheri et al. (1990) in their study consider the aircraft and the concrete slab as a single system and transverse inertia effect of the aircraft is taken into account. The slab is modeled as a thin, rectangular, elastic orthotropic plate and it is supported by a linear viscoelastic foundation. Likewise, the aircraft landing gear is modeled as a set of independent individual units moving at the same velocity. This eliminates the inertia effects caused by roll, pitch, and yaw motions of the aircraft. The mass of the aircraft is consolidated on the suspension systems modelled as dampers and all movements of the suspension except the vertical motions are constrained. As a result, each suspension system has one degree of freedom and the contact between the slab and the aircraft is assumed to be a point contact. In these studies, the rigid pavement was modeled as a series of thin plate elements, the subgrade medium was idealized as a viscoelastic foundation, and the traversing aircraft was modeled by spring and dashpot systems.

A detailed parametric study was presented by Taheri and Zaman (1995) to investigate the response of pavement to a traversing aircraft and a temperature gradient along the depth of the pavement. Using field test data, Fang (1999) plotted the variation of pavement deflections and strains with time as the aircraft wheels passed by. The analysis demonstrates that the maximum deflections occur between the dual wheels, whereas the maximum strains happen beneath one of the wheels. Brill and Parsons (2001) presented a three-dimensional finite element-based airport pavement design procedure for rigid airport pavements idealizing subgrade by the Winkler foundation.

An alternative model representing subgrade as a linear elastic foundation with elastic modulus E and Poisson's υ was also used. Stress computations using both models show that the Winkler foundation model is more sensitive to slab size than the infinite element model for dual-tridem (six-wheel) aircraft gear loads. Gopalakrishnan and Thompson (2006) had studied the rutting behaviour of flexible test pavements subjected to multiple-wheel heavy aircraft gear loading. They had reported that for a similar number of load repetitions, the low-strength subgrade test sections with reduced subbase thicknesses yielded larger mean rut depths. Similarly, Sawant (2009) presented a dynamic analysis of rigid pavements under moving vehicular or aircraft loads by providing a solution algorithm based on the finite-element method. There may be several possible methods available to study the load-deflection behaviour of the runway pavement. However, a mechanical modelling approach is preferred due to its simplicity for the analysis of structure to foundation interaction. This research idealises the soil subgrade by Winkler springs.

3.3 Basic runway pavement structure and layers

The runway consists of several layers including subgrade, subbase course, base course and surface course, which is a combination of binder and wearing courses (Fig. 3.2 and 3.3). The behavior of any pavement depends upon the native materials of the site, which after leveling and preparation is called the subgrade. The subgrade is the layer of material immediately below the pavement structure, which is prepared during construction to support the loads transmitted by the runway pavement. It is normally the *in situ* soil over which the pavement is laid. However, it can also refer to the top of a fill over which the pavement is constructed. The *subbase* materials comprise natural sand, gravel, bricks, crushed stone, crushed concrete, crushed slag or combinations thereof meeting the prescribed grading and physical requirements. Water bound macadam (WBM), or wet mix macadam (WMM) can be used for construction of *base course*. Likewise, bituminous macadam (BM) or dense bituminous macadam (DBM) is used for construction of binder course. *Wearing courses* are provided at top of the pavement surfaces to have an adequate skid resistance and a waterproof surface. Similarly, the semi-dense bituminous concrete (SDBC), bituminous concrete (BC) or premix carpet (PC) can be used for the construction of wearing courses (International Civil Aviation Organisation, 1983). However, when the surface course is a cement concrete layer, the subbase course is generally not provided.

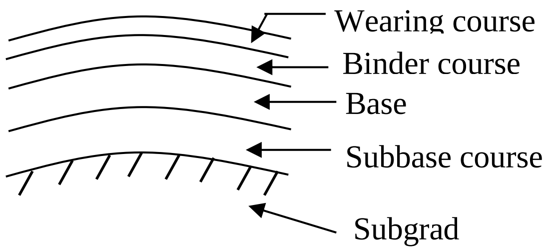

Fig.3.2. A typical cross-section of the bituminous concrete runway pavement

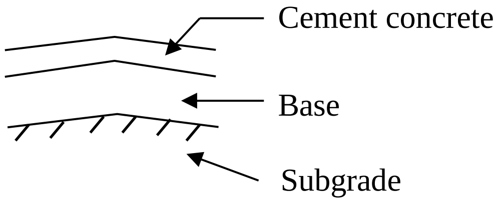

Fig.3.3. A typical cross-section of the cement concrete runway pavement

The runway pavement layers are complex in their load-carrying capacity and load-settlement behaviour. According to International Civil Aviation Organisation (1983), most runway pavements at modern airports are classified primarily as rigid or flexible type. The terms attempt to characterize the response of each type to loading. The primary element of a rigid pavement is a layer or slab of plain or reinforced Portland cement concrete (PCC). It is often underlain by a granular layer, which contributes to the structure both directly and by facilitating the drainage of water. A rigid pavement responds stiffly to surface loads and distributes the loads by bending or beam action to wide areas of the subgrade. However, the strength of the pavement depends on the thickness and strength of the PCC and any underlying layers above the subgrade. Therefore, the pavement must be adequate to distribute surface loads, so that the pressure on the subgrade does not exceed its evaluated strength. Likewise, a flexible pavement consists of a series of layers increasing in strength from the subgrade to the surface layer.

The pavements meant for heavy aircraft usually have a bituminous bound wearing course. A flexible pavement yields more under surface loading merely accomplishing a widening of the loaded area and consequent reduction of pressure layer. At each level from surface to subgrade, the layers must have strength sufficient to tolerate the pressures at their level. The pavement thus depends on its thickness over the subgrade for reduction of the surface pressure to a value which the subgrade can accept. A flexible pavement must also have thickness of structure above each layer to reduce the pressure to a level acceptable by the layer. In addition, the wearing course must be sufficient in strength to accept without distress tire pressures of the aircraft.

3.4 Analytical formulation

Fig. 3.1 shows an aircraft in its final phase of landing close to the runway. The velocity v of the aircraft prior to landing at the touchdown point has horizontal and vertical components as v_h and v_v, respectively. A typical aircraft applies an impact load on the runway at the time of landing, which is transmitted to the runway pavement through undercarriage of the aircraft (Fig. 3.4). The number of wheels, their spacing, tire pressure, and size determine the distribution of aircraft load to the pavement. The wheel loads applied by dual, dual-tandem, and adjacent legs of complex undercarriages overlap at the subgrade and other pavement layers of the runway. Consequently, the landing load may be assumed to act uniformly over the touchdown point. The contact between the landing gear and the runway during landing being instantaneous; it is practically not possible to know the exact contact time-interval. This makes it difficult to determine the vertical force or the impact load applied by the aircraft on the runway using Newton's second law of motion. With the known value of impact load, the deflection of the runway pavement can be estimated conveniently. However, in order to avoid calculation of impact load while estimating deflection, the landing impact can be considered as a free fall of the aircraft from a known height that results in the same vertical velocity of the aircraft as if it is generated prior to landing.

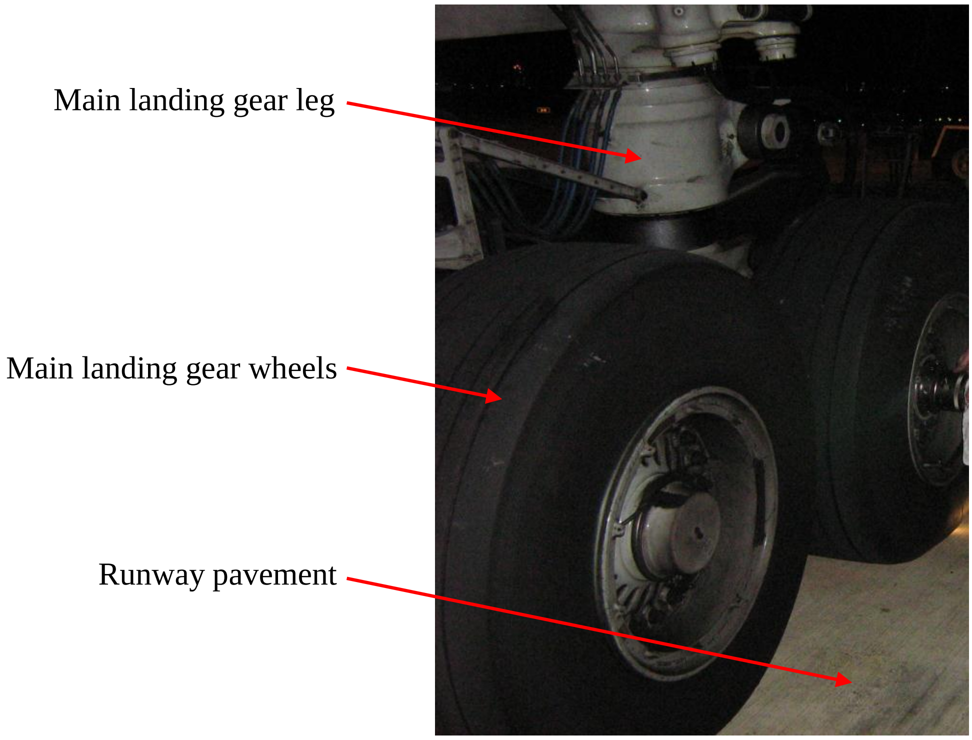

Fig.3.4. View of a main landing gear arrangement

If *m* be the mass of the aircraft causing the load on one main landing gear leg, and *h* is the height of free fall, then

$$\frac{1}{2} m v_v^2 = mgh \tag{3.1}$$

or

$$h = \frac{v_v^2}{2g} \tag{3.2}$$

where *g* is the acceleration due to gravity.

The concept of idealising the ground by the Winkler springs known as the Winkler foundation model (Winkler, 1867; Slevadurai, 1979) is frequently used in the design of highway and airfield pavements for representing the behaviour of soil subgrades (Ashford and Wright, 1992; Mallick and El-Korchi, 2009). Physically, Winkler's idealisation of the soil subgrade consists of a system of mutually independent spring elements with a spring constant, which is expressed as pressure per unit deflection and called modulus of subgrade reaction. One important feature of this foundation model is that the displacement occurs immediately under the loaded area and outside this region the displacements are zero although the surface deflections may occur not only immediately under the loaded region but also within certain limited zones outside the loaded region (Selvadurai, 1979). To estimate deflection through simple analysis, the complete runway can be idealised by the Winkler foundation as shown in Fig. 3.5. This idealisation appears more realistic for a large number of unpaved runways of stabilized soil layers, which are often being used by military and general aviation aircraft throughout the world (Tingle and Grogan, 1999).

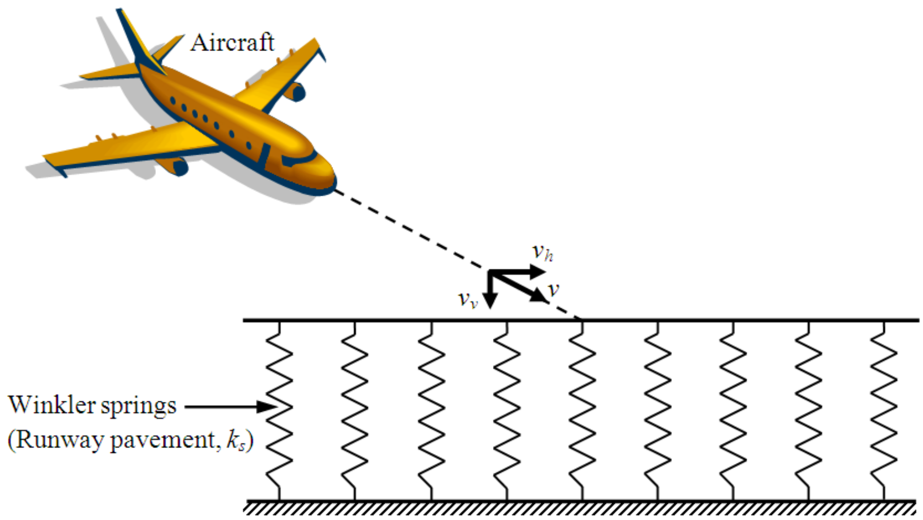

Fig.3.5. Idealisation of runway pavement by Winkler foundation model

If w be the deflection of the runway caused by the impact load, the principle of conservation of energy gives

$$mg(h+w) - \frac{1}{2}Ak_s w^2 = 0 \quad (3.3)$$

where k_s is the modulus of subgrade reaction of the runway pavement, and A is the equivalent area of contact between the landing gear wheels and the runway.
Substitution of h from Eq. (3.2) into Eq. (3.3) yields

$$mg\left(\frac{v_v^2}{2g} + w\right) - \frac{1}{2}Ak_s w^2 = 0$$

or

$$w^2 - \left(\frac{2mg}{Ak_s}\right)w - \frac{mv_v^2}{Ak_s} = 0 \tag{3.4}$$

Eq. (3.4) is quadratic in w, which is expressed as

$$w = \frac{\frac{2mg}{Ak_s} \pm \sqrt{\left(\frac{2mg}{Ak_s}\right)^2 + 4\left(\frac{mv_v^2}{Ak_s}\right)}}{2}$$

or

$$w = \frac{p}{k_s} \pm \sqrt{\left(\frac{p}{k_s}\right)^2 + \left(\frac{pv_v^2}{gk_s}\right)} \tag{3.5}$$

where

$$p = \frac{mg}{A} \tag{3.6}$$

is the equivalent static contact pressure exerted by the aircraft landing gear at the touchdown point of the runway. The pressure p is basically the tire pressure (Fig. 3.4), which is assumed to be uniformly distributed over the contact between the landing gear wheels and the runway at touchdown point. This assumption is made to develop simple steps in the analysis as it is generally considered by practicing engineers in pavement engineering analysis and design. With this simplification, the tire footprint of the wheels in a landing gear can be defined as an equivalent circular area A with a radius a calculated by

$$a = \sqrt{\frac{mg}{\pi p}} \tag{3.7}$$

Table 3.1 provides the calculation of radius a for different types of aircrafts. It should be noted that the radius increases with an increase in landing gear load.

Since the deflection caused by impact load will always be higher than that by static load, the negative sign in Eq. (3.5) has no practical significance. Therefore, considering positive sign only, Eq. (3.5) reduces to

$$w = \frac{p}{k_s} + \sqrt{\left(\frac{p}{k_s}\right)^2 + \left(\frac{pv_v^2}{gk_s}\right)} \tag{3.8}$$

Eq. (3.8) provides a general expression for dynamic deflection of the runway pavement at the touchdown point caused by a gear load during aircraft landing. It can be represented in non-dimensional form as

$$w^* = p^* + \sqrt{(p^*)^2 + p^* v_v^{2*}} \tag{3.9}$$

where

$w^* = \frac{w}{a}$, $p^* = \frac{p}{k_s a}$ and $v_v^{2*} = \frac{v_v^2}{ga}$ are nondimensional parameters.

It should be noted that Eq. (3.8) or (3.9) is based on some simplifying idealisations and assumptions. It can be used to calculate deflections of the simple runway pavement system, such as unpaved runway pavements constructed from stabilized soil layers. These types of runways are used by some military aircraft, civil aircraft for emergency service operations, and general aviation aircraft in remote locations. The equation can also be used for paved runway system to evaluate the deflection characteristics of the unpaved part of the runway.

Table.3.1. Load details for different types of aircraft and calculated value of the equivalent load radius of the tire footprints of the landing gears

Aircraft type	**Landing gear Configuration**	**All-up mass, M (kg)**	**Load on one main landing gear leg, *P = mg* (kN)**	**Tyre pressure *p* (MPa)**	**Equivalent load radius of the tire footprint, *a* (m), using Eq.(6)**
MD 11	Dual tandem	274650	1055.095	1.41	0.488
Airbus 320-200	Dual tandem	73500	338.541	1.21	0.298
Boeing 747-400	Boggy	395987	908.077	1.41	0.453
Boeing 737-200	Tricycle	52616	234.615	0.66	0.336
Boeing 767-300	Dual tandem	159665	743.241	1.21	0.442
Fokker 50	Tricycle	20820	97.529	0.41	0.275
Fokker 100	Tricycle	44680	209.299	0.98	0.260
Dash 7	Tricycle	19867	91.118	0.74	0.197

Note: The details in first five columns are based on the information in the Aerodrome Design Manual (International Civil Aviation Organisation, 1983)

3.5 Model parameters

The general expression for deflection in Eq. (3.8) or Eq. (3.9) involves three independent parameters, namely modulus of subgrade reaction (k_s), contact pressure (p), and vertical component of aircraft velocity (v_v) prior to landing. The modulus of subgrade reaction (k_s) is a strength parameter for the pavement idealised as a single layer, linear elastic, homogeneous, and isotropic material. It can be evaluated by several approaches as described in the geotechnical and pavement engineering books (Yoder and Witczak, 1975; Selvadurai, 1979; Bowles, 1997; Mallick and El-Korchi, 2009).

3.6 Conclusions

Bringing the aircraft on a runway during landing phase with the lowest possible vertical and horizontal velocities is considered as a technically successful landing. The movement of material in the runway pavement layers due to landing impact results in deflection in the pavement. The runway pavement layers are complex structure and the runway pavements are classified as rigid or flexible.

Several methods to study the load-deflection behaviour of the runway pavement may be possible, but a mechanical modelling approach is preferred due to its simplicity for the analysis of structure to foundation interaction. This research has idealised the soil subgrade by Winkler springs and a general expression for dynamic deflection of the runway pavement has been derived. The expression can be used to calculate deflections of the runway pavements.

CHAPTER 4

DEFLECTION ANALYSIS AND PARAMETRIC STUDIES

4.1 General

Deflection in a runway pavement is primarily influenced by modulus of subgrade reaction, the vertical velocity, and impact pressure caused by the landing loads of the aircraft. Therefore, it is important to consider the aircraft mass and the vertical velocity in deflection analysis. The vertical velocity depends upon the type of aircraft and its aerodynamics characteristics. This chapter analyses the relationship between the deflection, vertical velocity, and impact pressure.

4.2 Deflection analysis

The contact pressure depends on the type of the aircraft and its specific values for several aircraft are given in Table 3.1. The vertical velocity component of an aircraft prior to landing varies with the aircraft types and the landing situations at the time of actual landing operations. This velocity is rarely reported in textbooks or research publications. According to the field experience of the author as a pilot, this velocity generally lies in a typical range of 0 to 3 m/s. According Guillaume (2012), the maximum allowable vertical velocity of an aeroplane with its maximum landing weight (MLW) at touchdown is 10 feet/sec. Similarly, Federal Aviation Administration (2012c) indicates that an aeroplane is expected to land on a runway with a descent velocity of 0 to 10 feet/sec at the MLW.

An aircraft in flight experiences three dimensional movements. Actually, everything above the surface of the earth is immersed in an air mass, the atmosphere. Besides, the lift force is needed to overcome the gravitational pull. Therefore, the aircraft uses lift forces produced from the difference of pressures against upper and lower surfaces of an aerofoil pursuant to the Bernoulli principles and pilot of the aircraft adjusts the lift forces using flight controls in order to minimise the load imposed by the aircraft on a runway pavement during landing. As a result, the aircraft stabilises on the runway and it transfers the imposed load to the runway gradually (Fig. 4.0).

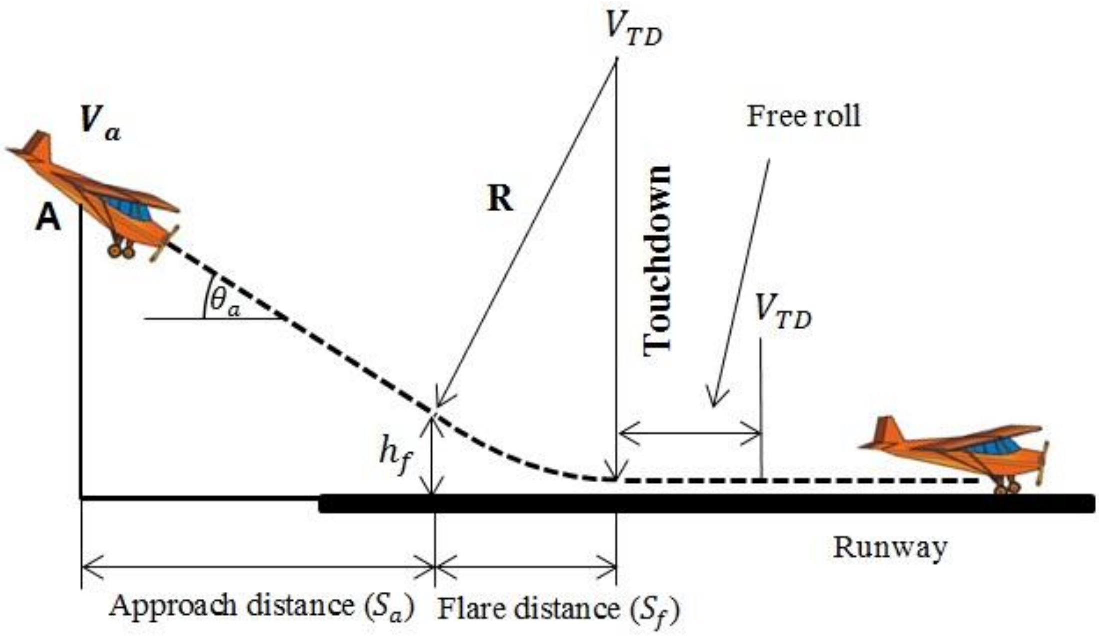

Fig.4.0. An aircraft flight path indicating flare profile during landing

Fig. 4.0 shows an airplane on a landing approach. At point *A*, the airplane is following a straight approach path with angle θ_a as indicated in the figure. The velocity of the airplane denoted by V_a at this point is required to be equal to 1.3 V_{stall}. The term V_{stall} is known as stalling speed[3] of the airplane (Anderson, 1999). At a distance of h_f above the ground, the aeroplane begins to flare, which is the transition from the straight approach path to the horizontal ground path. The flight path for the flare can be considered as a circular arc with radius *R*. The distance measured along the ground from the point *A* to the point of initiation of the flare is known as the approach distance S_a. Touchdown occurs when the wheels touch the runway pavement. The distance over the pavement covered during the flare is the flare distance S_f. The velocity of the aeroplane at the touchdown is 1.15 V_{stall} (Anderson, 1999). The airplane travels on the runway for few seconds after touchdown before coming to rest. This is known as free-roll. The free-roll distance is very short.

[3] Stalling speed is a minimum speed at which an aeroplane can be flown in steady level flight.

Therefore, the velocity over this length is assumed constant and equal to the velocity at touchdown V_{TD}. This phenomenon has been experienced by the author while landing the aircraft as a pilot. The gradual loading may be considered as static, and therefore the deflection caused by the aircraft landing is called static deflection (w_s), which may be given by

$$w_s = \frac{mg}{Ak_s} \tag{4.1}$$

Using Eq. (3.6), Eq. (4.1) can be expressed as

$$w_s = \frac{p}{k_s} \tag{4.2}$$

which is basically the response function of the Winkler foundation model.

During landing, it may be possible that the lift force balances the weight of the aircraft and brings the vertical velocity to zero almost instantly just before the touchdown. Therefore, it implies that the aircraft load is suddenly applied on the runway. Here, $v_v = 0$, and Eq. (3.8) gives

$$w = \frac{2p}{k_s} \tag{4.3}$$

Substitution from Eq. (4.2) into Eq. (4.3) yields

$$w = 2w_s \tag{4.4}$$

Many times, pilots are forced to go for the heavy landing, which is not considered as an ideal situation, because it may damage the aircraft and it reduces life of the runway pavement. This situation can be compared to the free fall of an object from a finite height as considered in the present study. Here, $v_v \neq 0$, and the general Eq. (3.8) or Eq. (3.9) can be used to determine the deflection of the runway pavement.

Substitution of Eq. (4.2) into Eq. (3.8) gives

$$w = w_s \left\{ 1 + \sqrt{1 + \frac{k_s v_V^2}{gp}} \right\}$$

or

$$w_{IF} = 1 + \sqrt{1 + \frac{k_s v_V^2}{gp}} \tag{4.5}$$

where

$$w_{IF} = \frac{w}{w_s} \tag{4.6}$$

is an impact factor. It is noticed that as v_v and/or k_s tends to zero, w_{IF} approaches 2 for any finite value of p. This also happens when p becomes extremely large with finite values of v_v and k_s. The impact factor w_{IF} can become extremely large when contact pressure p tends to be very small and/or pavement is rigid with a high modulus of subgrade reaction. Practically, a very high value of v_v is not allowed during aircraft landing, so the impact factor due to velocity cannot be expected to be extremely high.

In terms of nondimensional parameters, Eq. (4.6) is expressed as

$$w_{IF} = 1 + \sqrt{1 + \frac{v_v^{2*}}{p^*}} \tag{4.7}$$

4.3 Parametric studies

The runway pavement deflection depends upon the vertical velocity of the aircraft and the impact pressure at the time of touchdown on runway during landing. Fig. 4.1 shows the variation of the dynamic deflection (w^*) with the vertical component of the aircraft velocity (v_v^*) prior to landing for contact pressure p^*= 0.02, 0.04, 0.08, 0.1. It is observed that the deflection increases nonlinearly with an increase in vertical velocity for any value of contact pressure; the rate of increase is greater for higher values of vertical velocity as expected. For example, for p^*= 0.06, when v_v^* increases from 0.1 to 0.2, increase in w^* is 0.013, whereas this increase is 0.024 for an increase in v_v^* from 0.8 to 0.9.

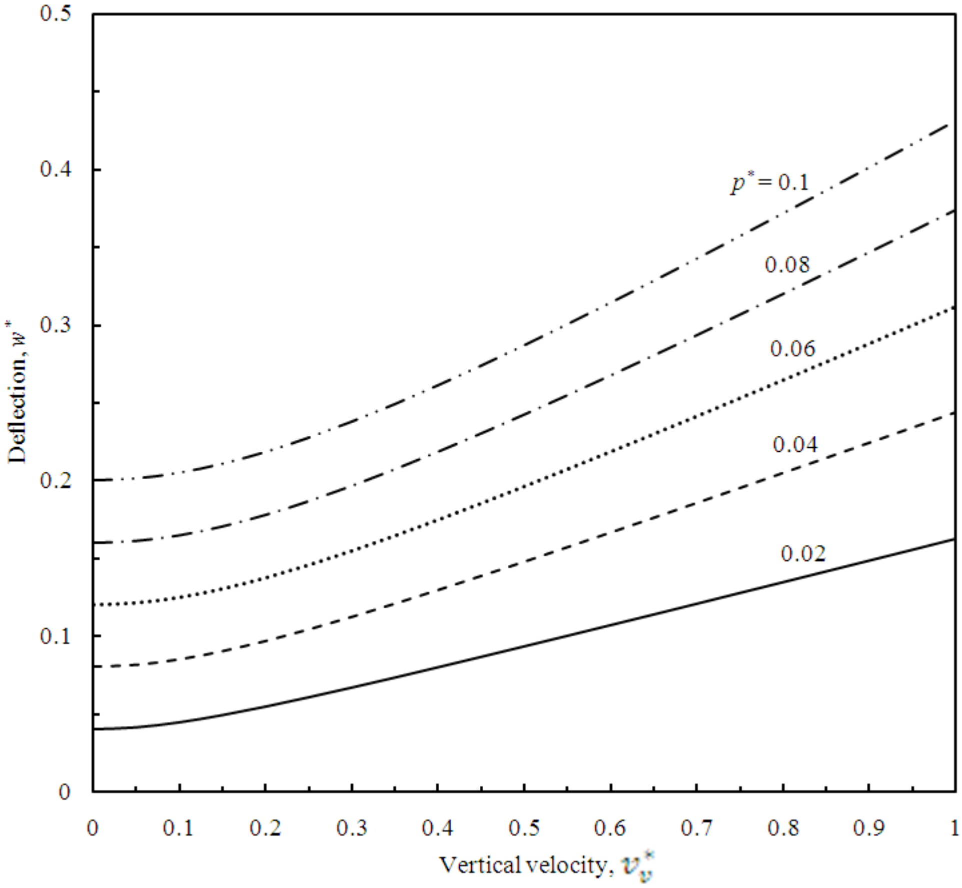

Fig.4.1. Variation in dynamic deflection with vertical velocity for different contact pressures in their nondimensional form

The effect of an increase in contact pressure p^* on the deflection can be noticed in Fig. 4.2. The deflection increases with an increase in contact pressure for any velocity, which is also an expected observation. For p^* less than about 0.01, the rate of increase in w^* is significantly greater for higher velocity.

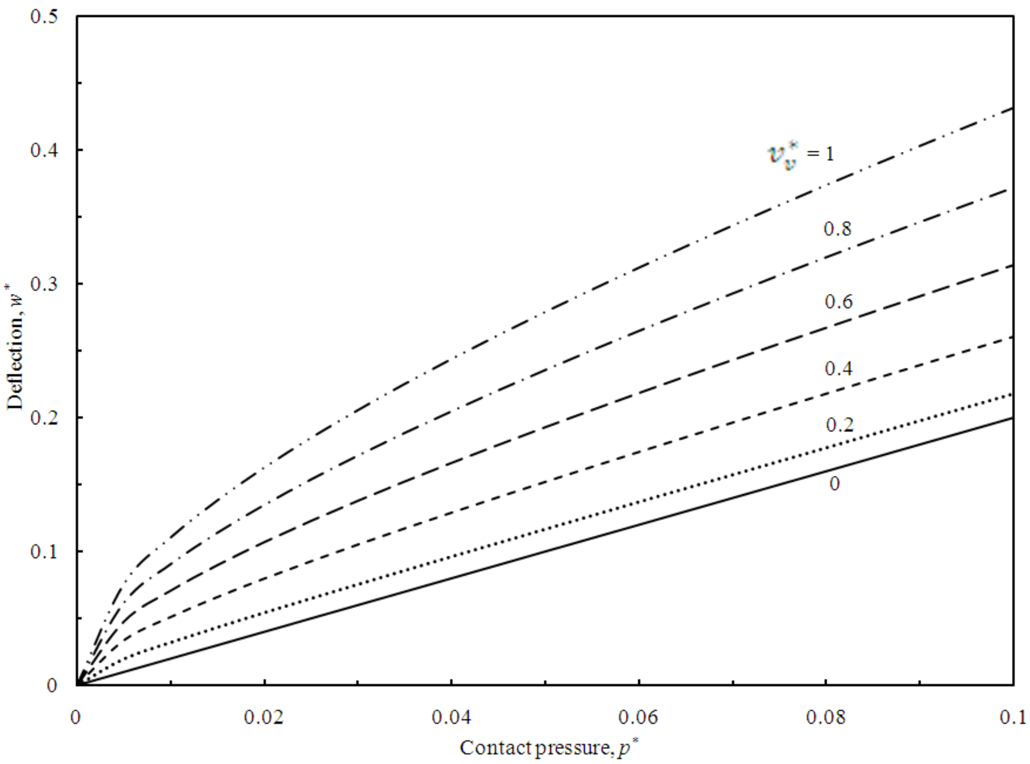

Fig.4.2. Variation in dynamic deflection with contact pressure for different vertical velocities in their nondimensional form

Fig. 4.3 shows the variation of the impact factor (w_{IF}) with the vertical component of the aircraft velocity v_v^* prior to landing for contact pressure p^*= 0.02, 0.04, 0.08, 0.1. It is observed that the impact factor increases with an increase in vertical velocity for any value of contact pressure.

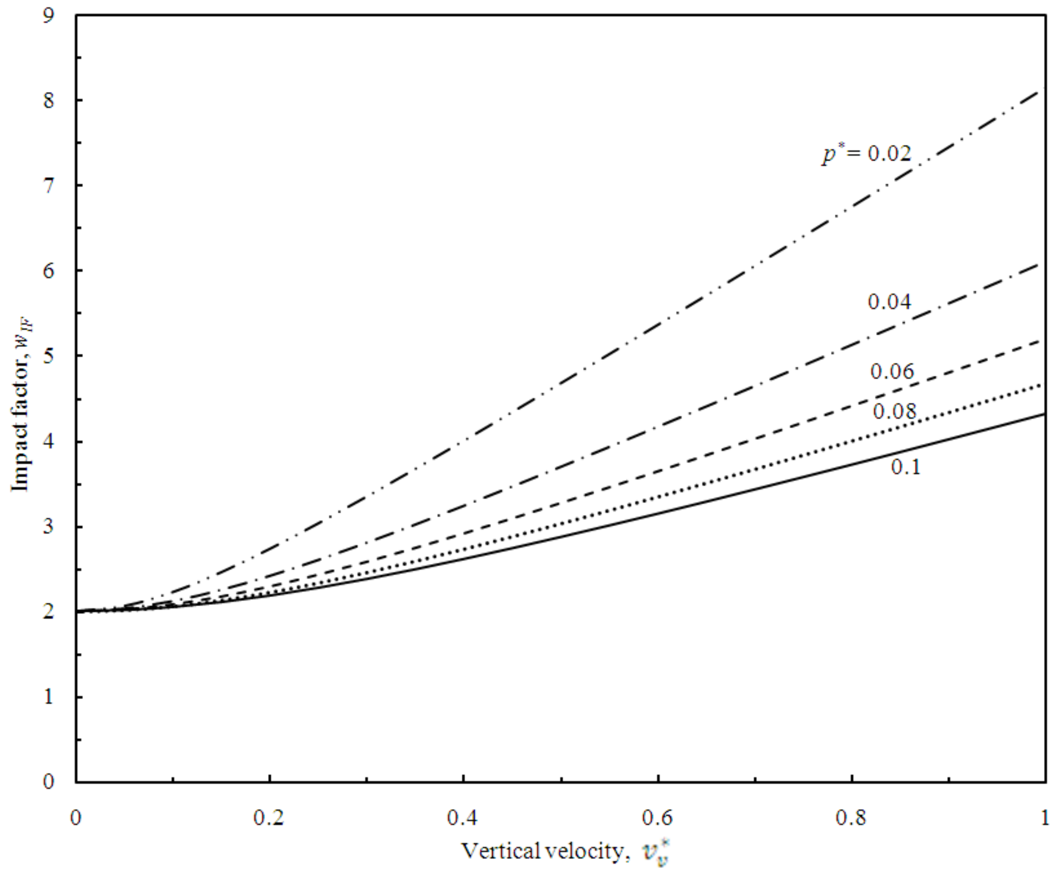

Fig.4.3. Variation in impact factor with vertical velocity for different contact pressures in their nondimensional form

For v_v^* = 0, the impact factor is 2, irrespective of the contact pressure values, which can also be seen in Fig. 4.4. This clearly shows the effect of contact pressure on impact factor. It is important to note that getting an impact factor of 2 is a real fact when the runway pavement is assumed to be elastic as it has been considered by representing the foundation by the Winkler model. It is observed that the w_{IF} becomes extremely large when contact pressure p^* tends to be very small. This occurs when p tends to become zero and/or pavement is rigid with a high modulus of subgrade reaction. It should be noted that values of v_v^* in Figs. 4.1 and 4.3 and the values of p^* in Figs. 4.2 and 4.4 vary continuously within their ranges considered.

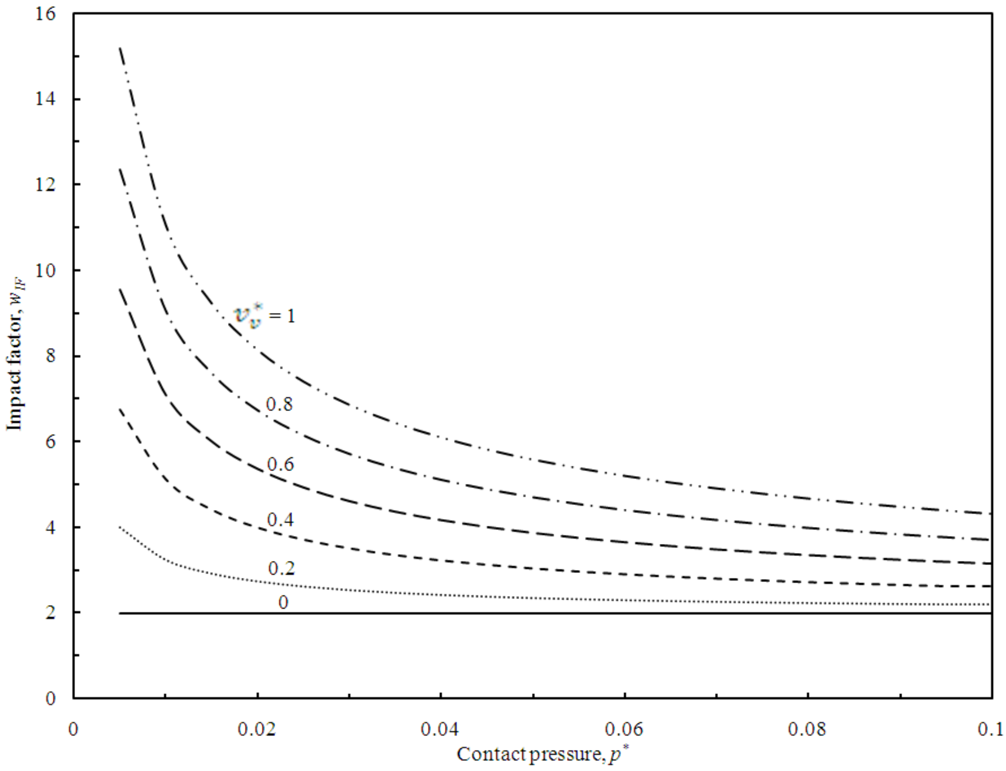

Fig.4.4. Variation in impact factor with contact pressure for different vertical velocities in their nondimensional form

The trends of variation of dynamic deflection obtained in the present study are well expected and they have been visually observed by the author at several runways in his aviation career. However, any attempt to compare the present observations with actual field data is encouraged for future studies in this area. Despite some simplified idealisations and assumptions, the present analytical deflection model can routinely be used for initial design stage of all types of runway pavements. Additionally, this model may be considered as a base for future development of more complex analysis on the concept described in this study for estimation of the runway pavement deflection.

4.4 Illustrative Example

From Table 3.1, for Boeing 747-400 aircraft,

Load on one main landing gear leg, $P = mg = 908.077$ kN
Tyre pressure, $p = 1.41$ MPa
Equivalent radius of the tire footprint, $a = 0.453$ m

Calculate the dynamic deflection of the runway caused by the gear load at the touchdown point considering the following:

Modulus of subgrade reaction, $k_s = 75000$ kN/m^3
Vertical component of velocity, $v_v = 1$ m/s

Also determine the impact factor.

Solution:
Using Eq. (3.8), dynamic deflection, $w = 0.0665$m = 66.5 mm
Using Eq. (4.5), impact factor, $w_{IF} = 3.5353$

Practising engineers may use the graphical presentations of Figs. 4.1 - 4.4 as the design charts to solve this problem. To use these charts, contact pressure and vertical velocity are first calculated in their nondimensional form as follows:

Contact pressure, $p^* = \frac{p}{k_s a} = 0.0415$
Vertical velocity, $v_v^* = \frac{v_v}{ga} = 0.4746$

For the preceding values of p^* and v_v^*, the dynamic deflection, $w^* \approx 0.1468$ is obtained from Fig. 4.1 or Fig. 4.2 with an interpolation while reading its value. Since $w^* = w/a$, therefore, $w = 0.1468 \times 0.453$ m = 0.0665 m = 66.5 mm.

Similarly, from Fig. 4.3 or Fig. 4.4, impact factor, $w_{IF} = 3.5353$

4.5 Conclusions

Primarily, the analytical expression involving three independent parameters known as modulus of subgrade reaction (k_s), contact pressure (p), and vertical component of aircraft velocity (v_v) prior to landing, can be used for predicting the dynamic deflection of the runway pavement at touchdown point caused by a gear load during aircraft landing. The dynamic deflection increases nonlinearly with an increase in vertical velocity for any value of contact pressure. Similarly, the rate of increase is greater for higher values of vertical velocity and it also increases with an increase in contact pressure for any velocity as expected. Likewise, the impact factor increases with an increase in vertical velocity for any value of contact pressure. For zero vertical velocity, the impact factor is *2*, irrespective of contact pressure values, for the elastic runway pavement as considered in the present work. It becomes extremely large when contact pressure tends to zero and/or pavement is rigid with a high modulus of subgrade reaction.

CHAPTER 5

TECHNICAL EVALUATION OF A RUNWAY PAVEMENT

5.1 General

Stringent civil aviation regulatory framework regarding aerodrome and the runway structure administered by national governments dominate the airport engineering field. The empirical methods of runway pavement's capability and evaluations based on ACN - PCN are still used for reporting the bearing strength of a runway pavement (International Civil Aviation Organisation, 2004). In the past, the aircraft were smaller and lighter, but with the introduction of fast and heavy aircraft, such as Airbus 380 a new approach to runway evaluation is needed.

Evaluation of a runway pavement is an indispensible tool in ensuring efficient utilization of the runway and safety of the aircraft. Primarily, it determines the requirements of maintenance to assess the residual qualities of the pavement with a view that enables technical and economic solutions. It also ascertains the type, mass of the aircraft that can use a particular runway, and the frequency of possible movements of the aircraft on a runway. Therefore, a runway pavement evaluation must undertake both the structural and functional characteristics of the pavement. This chapter is aimed at developing a new approach for technical evaluation of a runway pavement using deflection based analysis to predict runway capability and load bearing strength.

A typical flight includes various phases, but landing is considered as the most crucial phase of a flight to be performed. Improper landing may result in serious implications for the safety of aircraft and its occupants, if the runway conditions or qualities are compromised. The aircraft imposes a tremendous load on the runway during landing phase that causes deflection of the runway. Consequently, the runway technical evaluation results are largely influenced by the potential deflection, which primarily depends on the load-bearing characteristics of the runway pavement layers. Achieving an accurate estimation of the deflection in relation to landing loads is a fundamental difficulty in interaction analysis. This chapter examines the possibilities of using an analytically developed deflection model for runway technical evaluation in field applications. To this end, the study evaluates the loads imposed by an aircraft on runway during landing, discusses the performance of runway pavement, and reviews the runway evaluation practices of contracting states of the International Civil Aviation Organisation. Overall, the discussion instigates a new approach for technical evaluation of a runway pavement using deflection based analysis.

According to International Civil Aviation Organisation (2004), a runway pavement evaluation can be carried out by technical method representing a specific study of the pavement characteristics. Alternately, it can be done by using the aircraft experience representing a specific type of aircraft satisfactorily being supported under regular use. The ICAO allows the use of any of these methods at the discretion of the airport owner. However, both of these methods are based on empirical approaches and there are not enough analytical data available in public domain. This study argues that the pavement load bearing strength and serviceability of a runway pavement can be predicted by calculating deflection caused by the aircraft of various masses and equivalent single wheel load (ESWL). The study also recommends that a maximum allowed deflection threshold can be agreed upon for safe operation similar to the deflection limits set for roads. It is believed that this new concept of pavement evaluation using deflection method may revolutionise the runway field practices due to its simplicity and desk based solution unlike the empirical methods.

5.2 Runway pavement performance factors

An aerodrome runway pavement should be capable of withstanding the intended traffic loads caused by the aeroplanes during landing, takeoff, and taxi (Fig.1.2). Runways shall be constructed with minimum surface irregularities and the load bearing strength of the pavement must be suitable for the intended aircraft type, mass, and other factors. The surface irregularities may adversely affect the operation of the aircraft by creating excessive bouncing, pitching, vibration, and uncontrollability during takeoff and landing. Similarly, the inappropriate load bearing strength of the pavement may cause a significant deflection at the runway touchdown zone that may jeopardize the safety of the aircraft. Therefore, the bearing strength of the runway pavement is required to be reported in aeronautical information publication (AIP) of the concerned country (International Civil Aviation Organisation, 2004). The ICAO has adopted a pavement classification system for reporting airfield strength. The bearing strength of the pavement is reported by indicating the PCN, pavement type, subgrade category, allowable tyre pressure, and basis of the evaluation.

Vertical velocity of an aircraft during landing is one of the important factors that cause deflection of the runway pavement at touchdown point. The effect that an aircraft has on a runway pavement varies with the aircraft's all-up mass (AUM), tyre pressure, number and spacing of the wheels, and type and thickness of the pavement (Swatton, 2008). An undesirable amount of movement of material from the runway pavement due to aircraft landing loads causes distresses on the pavement. As a result, the runway pavement deteriorates progressively and it fails in the long run. Consequently, the runway design requirements and pavement evaluation are largely affected by the potential deflection, which primarily relates to the California bearing ratio (CBR) or the modulus of subgrade reaction of the soil subgrade of the runway (Ashford & Wright, 1992; Horonjeff and McKelvey, 1994). Therefore, the runways are classified according to their strength and they are given a load classification number (LCN) or single wheel loading (SWL) of its weakest point (Swatton, 2008).

An aircraft performance operating limitations require a length of runway, which is enough to ensure that the aircraft can either be brought safely to a stop or complete the takeoff safely after starting a take-off run. For the purpose of discussion, it is supposed that the runway, stopway, and clearway lengths provided at the aerodrome are only just adequate for the aircraft requiring the longest takeoff and accelerate-stop distances taking into account its take-off mass, runway characteristics, and ambient atmospheric conditions. According to the International Civil Aviation Organisation (2004), the takeoff must be abandoned or completed depending upon takeoff decision speed, if an engine fails during the takeoff. A very long takeoff run and takeoff distance would be required to complete a takeoff when an engine fails before the decision speed is reached due to insufficient speed and reduced power. Therefore, the surface characteristics and bearing strength of the runway pavement play a crucial role in safety of the aircraft under these emergency situations.

Stress and strain caused by frequency of loading lead a structure to irreversible damages and failure (Kulyk et al., 2011). Therefore, the areas subjected to repeated loadings due to landing must be designed to accommodate stresses. According to International Civil Aviation Organisation (1983), the previous observations have shown a strong general correlation between deflection of a pavement under a wheel load and repetitive landing applications of that wheel load resulting in severe deterioration and failure of the pavement. Therefore, it can be established that the performance of a runway pavement is directly related to the landing loads imposed by the aircraft at touchdown. However, it is extremely difficult to precisely define the pavement functional failure, because it deteriorates gradually over a period of time.

5.3 International practices of runway pavement evaluation

The runway pavement is subjected to both dynamic and static loading due to the aircraft landing and taxiing. However, the dynamic loading has a greater effect in touchdown zone as compare to runway threshold area due to heavy impact load caused by the aircraft landing. The runway pavement evaluation has been a major issue since the inception of international civil aviation. Therefore, the study of runway pavement deterioration and the related influencing factors are important to pavement engineers. With an extensive network of airports with paved and unpaved runways around the world, the cost of maintaining or replacing the pavements can become astounding. Furthermore, deteriorated runway pavement affects the aircraft structure and the life of landing gears that ultimately affect the safety and airworthiness of the aircraft. These factors add to the cost of flight operations, such as fuel and aircraft maintenance expenses.

The runway pavement evaluation starts with subgrade strength, thickness requirement, quality of pavement structure, and uses a design procedure pattern to determine the aircraft loading that a pavement can support (International Civil Aviation Organisation, 1983). According to Wood (2008), one of the simplest methods for measuring pavement profile is the surveying equipment like the auto rod and level. This method can be very time consuming and requires at least two people for operation. The profile can also be measured by non-contact high-speed digital profilers. The profile measurement helps in quantifying pavement roughness, which provides a valuable statistics for pavement maintenance planning and repair actions. Therefore, an efficient method of pavement evaluation is necessary for the effective management of a runway pavement system. The ICAO recommended practices on this issue use various indices developed for runway design and pavement evaluation (International Civil Aviation Organisation, 1983). Though it is not within the scope of this project to develop additional index, this study uses those indices to discuss the possibility of deflection based pavement evaluation practice.

Primarily, heavy loading, and a high frequency of loading deteriorate a pavement and they may also shorten the design life of the pavements. However, a pavement can sustain a definable load for an expected number of repetitions during its design life. Occasional minor over-loading is acceptable with only limited loss in pavement life expectancy, but civil aviation regulations require that the runway must be inspected for surface friction, slipperiness, roughness, cracks, and rutting at a predetermined interval (Civil Aviation Safety Authority, 2007a). Furthermore, the pavement structures of the runways and taxiways are required to meet the international standards recommended by the ICAO (International Civil Aviation Organisation, 2004). A frequent deterioration of the pavements occurs in aircraft wheel path areas of a runway due to high stresses imposed by the aircraft movements on the pavement. This requires a closely scheduled preventive and on-condition maintenance of the pavement to ensure safety of the aircraft and also to meet the regulatory requirements. Consequently, it adds cost to the airport operations and it also causes disruption to flight schedules at the airports by preventing aircraft operations while the pavement is undergoing maintenance.

In order to establish consistency in aeronautical practices related to the runway pavements around the world, the ICAO has formulated certain standards to be followed by civil airports (International Civil Aviation Organisation (2004). The evaluation can be carried out by representing a specific study of the pavement characteristics and application of pavement behaviour technology or by using an aircraft representing knowledge of the specific type and mass of the aircraft satisfactorily being supported under regular use. According to the set criteria occasional movements by aircraft with ACN not exceeding ten percent above the reported PCN is acceptable for flexible pavement. Similarly, occasional movements by aircraft with ACN not exceeding five percent above the reported PCN are accepted as standard practices. However, if the pavement structure is unknown, the five percent limitation apples and the annual number of overload movements should not exceed approximately five percent of the total annual aircraft movements. Additionally, the overload movements are not normally permitted on pavements with indications of deterioration or weakened subgrade. ACNs of various aircraft types are linked with rigid and flexible pavements according to the soil subgrade categories for pavement bearing strength reporting purpose. Furthermore, civil aviation regulations require that the runway must be inspected for surface friction, slipperiness, roughness, cracks, and rutting at a predetermined interval (Civil Aviation Safety Authority, 2007a).

Bearing strength of the pavement is reported by indicating the PCN, pavement type, subgrade category, allowable tyre pressure, and method of technical evaluation (International Civil Aviation Organisation, 2004). However, in some unavoidable situations, such as heavy landings the pavement deflection may become extremely high. This is undesirable from the point of view of service life of the runway pavement. Most of the pavement designs for deflection are based on prescriptive standards and empirical knowledge gained through long experience of the runway history (International Civil Aviation Organisation, 1983). The general practice is to present a plot of pavement thickness required to support the aircraft loading as a function of subgrade bearing strength for flexible pavements. Similarly, a rigid pavement design curve for a given aircraft is made as a plot of concrete slab thickness required to support the aircraft loading as a function of bearing modulus of the surface on which the slab rests. Though the working stresses are used for design and evaluation of pavement, but they have no relationship to the standard stress for reporting. Similarly, the results of pavement research affirm that the tyre pressure effects are secondary to load and they are categorized in four groups known as high, medium, low, and very low for reporting purpose (International Civil Aviation Organisation, 1983).

Currently, two mathematical models are used in the ACN-PCN method known as the Westergaard solution for a loaded elastic plate on a Winkler foundation (interior load case) for rigid pavements, and the Boussinesq solution for stresses and displacements in a homogeneous isotropic elastic half-space under surface loading for flexible pavements (International Civil Aviation Organisation, 1983). The use of these two widely used models permits the maximum correlation to worldwide pavement design methodologies with a minimum need for pavement parameter values. Additionally, the computer programmes have been developed using these mathematical models by various researchers, but these programmes were replaced later by reference tables for field use (International Civil Aviation Organisation, 1983). Similarly, the aircraft for which pavement thickness requirement charts have been published by manufacturers of the aircraft can also be evaluated using their graphical procedures.

According to the International Civil Aviation Organisation (1983), a rigid pavement evaluation procedure uses the conversion chart as shown in Fig.5.1 and the pavement thickness requirement charts published by the respective aircraft manufacturers. Fig.5.1 relates the derived single wheel load (DSWL) at a constant tire pressure of 1.25 MPa to a reference pavement thickness. It takes into account the four standard subgrade *k* values and a standard concrete stress of 2.75 HPa. Fig.5.1 also includes an ACN scale, which permits the ACN to be read directly. It may be noted that the tyre pressure corrections are not required under this procedure. Likewise, the flexible pavement procedure uses the conversion chart as shown in Fig.5.2 and the pavement thickness requirement charts published by the aircraft manufacturer. The reason for using the manufacturer’s charts is to obtain the equivalency between the effects of a group of landing gear wheels to a DSWL means of Boussinesq deflection factors.

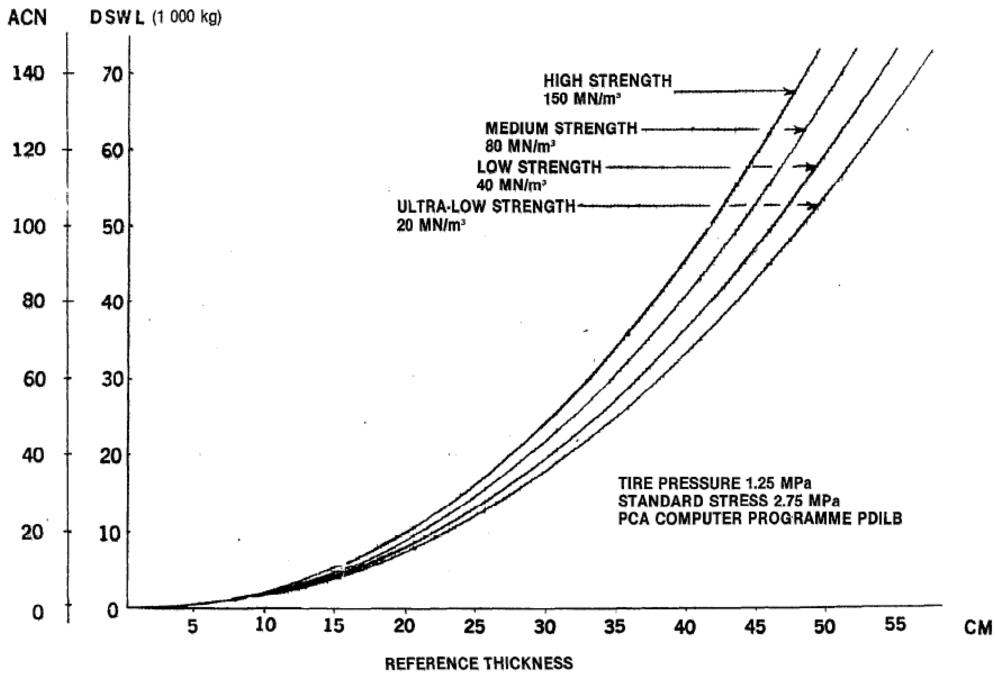

Fig.5.1.ACN rigid pavement conversion chart

(After International Civil Aviation Organisation, 1983)

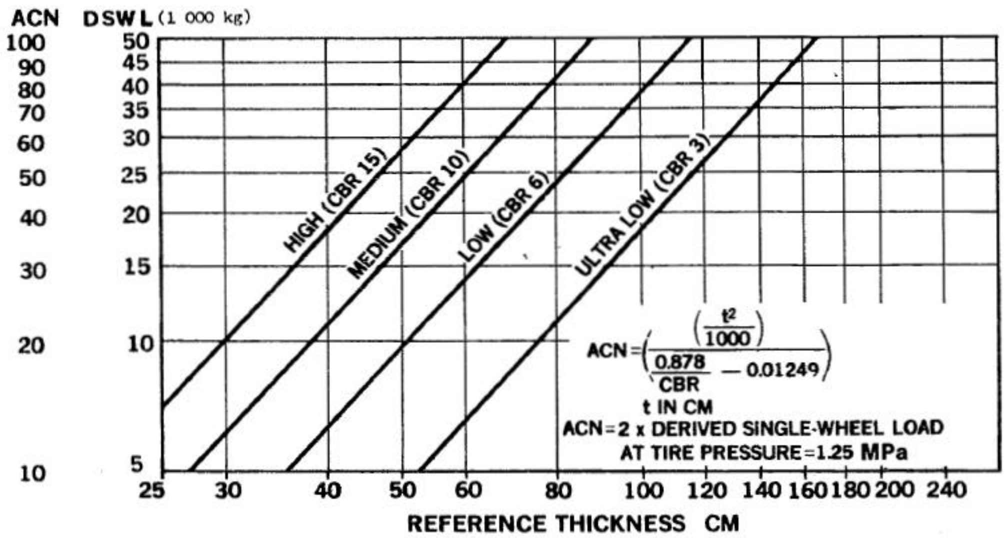

Fig.5.2. ACN flexible pavement conversion chart

(After International Civil Aviation Organisation, 1983)

5.4 Practices of major states of the ICAO

The evaluation of a runway pavement structure for an aircraft loading requires accurate information about thickness of layers within the structure as well as the physical properties of the materials in these layers. The International Civil Aviation Organisation (1983) mentions that a bore-hole survey can be conducted to determine this information under Canadian practice, if the information is not available from existing construction records. Equivalent granular thickness applied to a flexible pavement structure is the basis for comparing pavements constructed with different thicknesses of materials having different load distribution characteristics. The equivalent granular thickness is computed through the use of the granular equivalency factors for pavement construction materials listed in Table. 5.1. The granular equivalency factor of a material is the depth of granular base in centimeters considered equivalent to one centimeter of the material on the basis of load distribution characteristics. To determine equivalent granular thickness of a flexible pavement structure, the depth of each layer in the structure is multiplied by the granular equivalency factor for the material in the layer. The pavement equivalent granular thickness is the sum of these converted layer thicknesses.

According to the International Civil Aviation Organisation (1983), the Canadian practice is to conduct measurements of bearing strength on the surface of flexible pavements. However, the testing is not to be conducted until at least two years after construction to permit subgrade moisture condition reaches an equilibrium state. Conversely, the bearing strength of a rigid pavement is not normally measured; as the strength calculated on the basis of slab thickness and estimated bearing modulus are considered sufficiently accurate. The standard measure of bearing strength is the load in kilonewtons (kN), which will produce a deflection of 12.5 millimeter for ten repetitions of loading when the load is applied through a rigid circular plate of 762 millimeter in diameter. This definition applies for subgrade bearing strength as well as for measurements conducted at the surface of a flexible pavement. However, in actual practice, a variety of test methods are employed to measure bearing strength. These methods include both repetitive and non-repetitive plate load test procedures in which a range of bearing plate sizes may be used.

Table.5.1. Granular equivalency factor

(After International Civil Aviation Organisation, 1983)

S.No.	Pavement Material	Granular Equivalency Factor
1	Selected granular subbase	1
2	Crushed gravel or stone base	1
3	Waterbound Macadern base	1 - ½
4	Bituminous stabilized base	1 - ½
5	Cement stabilizes base	2
6	Asphaltic concrete (good condition)	2
7	Asphaltic concrete (poor condition)	1 - ½
8	Portland cement concrete (good condition)	3
9	Portland cement concrete (fair condition)	2 - ½
10	Portland cement concrete (poor condition)	2

When a bearing strength measurement has been made on the surface of a flexible pavement, and the equivalent granular thickness of the pavement structure is known, the subgrade bearing strength at that location may be estimated. The subgrade bearing strengths are normally established at existing airports through bearing strength measurement programme. Subgrade bearing strength values derived from measurements are used when designing new pavement facilities at the airport provided the subgrade soil conditions are similar throughout the site (International Civil Aviation Organisation, 1983). However, while evaluating pavements at an airport where strength measurements have not been made, a value of subgrade bearing strength is selected on the basis of subgrade classification. In addition to the pavement bearing strength evaluation, airport pavements are subject to an evaluation of surface conditions under Canadian practice (International Civil Aviation Organisation, 1983). The surface condition evaluation program consists of a visually based structural condition survey and quantitative measurements of roughness and friction levels on the runway surfaces.

Under French practice of a runway pavement evaluation, two approaches known as reverse design method (RDM) and non-destructive (NDT) plate loading tests are used (International Civil Aviation Organisation, 1983). The RDM uses subgrade data to determine a pavement structure that can bear a given traffic over a certain life, provided a normal maintenance of the pavement is performed. Conversely, once the characteristics of the subgrade and pavement structure are known, this method enables the traffic that can be accepted during a given time to be determined. According to International Civil Aviation Organisation (1983), the foregoing is the basis for evaluation of bearing strength of a runway pavement by means of RDM. However, considerable difficulties are encountered in determining the structural parameters that must be taken into account in evaluating a pavement and its subgrade when this method is used by itself. Even if the records of the pavement construction, maintenance, past reinforcement work, and accepted traffic are available, this method requires many trial borings and testing of the pavement. Moreover, the difficulties in obtaining some required parameters results in uncertainties under this method. Therefore, the RDM can only be used for a correctly constituted pavement. The NDT plate loading test on the surface of a runway pavement indicates an actual allowable load for a single wheel leg. However, the International Civil Aviation Organisation (1983) denotes that a NDT plate test can directly provide the allowable load for a single wheel at a large number of points on a flexible pavement and the allowable load at the corners of slabs in case of a rigid pavement. Therefore, these tests are insufficient to determine the allowable load for an aircraft with multiple wheels undercarriages.

Currently, a number of computer programme based on the plate test theory, multilayer elastic theory, and finite element analysis are available to obtained tabulated data for a pavement evaluation. According to the International Civil Aviation Organisation (1983), a reference construction classification (RCC) system has been developed in United Kingdom from the British load classification number and load classification group (LCG). Under the system, a simple two layer model is adopted for the reaction of an aircraft on a rigid pavement and the model is analyzed by Westergaard centre case theory to establish the theoretical depth of reference construction of an aircraft on a range of subgrade support values equating to the ACN-PCN method of the ICAO. Under this analysis, the effect of adjacent landing gear wheel assembly up-to a distance equal to three times the radius of relative stiffness is considered. Similarly, a range of equivalency factors appropriate to the relative strengths of indigenous construction materials is adopted to convert between theoretical model reference construction depths and actual pavement thickness. Consequently, the practical problems of the runway pavement evaluation are resolved using equivalency factors to relate materials and layer thicknesses to the theoretical model on which the reference construction depths for the aircraft are assessed.

The International Civil Aviation Organisation (1983) confirms that the practices approved by the Federal Aviation Administration (FAA) of the United States of America (USA) for a runway pavement evaluation uses the aircraft gross weight and types of undercarriages to predict the bearing strength of the pavement. This permits the evaluation of a pavement in respect of its ability to support various types and weights of the aircraft. The FAA believes that the runway pavements are designed for an anticipated load carrying capacity. Therefore, they must be evaluated based on their respective design method originally used. Hence, the FAA recommends the use of RDM for evaluation of flexible pavements. Similarly, the rigid pavement design curves and other parameters, such as slab thickness and annual aircraft departures are taken into consideration to establish the load carrying capacity of a rigid pavement runway.

5.5 Runway pavement evaluation using deflection analysis

A runway pavement and the operating aircraft represent an interactive system that must be recognized in the pavement evaluation processes. The evaluation of a runway pavement is a complex engineering problem, which involves a large number of interacting variables. For example, the velocity of dynamic and impact loads applied by an aircraft on a runway pavement significantly influences the pavement responses. Therefore, the issues associated with both the aircraft and the pavement should be considered while carrying out runway pavement evaluation in order to achieve satisfactory results.

The aircraft landing phase is one of the most crucial sections of a typical flight and it commences when the airplane reaches 1000 feet above the ground level (AGL) and ends at the point where the airplane reaches to the full-stop after landing on the runway (Swatton, 2008). According to Kopecki (2006), aircraft disasters are much more frequent during approach and landing as compared to other phases of flight. A typical landing begins with the aircraft in approach mode and starts descending from 50 feet AGL as shown in Fig.5.3 (Hull, 2007). The aircraft is flared to rotate the velocity vector parallel to the ground, as it reaches close to the runway surface and the landing phase ends when the aircraft comes to the rest.

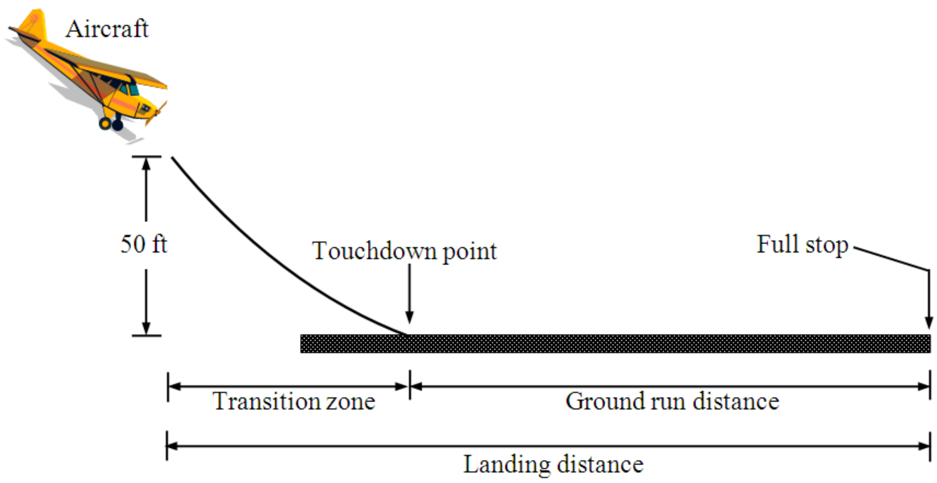

Fig.5.3. Aircraft in approach phase of landing

In Fig. 5.4, the weight is resolved into two components that act in the same rectangular coordinate system as the lift and drag forces. The aircraft approach path makes an angle θ with the horizontal. The component of weight acting in the vertical axis of the aircraft becomes $W \cos\theta$. This component acts through the centre of gravity (CG) of the aircraft opposite to the lift L. The longitudinal component of the weight opposite to drag D is $W \sin\theta$. Therefore, once the approach is stabilised and the aircraft attains the equilibrium again, the force equations become:

$$L = W \cos\theta \tag{5.1}$$

$$D = T + W \sin\theta \tag{5.2}$$

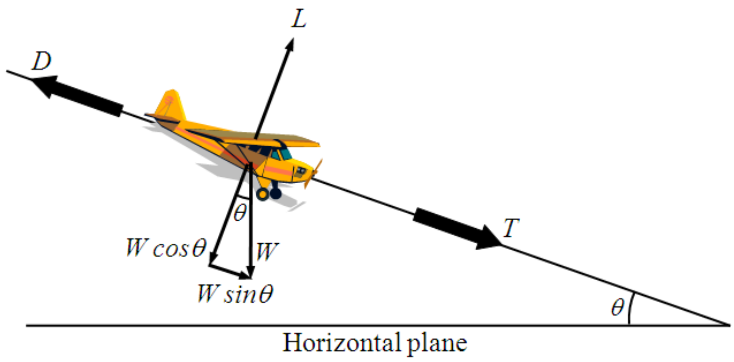

Fig.5.4. Forces acting on an aircraft during descent

[Note: T = thrust, D = drag, L = lift, W = weight of aircraft, θ = angle between the aircraft flight path to the horizontal plane]

Under standard aeronautical practices, the landing approaches, which are made at a glideslope angle of 3° or less, are classified as the normal landing approaches (Federal Aviation Administration. (2007). Various approach paths with respect to touchdown points as shown in Fig. 5.5 are possible for a typical landing. The path (a) is too steep with respect to the touchdown point. Therefore, the aircraft needs to descend at a high rate of descent (ROD). The high ROD results in a greater load factor at the time of landing. On the contrary, the path (c) indicates an overly flattened path and aircraft requires a high thrust component to reach to the touchdown point.

The aeroplanes are aerodynamically designed for high lift-to-drag ratio and the lift coefficient decreases as this ratio decreases. As a result, the stalling speed of the aircraft increases. Therefore, the touchdown speed is required to be maintained greater than the stalling speed of the airplane (Fig.4.0). According to Hull (2007), it is expressed as:

$$V_{TD} = 1.2\, V_{stall} \tag{5.3}$$

where, V_{TD} and V_{stall} are the speed at touchdown and stalling speed respectively.

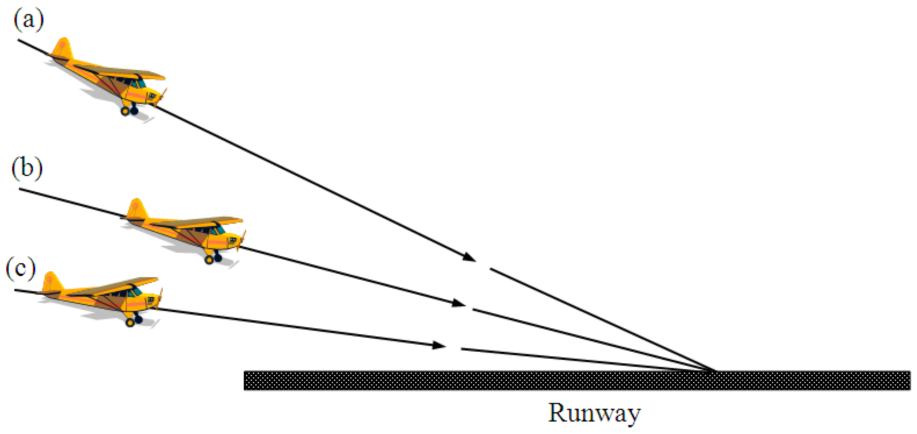

Fig.5.5. Various approach paths during landing

The lift coefficient C_L depends on various factors including angle of attack, but the total lift produced by the wings can be expressed as (Barnard and Philpott, 2006):

$$L = C_L \, \frac{1}{2} \, \rho V^2 S \tag{5.4}$$

where, L, ρ, V, S are the lift, air density, speed of airplane, and the surface area of the wings, respectively. When an airplane is in equilibrium in straight and level flight (θ = 0^0), Eq. (5.1) reduces to

$$L = W \tag{5.5}$$

From Eq. (5.4) and (5.5),

$$W = C_L \, \frac{1}{2} \, \rho V^2 S \tag{5.6}$$

The aircraft experiences the reduction in lift during landing and the weight component becomes larger than the lift due to reduction in aircraft velocity. The velocity of the aircraft reduces due the reduction in thrust during landing. Therefore,

$$W \propto C_L \frac{1}{2} \rho V^2 S \tag{5.7}$$

Let us consider the flight of an airplane while landing under the influence of the force of gravity and with minimal thrust. The lift is now acting at right angle to the flight flared flight path, while the drag acts directly backwards parallel to the flight path. Therefore, it can be seen that the angle formed between the total aerodynamic forces is same as the angle θ between the flared flight path and the runway. This angle can be called as the flare angle. Hence, the relationship between drag and lift can be expressed as:

$$\frac{D}{L} = \tan\theta \tag{5.8}$$

Therefore, the greater the value of $\frac{L}{D}$, the higher the flare angle would be. The bigger flare angle means the greater C_L. As far as possible, the lift/drag ratio at the time of touchdown should be at maximum in an ideal landing.

The accumulated periods of over-stresses can create a detrimental effect on useful service life of any runway pavement structure. Due to ultimate factor of safety in aviation, the limit load condition is rarely used as the critical design point and the structure usually possess a large positive margin of the strength. This fact alone implies that the structure must be grossly overstressed to produce an easily detectable damage. Similarly, the gross weight of the aircraft and the ROD at touchdown are considered as the primary factors responsible for the ground loads imposed by the aircraft on a typical runway during landing. Overstressing due to any of these forces may cause damages to the aircraft structure including landing gears and it also contributes to runway rutting.

One of the primary functions of the landing gears and a runway pavement is to absorb the vertical energy of the aircraft at touchdown during landing phase. An aircraft at a given weight and ROD at the touchdown has a certain kinetic energy that must be dissipated by the landing gear and the runway pavement. The impact of falling weights on the earth generates dynamic stresses that attenuate away from the point of impact (Mayne and Jones, 1983). The load placed on the landing gear increases as the square of any increase in the vertical rate of descent (Rozelle et al., 2004). Therefore, civil aviation regulations of the USA require the landing gear of transport category aeroplane must withstand touchdown load at a ROD of 12 feet/sec with the aeroplane at its maximum landing weight with a vertical acceleration of 1.0g (Federal Aviation Administration, 2012c). Aircraft manufacturers publish vertical acceleration thresholds that can be recorded by flight data monitoring equipment in view of hard landing limitations. Based on load components and aircraft roll and pitch angles (Fig. 5.6 and Fig. 5.7), the vertical acceleration can also be calculated using following expression (Guillaume, 2012):

$$a^z = g\,.(1 + \sin\theta\,.L_{long} - cos\theta\,.\; sin\emptyset\,.L_{lat} - cos\theta\,.cos\emptyset\,.L_{vert}) \qquad (5.8a)$$

where a^z, L_{long}, L_{lat}, L_{vert} are vertical acceleration, load component along longitudinal axis *x*, load component along lateral axis *y*, and load component along vertical axis *z* of the aeroplane, respectively (Fig. 5.6 and Fig. 5.7). Therefore, vertical acceleration varies in accordance with the aircraft weight, centre of gravity, pitch and roll motion.

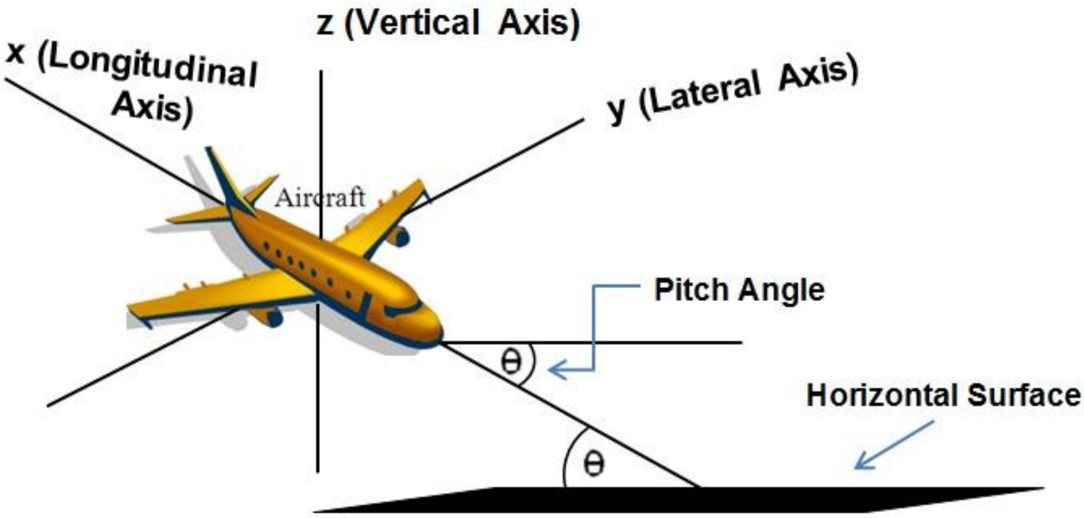

Fig.5.6. Aircraft axis and pitch angle during descent

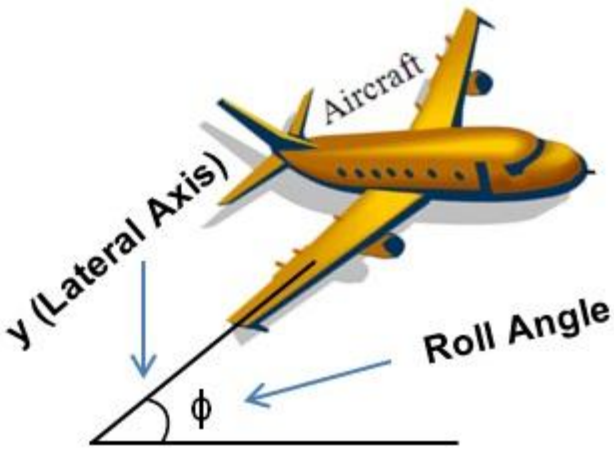

Fig.5.7. Aircraft roll angle during flight

The vertical landing loads resulting at touchdown can be simplified by assuming the action of the landing gear shock absorbers to produce a uniformly accelerated motion of the aircraft (Hurt, 1965). Therefore, the landing load factor n for touch down at a constant rate of descent is expressed as a ratio of the load in landing gear shock strut F to the aircraft weight W as given below:

$$n = \frac{F}{W} \tag{5.9}$$

The landing load factor *n* can also be expressed as

$$n = \frac{(rate\ of descent\ of\ aircraft)^2}{2gS} \tag{5.10}$$

where g and S are the acceleration due to gravity and effective stroke of the strut, respectively.

Hence, the average total force F_{total} applied by the aircraft to the runway during landing can be calculated by multiplying the load factor *n* to the gross weight of the aircraft at the time of touchdown. Therefore,

$$F_{total} \ = W + n \ \times W = (1+n)W \tag{5.11}$$

According to Eq. (5.11), the total force is directly proportional to the gross weight of the aircraft. Therefore, a higher gross weight produces the greater force depending upon the load factor. However, *S* will be influenced significantly by the factors, such as the internal friction forces within the shock absorber, the aircraft approach profile during landing, landing techniques, wind direction, and the wind velocity at the time of touchdown.

The overall distribution of the aircraft mass between nose and main undercarriage legs depends upon the load distribution of the aircraft and its centre of gravity (CG) at the time of touchdown on runway. According to the International Civil Aviation Organisation (1983), five percent and ninety five percent of the gross weight of a conventional aeroplane aircraft is carried by the nose leg (maximum forward load distribution) and the main undercarriage legs (maximum rearward load distribution), respectively. Therefore, the runway pavement design and evaluation are carried out using these figures of load distribution. However, the effect of braking action is not taken into account in evaluation of pavement. It plays a role only in specific studies, such as investigating the behaviour of the structures underneath the runway.

Therefore, the stresses caused by the main undercarriage legs of the aircraft are generally taken into consideration for pavement evaluation practices.

The International Civil Aviation Organisation (1983) mentions that the theories applied earlier to pavement behaviour have indicated proportionality between load and deflection. Thus the deflection should be an indicator of capacity of a pavement to support load. This also implied that a pavement deflection determined for a particular applied load could be adjusted proportionately to predict the deflection, which would result from other loads. Hence this can be used as a method for technical evaluation of a runway pavement. Many controlled tests and carefully analysed field experience confirm a strong relation between pavement deflection and the expected load repetitions life of a pavement subject to the load that caused the deflection (International Civil Aviation Organisation, 1983).

As discussed in earlier chapters of this thesis, the runway pavement can be idealised by mechanical model, such as the Winkler foundation model to carry out deflection analysis for the purpose of runway pavement evaluation. A similar mechanical concept has recently been applied by Sawant (2009) for deflection analysis of the runway pavement. It was observed that the maximum deflection decreases with increasing soil modulus and the velocity of moving load significantly influenced the pavement responses. Fig.3.5 shows the earliest and simplest model proposed by Winkler (1967). It is a one-parameter model consisting of closely spaced and independent linear springs. This model assumes that the deflection w of the foundation soil at any point on the surface is directly proportional to the stress q applied at that point and independent of stresses applied to other locations. Selvadurai (1979) also supports an argument that the Winkler model represents an accurate idealisation of operating conditions in many engineering applications.

According to Fig.3.5, the vertical component of the velocity of aircraft during touchdown causes an impact load on the runway pavement. The aircraft load is transmitted to the pavement through landing gears of the aircraft. According to the International Civil Aviation Organisation (1983), the number of wheels, their spacing, tyre pressure, and tyre size determine the distribution of aircraft load to the pavement. For the closely spaced wheels of dual and dual-tandem legs and even for adjacent legs of aircraft with complex undercarriages the effects of distributed loads from adjacent wheels overlap at the subgrade (and intermediate) level. In such cases, the effective pressures are those combined from two or more wheels and must be attenuated sufficiently by the pavement structure. Since the distribution of load by a pavement structure is over a much narrower area on a high strength subgrade than on a low strength subgrade, the combining effects of adjacent wheels is much less for pavements on high strength than on low strength subgrades. Hence, the relative effects of two aircraft types are not the same for pavements of equivalent design strength, and this is the basis for reporting pavement bearing strength by subgrade strength category. Within a given subgrade strength category the relative effects of two aircraft types on pavements can be uniquely stated with a good accuracy.

The International Civil Aviation Organisation (1983) argues that it is not sufficient to consider the magnitude of loading alone. There is a fatigue or repetition of load factor which should also be considered. Thus magnitude and repetition must be treated together and a pavement which is designed to support one magnitude of load at a defined number of repetitions can support a larger load at fewer repetitions and a smaller load for a greater number of repetitions. Hence, it is possible to establish the effect of one aircraft mass in terms of equivalent repetitions of another aircraft mass and its type. Application of this concept permits the determination of a single selected magnitude of load and repetitions level to represent the effect of the mixture of aircraft using a pavement. According to the deflection model developed in this study, the deflection estimation can be done by considering the aircraft landing as a free fall of a body from a known height and the potential deflection can be calculated using Eq. (3.8) and (3.9).

Though the deflection model indicates that the Eq. (3.8) and (3.9) are based on idealisations, the overall model can still be effectively used by runway maintenance engineers for routine technical evaluations of the runway pavements, instead of using the empirical practices recommended by the ICAO. However, many other secondary factors, such as spacing of the aircraft wheels and aircraft taxiing loads also influence the life of a runway pavement. Although subjected to the same loads, some runway pavements may experience different fatigue conditions. For example, a soft landing causes low impact on the runway. Similarly, when an aircraft rolls at a high speed for a takeoff or taxiing fast after a landing run on the runway, the loading phenomenon is transient and not severe due to lift forces created by the wings of the aircraft. However, these secondary factors will have the minimal effects on the accuracy of the evaluation results, because the deflection caused by landing impact is considered as the primary factor for the deterioration of a runway pavement. Consequently, a maximum allowed deflection threshold can be set to reduce the risk factor caused by the secondary factors similar to the deflection limits set for highways.

5.6 Conclusions

Impact load imposed by an aircraft landing is the primary contributory factor causing deflection in runway pavement. Consequently, it is important to consider the physical and operational characteristics of the runway pavement and related structures while carrying out technical evaluation of the pavement. The runway pavement deforms in touchdown zone due to the static and dynamic loads exerted by aircraft landings. Rutting is a primary failure criterion when determining the functional capabilities of an airfield pavement. Therefore, it plays a significant role in the development of a performance prediction model for the pavement. The ICAO recommends that the bearing strength of a runway pavement shall be reported using ACN- PCN system indicating the information about the pavement type for ACN-PCN determination, subgrade strength category, and the maximum allowable tire pressure category. Similarly, the pavement evaluation practices followed by various states of ICAO are based on semi-empirical approaches. Furthermore, the landing impact loads of heavy new generation aircraft on a runway pavement is a critical issue for modern aviation industry. Hence, it requires a new approach to deal with routine airfield pavement evaluation tasks.

This study observes that the load imposed on a runway pavement during landing primarily depends upon the ROD and weight of the aircraft. Furthermore, a runway pavement performance is influenced by various factors, such as frequency of loading, load factor, and modulus of subgrade reaction. Therefore, the technical evaluation of a runway pavement can be carried out by using the deflection profiles and predictions projected by the analytically derived deflection model discussed in this study instead of empirical practices currently followed by various states of the ICAO. The model can be used for both rigid and flexible pavements.

The runway pavement evaluation is primarily based on the gross mass of the aircraft. Furthermore, the type and configuration of landing gears dictate how the weight of an aircraft is distributed to the pavement and determine pavement response in terms of deflection to the aircraft loading. However, it would have been impractical to carry out pavement evaluation for each type of aircraft. Since the deflection for both flexible and rigid pavements is dependent upon the landing gear load distribution, some reasonable assumptions could be made to reduce the number of variables while carrying out pavement evaluation using deflection method.

CHAPTER 6

CIVIL AVIATION REGULATORY FRAMEWORK

IMPLICATIONS OF EVOLVING CIVIL AVIATION REGULATORY STRUCTURE

6.1 General

Air transportation plays a multi-faceted role in pursuit of development of a nation and it maintains international, social, and economic connections. An airport facilitates the air transport industry and it serves a key function in an aircraft operation. Therefore, airports have been contemplated as fundamental infrastructure rather than commercial entities by itself. Consequently, civil airports have always been publicly managed. However, the traditional airport management model seemed to be unsustainable as states become concerned about financial liabilities. As a result, the airport industry has evolved significantly in terms of aviation safety regulations, business model, and economic regulatory regime. Subsequently, the civil airports are regarded as a profit centre instead of a public managed community infrastructure. The structure of civil aviation legal framework has had an international outlook from the beginning. Therefore, the aeronautical components of civil airports, such as structure and operating systems of runways, taxiways, apron, and aircraft operational areas are strictly regulated by national regulations under the standards developed by the International Civil Aviation Organisation.

Traditionally, aviation has been a highly regulated industry due the inherent risk associated with aircraft operations (Fig.6.1). Consequently, the actions of airports and aircraft operators have been bound by a multitude of bilateral, national, and international regulations and standards. Generally, most legal frameworks in the world have a history of establishing on national basis before entering the international scene, but the peculiarity of aviation regulations and practices is that it has been both international and national from the very beginning. Since the establishment of the ICAO in 1944 as a specialized agency of the United Nations to develop aviation standards and recommended practices (SARPS), the civil aviation industry has been regulated significantly by the national aviation authorities (Department of Infrastructure Transport Regional Development and Local Government, 2008). The primary purpose of civil aviation regulations is to ensure safe operation of the aircraft while keeping the related risks to an acceptable level. The safety objectives are being achieved by various regulatory tools, such as licensing of airports, requirements of airworthiness certificates for aircraft, air operator certificates for airlines, licensing of safety personnel and so on. As a result, most national aviation authorities (NAA) used to have a team of specialist inspectors to inspect airports, airworthiness of aircraft, flight operations, and performance of aircraft personnel (Hunt and Macfarlane, 2003). Likewise, most safety sensitive aviation activities used to be regulated under prescriptive regulatory regimes.

Fig.6.1. Aircraft waiting for takeoff clearance from Air Traffic Control

Due to its global nature, the aircraft operation related activities of air transport are required to be regulated in accordance with the international standards (International Civil Aviation Organisation, 2006a). Therefore, all domestic and international flights operating in ICAO defined airspace are required to follow the international air traffic procedures. For example, all flights in Australian airspace above 11000 feet are required to follow the altimetry procedure that requires the pilot to read the aircraft altitude in terms of flight levels instead of feet (Airservices Australia, 2010). Similarly, the aircraft flying through this airspace must meet the internationally accepted airworthiness standard (International Civil Aviation Organisation, 2005, 2001). Likewise, all aeronautical parts and activities of a civil airport are required to meet ICAO standards. However, the aviation industry has evolved significantly since the invention of the first aircraft and as a part of liberalisation, a shift from the prescriptive rules to performance based legislation has been noticed in the civil aviation industry since last decade, especially with the formation of European Aviation Safety Agency (EASA)[4]. This chapter discusses the salient features of the traditional and outcome based regulations and it analyses the effects of these two different sets of legislative regimes on aviation safety in the civil aviation industry. Liberalisation and privatisation of the civil aviation industry have increased the commercial pressure by adding more competition to airports and aircraft operators. Though safety and economy are two different issues, but there are clear indications that the commercial concerns can put pressure on safety outcomes. Therefore, the influence of globalisation of certain sections of the aviation industry on aviation safety is also explored in this research. Example of maritime industry, airlines, airports, and aircraft maintenance repair overhaul (MRO) businesses are used to examine the potential aviation safety issues related to airports and aircraft operations arising as a consequence of the regulatory shift.

6.2 Prescriptive regulatory framework and challenges

Regulations increasingly shape the structure and conduct of civil aviation industries and they can influence flight safety. Some researchers argue that in industries, such as aviation, electricity, railways, telecommunications, banking, and pharmaceuticals, regulation is the single biggest uncertainty affecting capital expenditure, corporate image, and risk management (Beardsley et al. 2005). Similarly, regulation reflects an explicitly formal contract between business and society in many aspects. Even in the

[4] European Aviation Safety Agency was formed in 2003 by European Union (EU) countries as their representative body. However, neither EU is a member state of the ICAO nor is the EASA a regulatory authority of any such member state.

absence of regulations, the informal agreements may call upon organisations to meet certain social responsibilities. Therefore, when deciding on a regulatory stance, the aviation organisations must consider complicated trade-offs between maximizing profits while at the same time taking into account the safety of the aircraft operations.

Aviation regulatory system has come a long way. Passing from civilian hands to military and back to civilian control; it has gone through enormous technological advances in air navigation, aircraft, and airport systems. A Canadian study found that the regulatory focus has moved from strict economic regulations to looser ones, but it still holds control where public interest and flight safety are warranted (Fiorita, 1995). The civil aviation regulations may be divided into two broad categories. Firstly, the safety regulations, which cover flight operations, airworthiness of aircraft, air navigation, airport, airspace, and licensing of personnel[5] of aircraft. Secondly, the economic category that addresses commercial activities of the civil aviation industry, such as bilateral air transport services agreement and other commercial uses of aircraft and airports.

Since the beginning of civil aviation, the regulatory framework has been prescriptive in nature that prescribes what the safety requirements are and how they are to be met. The Australian civil aviation safety regulator states that the old prescriptive civil aviation safety regulations mostly prescribed the precise steps to be taken, leaving little or no discretion for deviation (Byron, 2006). Similarly, a prescriptive set of requirements does not provide flexibility required for continuous improvement of the system. For example, most civil aviation authorities in the world use prescriptive regulations to limit flight time and duty periods of flight crew (Benjamin, 2010). This approach has an advantage of providing clear-cut limits, but it is necessarily a one size fits all solution. Therefore, it is rarely the most efficient or cost-effective method of managing the fatigue-related risks of any one specific aeroplane fleet or route structure. Additionally, these prescriptive limitations have often been based more on industrial agreements than on evolving science related to fatigue and its effects on performance. It also gives an impression that the delivery of safety outcomes is

[5] Under Chicago Convention, the personnel of aircraft means the pilot, flight engineer, navigator, aircraft maintenance engineer, air traffic controller, flight radio telephone operator, and flight dispatcher (International Civil Aviation Organisation, 2006c).

primarily the concern of the regulator and the regulations. According to the ICAO, this regulatory system was based on a quality control concept rather than the quality assurance philosophy (International Civil Aviation Organisation, 2006b). It did not define the quality assurance system requirements and accountabilities of the management of the organizations for compliance with the regulatory requirements. As a result, it did not guarantee the measurable safety outcome. However, due to the prescriptive nature of the regulations under this regime the harmonisation of aviation practices is not much complex.

In recent years, the regulatory theory is developed along the process regulations. Under these regulations, the regulatory process is developed and it is measured against a criterion of efficacy and reliability rather than inspecting the end result (Michael, 2006). Consequently, the risks are to be identified and measures are placed to control them. This system is especially suitable to areas, such as safety regulations, because the performance based detection and enforcement is not as much of a challenge as design or process based prevention. Therefore, the process based regulations are primarily designed to prevent failure. Additionally, the process regulations necessarily enlist help of the regulated entities. In fact, it may extend further and vest them with primary responsibility for development of preventive programs. According to a major civil aviation safety regulator, an operator will always be better placed than the regulator to know and understand the safety risks they face in their particular circumstances (Byron, 2006). It is obvious that the civil aviation authorities do not fly or maintain aircraft, manage aerodromes or train pilots and aircraft engineers. Therefore, it is convincible that those involved in the industry may be best suited to identify the greatest safety risks.

As a result, the civil aviation authorities are seeking partnership with the organisations in addressing the regulatory issues related to aviation safety, because the implementation regulations alone does not ensure safety. In fact, the regulations only seek to cover the minimum necessary requirements and they can never hope to cover all situations and circumstances. Therefore, the civil aviation authorities in future may encourage the aircraft and airport operators to go beyond the regulations and look for more innovative ways to manage their risks, particularly those not covered by the regulations. For example, granting flexibility to airlines in managing working[6] hours of the flight crew provided the risks are identified and addressed; or allowing airport operators to carry out runway pavement evaluation based on predicted runway deflection suggested by this thesis in earlier chapters. This may encourage the industry to adopt more research based approaches than merely performing empirical procedures.

6.3 Outcome focused aviation safety regulations

In the last decade, the idea of having government regulatory agencies setting goals for performance has attracted increasing attentions from public and the industry experts. Subsequently, interests in performance-based regulations become visible in a number of regulatory developments. For example, the then presidents Clinton and Bush of United States of America (USA) had directed their federal government agencies to specify performance objectives rather than behavior in crafting new regulations (Coglianese et al. 2004). The focus on performance is based on an intention to achieve the same results as other standards while giving organisations a flexibility to achieve those results in a cost effective manner. For example, the Civil Aviation Safety Authority of Australia (CASA) is encouraging the aviation industry to actively manage its own safety risks (Byron, 2007; Ward, 2008). The CASA believes that the best balance is struck when the organisations have responsibility to determine desired aviation safety outcomes and then consider an optimal course of action to achieve them.

A recent study ascertains that the outcome or performance based regulations set goals for outcome of the behavior instead of establishing specific prescriptions for that behavior (Coglianese et al. 2004). A performance based regulation sets performance goals and it allows individuals and organisations to decide how to meet them. Under outcome based aviation safety regulations, safety is recognised as being a responsibility of everyone involved in an organisation and the top management of the organisation must be committed to safety anticipating that the errors may happen. According to a regulatory expert, the outcome based regulations specify the safety

[6] Flight duty time limits of flight crew are regulated under national civil aviation regulations of the contracting states as recommended by the ICAO (International Civil Aviation Organisation, 2001).

requirements that are to be met, but provide flexibility in terms of how safety requirements are met (Byron, 2006). However, the expert does not indicate any effective and affirmative regulatory tool to assess the safety outcomes under performance based regulatory regime. Byron (2006) indicates that the new CASA regulations emphasise the required outcomes and aim to make the regulations less prescriptive as much as possible. This approach allows a level of freedom to the civil aviation authorisation holder to identify the means by which to achieve the outcomes by designing and implementing compliance assurance systems. The new regulations are focused on safety risks and safety outcomes and they are supported by guidance materials, such as the acceptable means of compliance[7] (AMC) and manuals. This is a very different approach to the past and it is also claimed that the new regulations will be simpler, shorter, and easy to comply with. However, the regulations themselves will not detail how to achieve compliance. This regulatory philosophy is primarily based on the EASA regulated European civil aviation regulation model. The EASA based regulations defines regulatory obligations of the organization by holding it responsible for ensuring that all activities, such as management accountability, safety management system, and quality assurance system are performed to the required standards. Requirements for key management of the organizations and the quality system are more evident than in the previous regulations. It is also suggested that the new regulations introduce a well-defined balanced approach in-line with the ICAO recommendations. In fact, the ICAO encourages a balanced approach to safety oversight system where a contracting state and the industry share responsibilities for safe, regular, and efficient conduct of the civil aviation activities.

Financially, there is no single answer whether the outcome based regulations are more cost effective than the prescriptive system. A contemporary study establishes that the performance standards give organisations flexibility and make it possible for them to seek the lowest cost means to achieve the stated level of performance (Coglianese et al. 2004). The performance standards can better accommodate technological changes and the emergence of new hazards than the prescriptive ones. Nevertheless, the outcome based standards can sometimes be ambiguous, if they are loosely specified.

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[7] An AMC generally explains how one or more requirements of relevant regulations for the issue of a certificate, licence, approval or other authorisation can be met by an individual or organisation applying to a regulatory authority for the authorisation.

Additionally, measuring the performance presents distinct challenges, such as when the standards are based on predictions rather than actual measurable events. As a result, the outcome based safety regulations may impose excessive costs on the operators. Consequently, the small airports and airlines may be affected significantly, because under this regime the organisation must search for ways to meet the regulatory standards even though the compliance guidance material is to be supplied by the regulator. Small aviation operators may simply prefer to be told exactly what is to be done rather than incur costs in deciding methods to achieve a performance standard. Though non-binding guidance materials, such as manuals, advisory publications, and acceptable means of compliances are provided by the CAAs to assist the companies, but such documents sometimes becomes prescriptive standards that the performance standards are supposed to replace.

6.4 Effect of globalisation and privatisation on aviation regulatory framework

The civil aviation industry has experienced a significant change in the last fifteen years. International air transport has been reshaped and globalised through complex global airline and airport alliances. It has been observed that the flag carriers are being replaced by the airlines flying under global branding and they have started sharing the important operational functions involving safety, such as crewing and aircraft maintenance with their global partners (International Transport Federation, 2005). In addition, the deregulation seeks to reduce government role in the aviation industry and airlines and airport operators are under pressure to reduce cost of operations. Consequently, airlines are moving away from their traditional role of operators that own aircraft, employ pilots and aircraft engineers to fly and maintain the aircraft. The business model is changing to focus on the core businesses of organizing people to travel by air under a global airline brand whose services are often supplied by contractors, franchisees, and alliance partners. Similarly, airports are also becoming private business entities rather than state owned infrastructure. As a result, the modern aviation industry increasingly operates under a liberal market context. Therefore, liberalisation of the aviation industry has significantly contributed to globalisation. It was started with airlines and now many airports are progressively becoming private entities and business centres. Therefore, the regulatory models are also evolving to address issues arising as a consequence of the privatisation and globalisation.

The aviation safety rules place primary responsibility for the implementation of safety regulations on the operator, but the airlines and airport operators are increasingly sub-contracting some of the safety related tasks, such as aircraft maintenance, aeronautical facilities development at airports, management of air navigation equipment etc (International Transport Federation, 2005). This has created a challenge for the traditional regulatory framework established in civil aviation and monitoring the flight safety by respective national aviation authority (NAA) becomes complex as compared to the past. The ICAO sets safety and regulatory standards for civil aviation products and activities, such as airworthiness and operation of aircraft, air traffic control and management, runways and aerodrome specifications etc. For example, the ICAO is currently developing a multimedia service implementation program for air traffic management (ATM) and air traffic control (ATC) to improve air traffic processes and interaction between pilots and air traffic controllers (Zhukov, 2010). It also develops aircraft operation procedures and practices to address social and environmental impacts of civil aviation activities. Noise abatement is a typical issue in aircraft operations. Therefore, the international agency promotes a standard procedure for an aircraft takeoff and departure from a runway to keep the noise at an acceptable level (Vanker et al. 2009). These programs and regulatory standards are designed to be implemented globally, but responsibility of the implementation stays with individual contracting states. Nevertheless, the ICAO has established an audit program known as universal safety oversight audit programme (USOAP) to ensure compliance of the recommended aviation standards and practices (International Civil Aviation Organisation, 2009b). The objective of the programme is to identify whether the contracting states are adequately discharging their responsibility for the aviation safety oversight or not. Unfortunately, the economic climate dominated by liberalization and deregulation has tried to reduce the role of ICAO and to have civil aviation treated as just another commercial service dealt with by the World Trade Organisation (International Transport Federation, 2005).

Despite claiming economy and safety as separate issues, the economic liberalization causes an impact on technical aviation safety standards (International Transport

Federation, 1994). Hence, robust standards are needed to prevent the liberalized aviation organisations cutting aviation safety margins under commercial pressure created by globalisation. An example of maritime industry may be considered to explore this issue further. According to a report, the current legal framework for international shipping is based on the concept of flag state (FS) sovereignty (International Transport Federation, 2003). This means that a ship will have nationality of the state whose flag they fly. Therefore, the flag states have a wide range of responsibilities placed upon them by international law including safety oversight of ships flying their flags. Traditionally, flag states would only register the ships of ship-owners from their own country and they used to apply strict nationality rules, but increasingly, shipping companies began to look for ways to escape the obligations placed on them by their flag states. Consequently, it was found that a number of states were ready to rent out their flags to ship owners seeking to evade their own country's rules. This is commonly known as the flags of convenience (FOC). A flag of convenience ship is one that flies the flag of a country other than the country where its beneficial ownership is based. The FOC has become a safe haven for ship owners wanting to shelter from the regulatory regimes of their own governments. This was not expected under the regulatory philosophy of the maritime industry, whereby the right to fly a national flag is subject to stringent conditions. Therefore, one of the major concerns is a risk of the airlines or airports seeking to step outside proper regulatory oversight control similar to the maritime industry, because the FOC has led to an enormous abandonment of safety standards in shipping industry. Hence, the experience of maritime industry leads to a conclusion that a smart and more effective regulatory framework is required to prevent the spread of such culture to the aviation industry.

It has been noticed that the contemporary aviation Maintenance Repair Overhaul (MRO) business is subtly heading towards a similar flag of convenience. For example many aircraft maintenance organisations (AMO) located and owned by local entities in the contracting states other than EU member states are progressively seeking regulatory approvals from EASA instead of their local relevant regulatory authorities to carryout aircraft maintenance and repair work despite the fact that the EASA does not have any jurisdiction outside EU. In fact, EASA is not a regulatory body of any contracting states as such. Under ICAO SARPS, an AMO must hold the required regulatory approval from the contracting state where they are primarily located (International Civil Aviation Organisation, 2006a). Observers in aviation industry are afraid that the EASA regime may unilaterally enforce the standards at odds with those agreed globally through the ICAO, as European Commission (EC) a previous similar regional organisation of Europe had done in the past (Chung, 2004). This will affect ICAO's efforts of harmonisation of international civil aviation standards and practices including aeronautical activities at aerodromes across the contracting states.

Modern airport infrastructure and operational concept are going through a major transformation and governments are reluctant to support airport expansion requirements due to financial constraints (Frost and Sullivan Report, 2006). Consequently, the traditional management model was becoming unsustainable and the industry started to evolve with changes being brought about in the airport regulatory regime, which were later known as deregulation and privatisation. Currently, airports are considered as potential profit-making enterprises rather than a part of social infrastructure. With the global wave of airport privatizations, private investors entered the scene resulted in creation of privately owned airport companies. Generally, airports are privatised under two different models. First one involves total ownership of assets and the other model provides control of an airport management in private hand while government retains ownership of the infrastructure (Bel and Fageda, 2010). Therefore, it is not clearly established yet whether the trend to privatise and deregulate the airport industry is only for profit and growth opportunities or whether it may also enhance safety standards of aeronautical activities, because airports are natural monopolies.

According to observations, aircraft safety is a concern at some airports that are in process of privatization (Craig, 1999). Furthermore, violations of international safety standards are found at privatised airports, and also at new airports proposed for private sector development. Craig (1999) had also reported that enforcement of ICAO standards are lacking at small regional airports in some contracting states. Similarly, deficiencies including insufficient obstacle clearances, use of airport by aircraft beyond the code for which the airport was originally constructed, upgrading of instrumentation from non-precision approach aids to installation of instrument landing system (ILS) without complying with wider-strip and obstacle clearances associated with precision approaches are also noticed. Privatised airport owner responsible for these non-compliances end up into risk of high cost, if relevant NAA enforce the compliance. Likewise, it is hard for a NAA to enforce safety standards at a privatised airport, because these airports are commercially entities defied by a consolidating airline industry putting pressure on airports to lower their service charges including aeronautical fees. Government agencies would hesitate to suspend an airport license and thereby affect the business of the airport, while encouraging privatisation at the same time. Additionally, it has also been observed that driven by profit motives the airport designers of the privatised airports adopt a minimalist approach to reduce cost in areas, such as obstacle clearances and pavement widths (Craig, 1999). Instances of airport owners over ruling the advice of airport engineers resulting in substandard development and violation of safety standards have been occurred too.

Therefore, airport regulatory framework should be designed to provide incentives for the airports to invest in aeronautical infrastructure to ensure compliance with ICAO SARPS. It is understandable that regulatory authorities struggle with regulatory challenges, because issues are often extremely complex and interdependent. However, when deciding on a regulatory stance, the regulator must also consider social factors, especially while deregulating a monopolistic industry, such as airports. Hence, regulators could treat airports as a public good similar to roads and railways. Moreover, regulations form a contract between business and society and in absence of an existing law to address certain issues; an informal agreement may force companies to meet certain social obligations. Failure to accomplish these obligations may drive the regulator toward imposing prescriptive rules with strict liabilities.

6.5 The aviation safety risks

With the advent of outcome-based regulations the government presence will diminish significantly with time. The CASA admits that it is the operating company who takes the day-to-day responsibility for safe operations of aircraft and this is the reality of aviation safety (Byron, 2007). Therefore, it is important for the operators to be able to define the risks involved in their particular operation and integrate a safety system to manage those risks. Especially in the areas of potential private monopolies, such as airports and air navigation services, the strong regulatory surveillance will be required to ensure safety and risks remain at an acceptable level. Hence, this is a call for smart safety regulations that can be sustainable and compatible with the long term social, economic, and environmental needs of the industry. Regulatory systems must be measurable to the extent that any regulation does not overburden the industry and at the same time provides adequate protection for affected parties.

It is understandable that safety is impossible to assure, because the safety regulations are not easy to supervise as there is no traditional end of the pipe inspection. For example, no one can say that an aircraft is hundred percent safe, but the regulated industry can be relied upon. Nevertheless, the initial reassurances must be supported with reaction and the credibility be signalled by government involvement. Similarly, the confidence must be backed with results. In a recent study by Roy Morgan, the 61 percent of the respondents felt that the CASA should supervise the airlines more closely and only 6 percent of the population believe that the CASA should give airlines more freedom (Roy Morgan Research, 2008). This result clearly indicates that the public wants an extensive involvement of the government in aviation affairs. Therefore, the public interest in a democratic society must not be ignored while changing focuses of the aviation safety regulations, because safety is not a static concept and it is not easy to monitor. For example, some simple trends indicating number of loss of life or incidents per year at an enormous infrastructure system, such as airports are not enough to determine whether safety is assured at the airports (Bruijne et al. 2005). Furthermore, a lack of transparent and easily comparable data about safety performance of various runways and operational area of airports may influence identification process of potential risks. Additionally, maintaining an adequate level of safety is not sufficient; the aviation operators whether airlines or airport must be regulated to ensure that safety risks are kept as low as possible. It is also believed that the outcome based safety regulations may create adverse unintended behaviors, because the flexibility provided by the regulations to airlines or airport operators may be used in ways that causes undesirable side effects, even the operator still meet the performance goal (Coglianese et al. 2004). Thus, letting the industry choose its own path always presents the possibility of generating new or even larger risks. In contrast, the prescriptive standards provide clear direction to both regulated entity and the regulator. Therefore, choosing an outcome based regulatory framework in a high risk area, such as aviation safety is a debatable issue, because it may not be a very suitable model.

6.6 Analysis and discussion

Many contracting states are going through a revolutionary change in aviation safety regulations and gone is the prescriptive and restrictive legislation of the past (Bartsch, 2007). The new regulations recognise the fact that modern complex organisations necessarily acquire a high level of organisational specialisation and the elusive one-size-fits- all type of regulation simply may not exist. The CASA has acknowledged that compliance with traditional prescriptive legislation does not guarantee safety and compliance to the prescriptive legislation may become an obstacle to aviation safety due to complex technical specialisation of modern aviation organisations. Some regulatory experts argue that the regulatory authorities should be interested in safety outcomes, not necessarily how the outcomes were achieved (Byron, 2007). They can be achieved by many ways. The similar approach has been adopted by the EASA. However, it has been observed that flexibility to meet the requirements by a method of one's own choice might have influenced some people, but the concept has not been embraced by many in the aviation industry even though the outcome based regulations are being supported by the manuals and other guidance materials.

The highly regulated aviation industry is around 100 years old now and quite a few large corporations do aviation business or becoming involved in the operation of aircraft or airports. Therefore, it may be a call for the aviation regulatory authorities to deregulate few activities and shed some of its aviation safety responsibilities to the industry. This may be considered as a normal process once an industry becomes mature enough to take-over the obligation of self-regulation. For example, initially the aircraft used to be flown by the people who have high technical knowledge about the aircraft, but later on the people without any formal education were allowed to become pilots. Presently, under American Federal Aviation Administration (FAA) regulations, one who can read and write English can become a pilot provided he or she meet medical and other competency requirements of a pilot licence (Federal Aviation Administration, 2010a). Similarly, there is no minimum educational requirement to become an aircraft maintenance engineer under Australian civil aviation regulations (Civil Aviation Safety Authority, 2007b).

Thus, the performance standards under the outcome based regulations need to be set carefully and the outcome must be tested over a period of time, because a loosely specified standard to reduce cost may jeopardise the aviation safety. For example, a performance standard could require that the construction of high rise buildings in the vicinity of an airport be controlled so that they do not become a safety hazard for aircraft landings and takeoffs. Such a regulation provides lesser guidance to the airport owner and the regulator than a tightly specified regulation limiting the height of the building quantitatively. The loosely specified standards require the regulators to make quantitative judgements, while tightly established standards employ a quantitative measure of performance. Furthermore, it has been acknowledged that there is a scarcity of empirical studies aimed at measuring the effectiveness of the performance based standards especially in comparison with the effectiveness of other regulatory instruments (Coglianese et al. 2004). This makes bench marking of outcome based regulations really difficult, if not impossible. No one can afford to wait till an aircraft accident happen and then collect the data. Therefore, it is a matter of debate as to who will own the uncertainty. Should it be the regulator, the standard-setting organizations, or the industry? Without reliable data, the role and reliability of the performance based regulations will continue to be questionable. It can also be argued that even though the outcome based regulations are advantageous in decentralized governance by giving greater flexibility to the airlines or airports, the civil aviation authority (CAA) must still monitor the performance of each company and may be required to get so involved that it is essentially running everything again. In a perspective, the information requirements for either a performance standard or a prescriptive standard may be so demanding that both approaches could be very similar in terms of what the CAA needs to know.

Some CAAs and the industry operators may resist adoption of the outcome based regulations, because they consider them ambiguous (Coglianese et al. 2004). The CAA inspectors find it especially difficult to make the transition from hardware oriented checklist inspections to inspections that call for them to judge the quality and effectiveness of an entity’s performance. Similarly, the industry generally prefers the flexibility inherent in the outcome based regulation; many companies are anxious about the ambiguity and associated increase in regulators' discretion that sometimes accompanies performance based regulation. Therefore, the regulator’s comfort with the existing prescriptive approach, measurement problems, and the institutional path dependence of the existing legislation may also become the inhibition factors for transition to the outcome based regulatory framework. Hence, it is suggested that this evolutionary process possibly may take a generation to be developed as a fully performance based civil aviation. Consequently, it is important for all stake holders to foster comfort with this new approaches to the civil aviation safety regulation and to adopt a long term outlook instead of looking at them as a cost-cutting tool.

As neither performance-based nor prescriptive standards offer aviation operators any incentive to go beyond compliance, it is suggested that the regulators should introduce some incentives to encourage continuous improvements in safety outcomes (Coglianese et al. 2004). Similarly, in addition to a performance based goal, the CAA could charge a fee from the organisations for behaviors that increase risk. This is one of the advantages of market based or incentive based regulations. When an airport or airline is expected to pay a safety tax and if it is allowed to trade credits, it may reduce its risk to a level lower than it otherwise would have. The safety performance of an airport or aircraft operator cannot be directly measured for rare and catastrophic accidents. It has to be predicted making the implementation of the performance standards more difficult. Since the consequences of regulatory failure in area of aviation safety are significantly high, the nature and extent of these consequences may affect the choice of performance versus prescriptive standards. According to a report, the prescriptive standards might be preferred when there is high risk and existing systems are known to work well (Coglianese et al. 2004). Hence, it is worthwhile to debate why the aviation industry is moving towards the outcome based regulatory framework? Although it can be suggested that the outcome based aviation safety regulations are probably preferable to the prescriptive rules in most situations there is little empirical evidence to support this claim.

A current study about privatisation of airports indicates that the privatisation spurs regulatory reform and it may lead to more detailed regulations (Bel and Fageda, 2010). Though the study was primarily focused on economic regulations, but the same might be true for safety regulations too. Regardless of potential economic benefits, deregulation involves risks and it requires vigilant monitoring from a competent aviation regulatory authority. An effective check and balance mechanism needs to be established to examine the predicted safety outcomes of aeronautical activities at a deregulated airport. A series of safety or compliance audits by the regulatory authority might not be enough to ensure the same level of compliance standards that could be attained by prescriptive regulations. This study has found that certain categories of airports are deregulated to such an extent that they are not subject to any safety audit by aviation safety regulator. For example, under Australian civil aviation regulations, an airport used by any non-public transport aircraft of less than 30 seats capacity need not be a certificated aerodrome (Civil Aviation Safety Authority, 2012). Therefore, the airport is not required to be certified under Australian Civil Aviation Safety Regulation (CASR) 1998 Part 139 B that deals with certification and safety standards of civil aerodromes in Australia. Consequently, the civil aviation safety regulator of Australia does not have any legal authority to audit such airports directly. However, this category of airports can be audited by the regulator through airlines or aircraft operators, because the regulation outsources the responsibility of ensuring the safety standards of such airports to aircraft operators who use them for their operations (Civil Aviation Safety Authority, 2003). This does not make a good sense by itself in terms of purpose and concept of a regulatory philosophy, because airlines and aircraft operators are private entities and an audit carried out by one private entity on other private establishment neither have any legal binding nor does it apply to other operators. This is unlike the case, if the audit is carried out by the regulator. Consequently, this ambitious deregulation exposes the aircraft operations to flight safety risks on this category of airports. Therefore, there is a potential risk that deregulation and outcome based regulatory framework for the aviation industry may create a maritime industry kind of flag of convenience situation in some sections of the aviation industry, such as airlines, airport, and MRO businesses. This will jeopardise the safety of aircraft operations as a result.

6.7 Conclusions

Role of air transport in present globalised world is considered significant in connecting the society, economically and socially. The aviation industry has been highly regulated since its beginning and due to its safety sensitive nature of operations, the ICAO develops safety standards. Traditionally, the aviation safety regulations administered by the NAAs have been prescriptive types. However, the new safety legislative regimes based on outcome based regulatory philosophy are becoming popular in recent years. The performance based aviation safety regulations are focused on achieving results while giving organisations the flexibility in achieving them in a cost effective manner. These regulations set goals for outcome of the behavior instead of establishing a specific instruction to attain that behavior. Nevertheless, the ICAO promotes a balanced approach where a state and the company share regulatory responsibilities for safety sensitive aviation activities.

Globalisation and liberalisation of the aviation businesses has put an enormous commercial pressure on airlines and airports due to the increased international competition. Thus, the airlines are drifting away from their traditional role of aircraft operators to the business model of arranging air travel under a global partner airline. Consequently, outsourcing of safety sensitive activities has created a challenge for the existing civil aviation regulatory framework and the NAAs. The economic issues have influence on the safety outcomes. This has been analyzed by an example of maritime industry practice. The outcome based regulations seem fascinating due to the inbuilt flexibility, but it is hard to assess the performance outcomes, because there is no 'end of the pipe' inspection possible in the aviation industry. Therefore, any loosely specified performance standard under outcome based regulations may jeopardise aviation safety. Though the outcome based aviation safety regulations are probably preferable to the prescriptive rules in most situations, there are not enough empirical evidence to support this assertion. In addition, this study has indicated that the liberalisation and outcome-based regulations will reduce government involvement, which may increase the risks in certain sections of the aviation industry. This requires a smart regulatory system, which can manage the flight safety risks to an acceptable level. Hence, it is argued that choosing the outcome or performance based regulatory framework for safety sensitive aviation activities may not be a suitable option.

CHAPTER 7

CIVIL AVIATION REGULATORY FRAMEWORK

REGISTRATION OF AERONAUTICAL PERSONNEL

7.1 General

Aviation is a truly global industry and it is experiencing exceptional growth in most part of the world. Consequently, aeronautical engineers and other airport personnel frequently work in different countries. This industry is highly regulated and a major part of the aeronautical engineering workforce is required to be licensed or authorised by statute to carry out certain tasks related to an aircraft or aeronautical product. As a result, the personnel holding such a license or authorisation encounter difficulties when they move to another country to perform similar tasks, because the other country may not recognise the licenses they hold. Consequently, they need to convert their licence before starting their professional work in that country. This could be a complex procedure in some countries. Licensing is primarily an instrument to control a profession, and it can sometimes be used as a tool to protect a trade in the current globalised aviation industry. This chapter discusses the history of licensure, key licensing standards, and systems that are related to aeronautical personnel and are currently in practice in a major part of the world. The study is primarily focuses on the standards developed and recommended by the ICAO. It also suggests regulatory harmonisation of aeronautical industry activities at a global level as recommended by the ICAO.

7.2 Overview of licensing

Professional certification, trade certification, or a professional title is a designation earned by a person to certify that he or she is qualified to perform a specific job. Licensing engineers and other professionals protects the public by enforcing standards that restrict practice to appropriately qualified individuals (National Council of Examiners for Engineering and Surveying, 2012a). Professional certifications are awarded by professional bodies. The difference between licensing and certification is that licensing is required by law, whereas certification is generally voluntary. Sometimes the word certification is also used for licensing. Certification or licensing may be perpetual, may need to be renewed periodically, or may be valid for a specific period of time. Regarding renewal of licenses, it is common that the individual must show evidence of continual learning, which is often termed as continuing education or current experience.

To elucidate the role of licensing in the flight safety chain, a state authorises an engineer to perform specific activities, which unless performed properly could jeopardise the safety of aviation operations (International Civil Aviation Organisation, 2006a; Civil Aviation Safety Authority, 2008). The licence or authorisation provides evidence that the holder has demonstrated competences meeting the standards that are recommended by the ICAO.

The first regulation to control a profession was established in Europe in the 12th century by King Roger of Normandy, who decreed that doctors must present proof of competency before being allowed to practice medicine (Old And Sold, 1911). Similarly, the first licensing law governing the practice of engineering was enacted by Wyoming in 1907 (National Council of Examiners for Engineering and Surveying, 2012; National Society of Professional Engineers, 2012). With the formation of the ICAO in 1944, the member states agreed to develop international standards for licensing aviation engineers and other personnel associated with civil aircraft (International Civil Aviation Organization, 2006a). Consequently, the states were required to undertake the highest degree of uniformity in complying with the international standards (Wells and Wensveen, 2004).

7.3 Should all engineers be licensed?

An engineer uses creativity, technology, and scientific knowledge to solve practical problems as a part of the profession of engineering. Engineers also apply established principles drawn from mathematics and science in order to develop economical solutions to technical problems while working on testing, production, design or maintenance of a product (Fig.7.1). The title *engineer* is normally used only by individuals who have an academic degree or equivalent work experience in one of the engineering disciplines. In some countries of continental Europe, the title is limited by law to people with an engineering degree. Similar laws exist in most US states and Canadian provinces (Edwards, 2010). The debate about licensing the practicing engineers of all fields of engineering profession has been going on for years. This begins with a discussion regarding engineering and its status as a profession, and the argument has led to engineering as we know it today that requires a standard four-year undergraduate degree in engineering discipline.

Fig.7.1. Engineers inspecting an aircraft before a test flight

Is such a level of education sufficient for a status as a professional? A number of stakeholders may promote the idea of an educational requirement that goes beyond a four-year degree suggesting a professional school approach similar to the professions of law, medicine, and pharmacy, where an engineer would receive additional technical training or business training in order to meet the contemporary demands of the industry. Engineers who work in industry, government, education or private practice satisfy the identified characteristics regardless of whether or not they are licensed. All engineers should therefore be held responsible for protecting the public health, safety, and welfare, whether they provide services to the public directly or indirectly. Bringing all categories of engineers into the licensing fold may consequently be beneficial for both the public and the engineering profession.

7.4 Licensing standards and systems in the aeronautical industry

Aeronautical engineering is one of the fastest evolving disciplines. It has changed significantly since its beginning. Enormous development in aircraft designs, materials and interface systems, such as navigational computers, fly-by-wire flight and engine controls (Fig.7.2), etc, has enhanced the capability of the modern product significantly. Though the industry is heading towards deregulation, the engineering personnel related to design, manufacture, airworthiness and maintenance of an aircraft or aeronautical product are still controlled by means of licenses or task authorisation under relevant civil aviation regulations of the respective member state (Civil Aviation Safety Authority, 2008; Civil Aviation Safety Authority, 2011; Federal Aviation Administration, 2012b; International Civil Aviation Organization, 2006c). The licences or authorisations for aeronautical maintenance engineering personnel may be granted in various categories such as mechanical, avionics, or structural repairs with respect to a specific type or group of aircraft. By granting the licenses to individuals, a member state can ensure that maintenance of an aircraft is certified by people who are properly trained to meet ICAO standards. Civil aviation regulations have however evolved considerably in recent years as part of deregulation. A member state may consequently authorise an aircraft maintenance organisation to grant approvals to aircraft maintenance personnel employed by the organisation (Civil Aviation Safety Authority, 2011b). Nevertheless, when a state authorises a maintenance organisation to grant such approvals, the employee must meet the standards mentioned in annex 1 of the ICAO SARPS (International Civil Aviation Organization, 2006c). Similar to the licensing of maintenance personnel, the professional aeronautical engineers who are involved in the certification of aircraft design, alteration, and modification are also granted specific authorisations related to the task by the civil aviation authority of the respective member state. For example, the civil aviation safety authority (CASA) of Australia grants specific authorisations to these personnel and it requires the applicant to hold a four-year undergraduate degree in a relevant engineering discipline (Civil Aviation Safety Authority, 2008).

Under the regulations, no one other than the authorisation holder is allowed to certify these tasks.

Fig.7.2. Technical experts testing an aircraft engine on a test bench

These practices of licensing or authorising aeronautical engineering personnel carried out by respective member states not only are to ensure quality and safety of aircraft and aeronautical products, but also are required to meet ICAO standards. Under article 33 of the Chicago convention, SARPS adopted by the ICAO as minimum standards should be implemented by all member states and a license, certificate or authorisation granted by a state should be recognised by another member state (International Civil Aviation Organization, 2006a). Similarly, the states are expected to use precise phrases and terminology in their national legislation as mentioned in the ICAO SARPS and also to indicate any departures from ICAO standards in the legislation. Furthermore, under article 38 of the convention, the states are also required to notify ICAO of differences between their national regulations and the SARPS (International Civil Aviation Organization, 2006a). Additionally, the ICAO also advises the states to publish these differences in their aeronautical information publication.

Licenses and authorisations for aeronautical engineering personnel in the European Union (EU) are granted under the regulatory framework of the European Aviation Safety Agency (EASA), though the EU is not a member state of the ICAO and the EASA is not a regulatory authority of any such member state. Three levels of licenses known as *A*, *B*, and *C* are granted to aeronautical maintenance personnel under the EASA system (Kingston University, 2012). The levels primarily define the scope and privileges of the license. While the EASA claims that its license standard and system conforms to ICAO standards, the level *C* license does not indicate any relation to the standard of aircraft maintenance personnel license mentioned in annex 1 of the ICAO SARPS. The EASA system projects this level as a maintenance management category of the license, but the ICAO annex 1 standard does not have any provision for such a category (International Civil Aviation Organization, 2006c). A reduction in the time period allocated for aircraft type training courses has also been noticed under the EASA system. For example, for a typical wide-body transport aircraft, such as a Boeing 777, *B1* and *B2* license training course is being completed within a span of 35 days at training schools in Germany under EASA system approval (Lufthansa Technical Training, 2010). A typical training course of such scope used to consume more than 60 days to complete in the past. It seems to be a dilution of the standard, but a detailed academic investigation is required to establish this. Although the FAA of the USA does not grant licenses or authorisation to aeronautical engineering personnel in conformity with ICAO standards, it divides them in three broad categories known as certificated mechanics, repairmen, and engineers to carry out relevant engineering and maintenance tasks (Federal Aviation Administration, 2012b). The US authority also grants approvals known as inspection authorisation to engineering personnel to certify certain tasks, such as major alteration or modification of an aircraft. These approvals are granted for a similar purpose by most member states of the ICAO, and they more or less meet the required standards, even though the procedural instruments differ significantly across the states. Nevertheless, this study of various licensing or authorisation systems of aeronautical engineering personnel suggests that harmonisation of the systems is possible. It also leads one to believe that a fully convertible licensing system under the ICAO regime would be beneficial for all stakeholders in the contemporary globalised aeronautical industry.

7.5 Discussion and analysis

Under current practices, licensing is not mandatory for all engineers in the aeronautical field, and only the personnel who certify certain tasks related to aircraft or aeronautical products are required by statute to be licensed or authorised. Nevertheless, licensing is becoming increasingly significant in deregulated or privatised industry to ensure the safety of aircraft and the flying public. Heightened public attention concerning aircraft safety in commercial aviation also focuses on licensing and the competency standards of aeronautical engineering personnel. Engineering practices in the industry are constantly changing and the activities that are exempted today may eventually move into a practice area requiring a license. This may also be beneficial to the personnel. For example, 74 % of aeronautical engineers in Canada believe that licensing provides professional recognition and broadens their career (Engineers Canada and Canadian Council of Technicians and Technologists, 2009). In the present era of cost cutting and lean engineering processes, the licensing of personnel is an instrument to assure the quality of the product, thereby ensuring the safety of the flying public. The current trend of deregulation in the industry may also influence the licensing system or standards. There is a growing concern within the industry that if the status of engineering personnel is eroded in any way, the safety of the aircraft will be affected. This will ultimately cause the loss of lives. On the negative side, the licensing approach may be viewed as limiting the number of qualified engineers or reducing competition, which could benefit the engineers who are already licensed. Nevertheless, the primary purpose of licensing engineers is quality assurance, which subsequently improves the safety of aircraft and the public.

The priority in the aviation field is safety, and it may be improved by keeping risks at an acceptable level. Ensuring airworthiness of the aircraft and aeronautical parts is a determinative factor in aviation safety assurance. This instigates a need for developing competency requirements for aeronautical personnel who deal with the airworthiness activities beginning with prototype design stage of an aircraft and aeronautical parts to final stages, such as maintenance and flight testing. Creating technical standards and licensing at every appropriate level related to aeronautical engineering personnel could be a major step in accomplishing this. However, in complex aeronautical operations, such as aircraft maintenance, safety cannot be achieved by standards alone. It requires the on-going support of social engineering and an organisational structure committed to training, human factors, accountability reviews, and risk management processes. For example, two methods of standardising the competencies of aeronautical maintenance personnel, state licensing and company approval, exist in the industry around the world. Under the licensing system, a contracting state conducts related technical examinations and grant a license to the candidate provided the candidate meets other requirements, such as technical experience. The state is responsible for ensuring that the candidate possesses the required competencies before he or she is granted a license. In the company approval system, the organisation substantiates that the required competencies are met, and it maintains the assessment system. As a result, the organisation grants company approval to the candidate, and this approval is valid primarily for the organisation that issued it. The state in this case monitors and audits the training and assessment system managed by the organisation. Consequently, the procedures and competency standards may vary from one organisation to another, and that may create difficulties harmonising standards at the national and international level. Most states support licensing as superior to the company-managed approval model (Haas, 2009). According to Haas (2009), it is believed that a company approval system does not guarantee the required quality and independence due to economic pressure.

However, neither of these models completely addresses the accountability requirements of all categories of aeronautical engineering personnel involved in the design, manufacture, airworthiness, and maintenance of aircraft, because only the key personnel are licensed or approved under the systems. The manufacturing and airport engineering sectors especially requires attention (Fig.7.3, 7.4), and the engineers involved in these sectors may also be considered for licensing similar to the aircraft maintenance industry instead of registration, because the registration of professional engineers is mandatory in some jurisdictions, but voluntary in others. For example, a professional engineer is required by statute to be registered with the Board of Professional Engineers Queensland, if the engineer provides professional engineering services in Queensland State of Australia (National Engineering Registration Board, 2012). Conversely, the other states do not have such requirements and registration with the National Engineering Registration Board (NERB) of Australia is voluntary. The introduction of licensing in these sectors of the aviation industry may enhance the individual accountability of the engineers and consequently improve flight safety in the current trend of lean manufacturing and low cost operations. Furthermore, a comprehensive approach of bringing the personnel under a state licensing system will also augment the harmonisation of international standards and the regulatory framework in the aeronautical manufacturing and airport engineering industries amongst the contracting states. This will eventually benefit the globalised aviation industry.

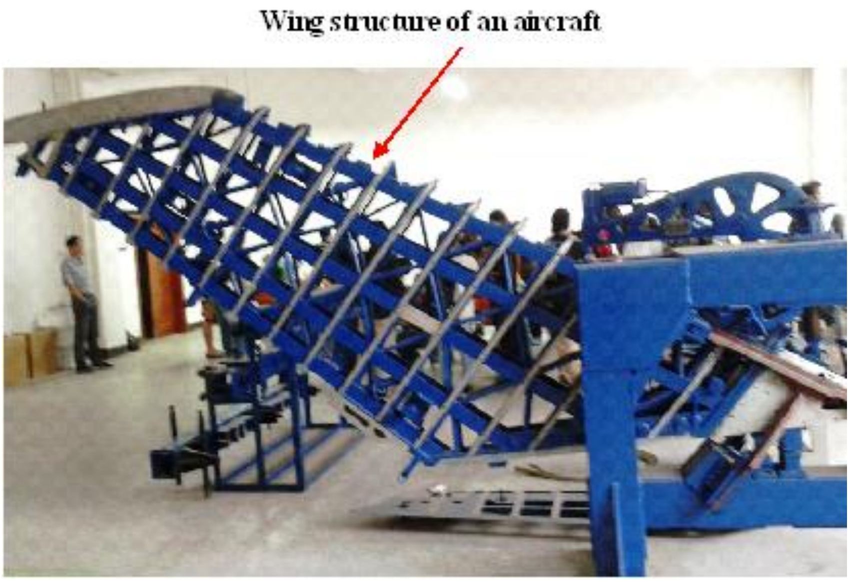

Fig.7.3. Aeronautical engineering personnel in a manufacturing workshop

Fig.7.4. Runway pavement engineering work in progress

In the foregoing debate regarding the mutual recognition of the licenses and authorisations of aeronautical personnel by member states of the ICAO, it can be inferred that the concept of mutual recognition may be advantageous for all. It will improve the movement of the personnel between member states, and it will also boost the body of available intellectual knowledge in the public domain. It is widely believed by the aeronautical community that the policy of non-acceptance of licenses or authorisations granted by another member state is more related to protecting trade than standards.

7.6 Conclusions

The complexity and global nature of the aeronautical industry has encouraged the standardisation and licensing of engineering personnel. Licensing of the personnel has been introduced as a tool for controlling and regulating their functions and responsibilities to ensure safety of aircraft and aeronautical products. A major portion of the aeronautical engineering workforce must therefore be licensed or authorised by law. As a result, engineering personnel experience difficulties in practicing their profession in different countries, because they are required to be licensed in that country to perform similar tasks. This is mostly viewed as protection of trade rather than standards. This study has discussed the history of licensing, licensing standards, and various categories of licensed aeronautical engineering personnel. It has been argued that there is a need to license engineering personnel in the aircraft manufacturing and airport engineering sectors in a way similar to the aircraft maintenance industry to improve flight safety, airport operations, and the quality of aeronautical products. The discussion has also explored relevant SARPS of the ICAO and subsequent approaches of major member states.

CHAPTER 8

CIVIL AVIATION REGULATORY FRAMEWORK

RUNWAY PAVEMENT BEARING STRENGTH REPORTING SYSTEM

8.1 General

Landing phase of a typical flight is considered as crucial and a flawed landing may result, if the runway pavement structure quality is compromised. Load bearing capacity of a runway is largely affected by potential deflection (Ashford & Wright, 1992; Horonjeff and McKelvey, 1994). According to Ashford and Wright (1992), the ICAO recommends ACN-PCN based classification system for reporting airfield strength. This system reports a unique PCN for a runway, which indicates that an aircraft with an ACN equal to or less than the PCN can operate on the runway pavement subject to some limitation on tyre pressure of the aircraft. The load bearing strength of a runway pavement is reported by indicating the PCN and other relevant factors, but it does not include potential runway deflection for this reporting.

This chapter presents an argument to include analytically calculated potential deflection for runway load bearing strength reporting system. It may be considered as a step towards rationalizing the ACN-PCN system. The study reviews the international practice of classification numbers system of airfield strength reporting and it also analyses the suitability of the practices. In conclusion, this academic research suggests that the landing phase is the most crucial operation on a runway and the vertical velocity and weight of the aircraft during landing significantly affect the runway characteristics and they causes deflection on the pavement. Hence, the bearing strength of a runway pavement should be reported based on analytically calculated potential deflection caused by the aircraft during landing.

8.2 Current international practices for reporting the bearing strength

Bearing strength of the pavement is reported by indicating the PCN, pavement type, subgrade category, allowable tyre pressure, and method of technical evaluation (International Civil Aviation Organisation, 2004). This prescriptive standard had been established through semi-empirical knowledge and long experience in the field. According to International Civil Aviation Organisation (1983), the general practice is to present a plot of pavement thickness required to support the aircraft loading as a function of subgrade bearing strength for flexible pavements. Similarly, a rigid pavement design curve for a given aircraft is made as a plot of concrete slab thickness required to support the aircraft loading as a function of bearing modulus of the surface on which the slab rests. Though the working stresses are used for design and evaluation of pavement, but they have no relationship to the standard stress for reporting. Similarly, the results of pavement research affirm that the tyre pressure effects are secondary to load and they are categorized in four groups known as high, medium, low, and very low for reporting purpose (International Civil Aviation Organisation, 1983). Current models used in ACN-PCN method permit a maximum correlation to pavement design methodologies with a minimum need for pavement parameter values.

Table.8.1. ACN of Boeing 747 aircraft models for airport reporting purpose (After Boeing Commercial Airplanes, 2002)

				ACN FOR RIGID PAVEMENT SUBGRADES – MN/m³				ACN FOR FLEXIBLE PAVEMENT SUBGRADES – CBR			
AIRCRAFT TYPE	MAXIMUM TAXI WEIGHT/ MINIMUM WT LB (KG)	LOAD ON ONE MAIN GEAR LEG (%)	TIRE PRESSURE PSI (MPa)	HIGH 150	MEDIUM 80	LOW 40	ULTRA LOW 20	HIGH 15	MEDIUM 10	LOW 6	ULTRA LOW 3
747-400, -400F	877,000(397,800) 395,000(179,200)	23.33	200(1.38)	53 19	62 21	74 25	85 29	53 20	59 21	73 23	94 30
747-400ER, -400 ER FREIGHTER	913,000(414,130) 362,400(164,400)	23.40	230 (1.58)	59 19	69 20	81 23	92 27	57 18	63 19	78 21	100 26

Horonjeff and McKelvey (1994) establish that the ACN can be found from the runway pavement design charts or analytical equations. The ACN-PCN method does not include any reference to the pavement thickness and deflection (Table.8.1, Fig.8.0). Consequently, the overload movements are not normally permitted on pavements with indications of deterioration or weakened subgrade. ACNs of various aircraft types are linked with rigid and flexible pavements according to the soil subgrade categories for pavement bearing strength reporting purpose.

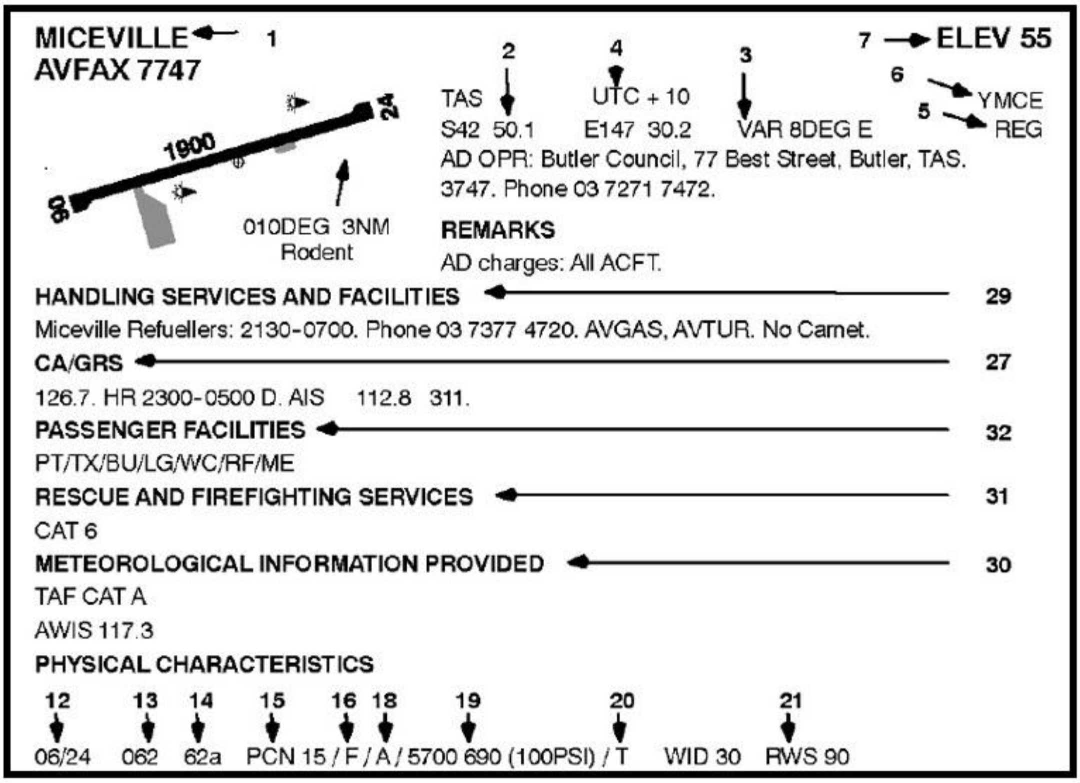

Fig.8.0. PCN of an aerodrome runway for reporting purpose (Adopted from Airservices Australia, 2013)

8.3 Reporting model based on potential deflection

Deflections of a runway pavement under a wheel load, number of landing repetitions, and weight of the aircraft are primary factors that affect life of a runway pavement. Rutting or deflection in a runway pavement is a significant indicator of the pavement capability, potential deterioration, and condition monitoring. Deflection can also affect the safety of the aircraft during landing, especially if it occurs in wheel path area of touchdown zone of the runway. Furthermore, considering deflection as a part of the strength reporting practices may also be useful for practicing engineers who are involved in the pavement technical evaluation activities. Consequently, the interactive phenomenon between a runway pavement and the operating aircraft must be taken into consideration while reporting bearing strength of the runway. Similarly, vertical velocity of the aircraft during landing imposes dynamic and impact loads that affect the runway pavements (Fig.8.1).

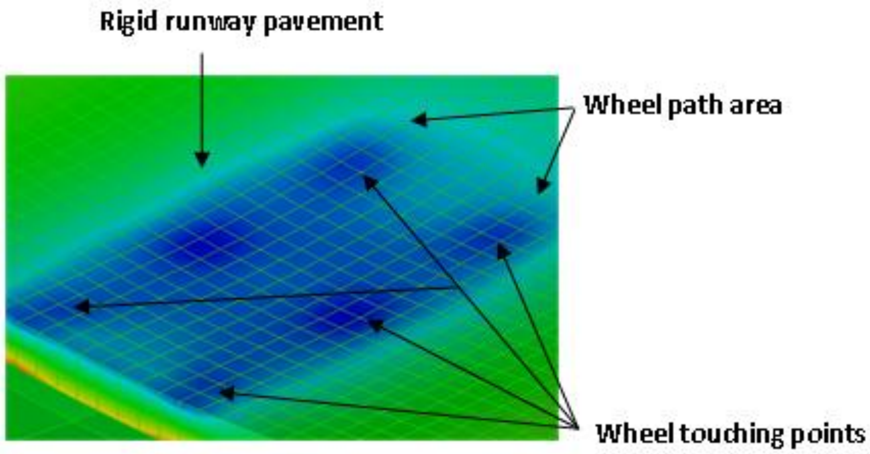

Fig.8.1. Rigid runway pavement showing stress peaks at wheel touching points in touchdown zone (Adopted from Federal Aviation Administration, 2010b)

During landing, the aircraft is flared to rotate the velocity vector parallel to the ground as it reaches close to the runway (Fig.8.2) and weight of the aircraft is resolved into two components (Fig.8.3) acting in the same rectangular coordinate system as the lift L and drag D forces. Likewise, T, W, and α stand for thrust, weight, and glideslope angle of the aircraft, respectively. As discussed in earlier chapters of this thesis, the weight and ROD of the aircraft at touchdown are responsible for ground loads imposed by the aircraft on the runway pavement during landing. Therefore, the kinetic energy produced by the landing impact is to be dissipated by landing gears of the aircraft and the runway pavement.

Fig.8.2. Aircraft flared before touchdown on a runway

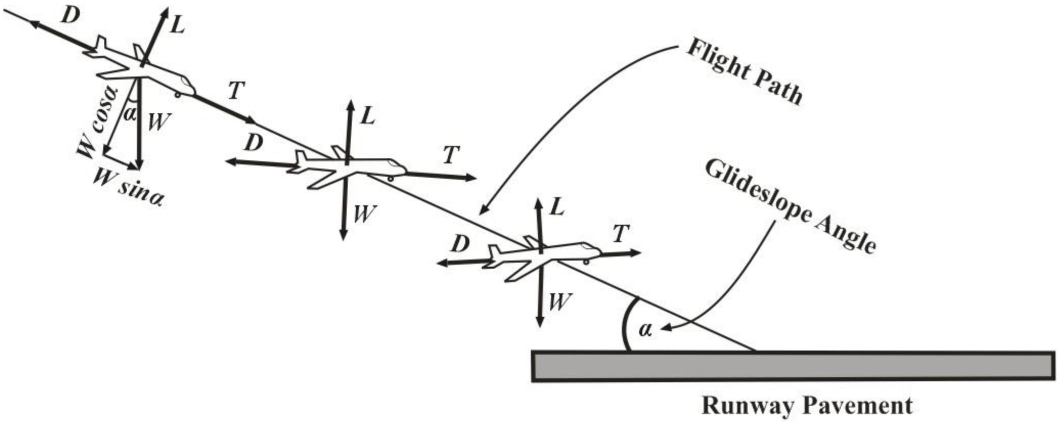

Fig.8.3. Resolution of forces during landing

Several types of aircraft with various loading configurations are used in aviation industry to transport passengers and cargo. Many small aeroplanes are equipped with a tricycle type of landing gear arrangement (Fig.8.4). Overall distribution of the aircraft mass between nose and the main undercarriage legs depend upon load distribution of the aircraft, such as position of centre of gravity of the aircraft structure. However, the load imposed by nose leg is considered negligible and the main undercarriage leg generally causes the greatest stress (Fig.8.1). Hence, the deflection caused by main legs can be used for the reporting purpose.

Fig.8.4. Tricycle type landing gear arrangement

Landing load exerted by an aircraft on a runway pavement is primarily caused by vertical velocity of the aircraft and its gross weight and Eq. (5.10) and (5.11) indicate that the total force produced by the load is directly proportional to the gross weight of the aircraft. A direct relationship between load and deflection has been proved in earlier chapters of this thesis. Thus the deflection being an indicator of load carrying capacity of a pavement also implies that the deflection determined for a particular applied load could be adjusted proportionately to predict the deflection resulting from other loads too. Hence, it is possible that it can be used for a runway pavement bearing strength reporting purpose and the deflection can be predicted analytically using Eq. (3.8) and (3.9).

Therefore, the potential deflection for various typical aircraft models of different weight categories can be predicted using the above mentioned equations. For example, deflection w caused by landing of a typical aircraft, such as BAe 146 may be calculated using landing phase data available from the aircraft flight manual and real-time data from various instruments of the aircraft. According to International Civil Aviation Organisation (1983), the tyre pressure p and all-up-mass (AUM) for BAe 146-100 aircraft is 0.80 MPa and 37308 Kgs, respectively. Assuming modulus of subgrade reaction k_s as 70000 kN/M^3 and vertical component of the velocity v_v of the aircraft during landing as 1.5 m/s, the deflection w comes to 63.84 mm by using Eq. (3.8). The result is consistent with the outcome obtained using charts and data for other type of aircraft. Hence, the potential deflection for various type and size of aircraft can also be obtained using this equation. Consequently, a runway pavement bearing strength can be reported as a relationship between ACN and the potential deflection estimated by the analytical expression instead of using ACN-PCN method.

According to Stet and Verbeek (2005), the ICAO does not enforce a specific design method for PCN assignment. Thus, PCNs can vary depending on the evaluation method used. Nevertheless, the ICAO relates PCN to the structural life of the pavement and the volume of the potential traffic. Therefore, PCN can function largely as a pavement management tool, but it may not provide an accurate value for pavement performance on long term basis, because load bearing strength of the pavement changes with time. As a result, it becomes necessary to re-examine the PCN periodically. The deflection based bearing strength reporting method therefore can present a realistic indication about load bearing capacity of a runway pavement.

The reporting model suggested by this academic research is based on limited data related to the aircraft operations due to lack of availability of comprehensive field data about a large aircraft landing phase, especially the touchdown instant parameters. It is recommended that additional mechanistic empirical data may still be required to accurately calibrate the functions, so that the predicted distress can closely match with field applications. Furthermore, airfield practitioners may consider collecting comprehensive real-time field data and develop a software based on the strength reporting approach suggested by this study. It is believed that the software will be useful for runway pavement engineers, airport operators, and the civil aviation regulatory authorities responsible for a runway strength reporting.

8.4 Conclusions

An aircraft landing on a typical runway imposes a tremendous load on the runway pavement, which causes deflection on the pavement. The vertical load imposed by an aircraft on a runway pavement during landing is a primary factor that contributes to potential deflection of the pavement. Therefore, the deflection plays a significant role in assessing load bearing strength of a runway. Consequently, a runway is classified according to its strength indicated by the LCN system, which is also used for the runway pavement bearing strength reporting purpose. Under this semi-empirical approach, the load bearing strength of a pavement is reported by indicating ACN-PCN method that does not include potential runway deflection for this reporting. This chapter has investigated the main factors responsible for imposing total load on the pavement in touchdown zone of a runway during landing. The imposed load causes severe stresses resulting in deflection of the pavement in this zone. Therefore, the study presents a case to include analytically calculated potential deflection for runway load bearing strength reporting system. This rationalises the ACN-PCN system and presents a new approach to the strength reporting based on potential deflection that may provide an effective indication of load bearing capacity of a runway pavement.

CHAPTER 9

SUMMARY AND CONCLUSIONS

9.1 Summary

Function of a runway in contributing to safe outcome of an aircraft operation during landing phase is considered vital. It is emphasised therefore to consider the physical and operational characteristics of the runway pavement and related structures while designing, evaluating, and reporting the bearing strength. A runway pavement deforms in touchdown zone due to the static and dynamic loads exerted by aircraft landings. This deformation in a wheel path at touchdown point is known as deflection or rutting. Rutting is a primary failure criterion when determining the functional capabilities of an airfield pavement. Hence, it plays a significant role in development of a performance prediction model. Subsequently, estimating deflection in field situation is a demanding task. Primarily, the methods used for reporting the load-bearing capacity of the airfield pavements emphasises on the development of a procedure for measuring and classifying the load rating of different aircraft. The allowable bearing pressure on a pavement known as pavement strength is usually defined as the load rating of the heaviest aircraft that can use the pavement on an unrestricted basis without exceeding the permissible rutting.

The ICAO recommends that the bearing strength of a runway pavement shall be reported using ACN- PCN system indicating information about type of the pavement for ACN-PCN determination, subgrade strength category, and the maximum allowable tire pressure category. This is a semi-empirical practice and the ACN-PCN method is primarily meant for publication of the pavement strength data in aeronautical information publications. This system is not intended for design of the pavements.

Though the prior research on the issue recognises the importance of a runway rutting, but not much attention had been given to present a simplified runway deflection model for routine design, technical evaluation, bearing strength reporting of a runway pavement. Review of the relevant research literature indicates that a significant research work is not available in this area of study. As a result, these practices are still based on semi-empirical approaches. The landing impact loads of a heavy new generation aircraft on a runway pavement is a critical issue for modern aviation industry. In view of the importance of the runway rutting, this research has developed a model for determination of the deflection considering the aircraft-runway interaction as a structure-foundation interaction issue. In order to present a simple model for the field applications, the runway pavement is idealised as a Winkler springs mechanical model and an analytical model to predict runway pavement deflection caused by an aircraft landing has been developed in this study. Additionally, a parametric study has been carried out to analyse the deflection profiles.

Heavy impact load caused by a large new generation aircraft on a runway pavement during landing is a critical issue for the airport industry. Thus, a new approach is required to carry out airfield pavement evaluation. It is established that the impact load notably depends upon the ROD and weight of the aircraft. Factors, such as frequency of loading also influence the bearing strength profile of a pavement and the potential deflection. Therefore, it is suggested that the technical evaluation of a runway pavement in field situations can be carried out by using a predicted deflection profile of the pavement based on the deflection model developed by this study instead of semi-empirical practices currently followed.

Similarly, this research presents a case for using analytically predicted deflection as part of runway pavement bearing strength reporting practices. Under existing practices, the load bearing strength of a pavement is reported by indicating ACN-PCN method recommended by the ICAO. This system does not include potential runway deflection for this reporting though it has been established that deflection is an important parameter in assessing the health of a pavement. This study has investigated the main factors responsible for imposing total load on the pavement in touchdown zone of a runway during an aircraft landing. The imposed load causes severe stresses resulting in deflection of the pavement in this zone. Therefore, the study presents and argument to include potential deflection for runway load bearing strength reporting system. This will compliment the ACN-PCN system in providing effective information regarding a runway pavement.

Additionally, this project has investigated the influences of evolving civil aviation safety regulations in the contemporary globalised aviation industry. Liberalisation of airport operations and other aviation businesses has brought an immense commercial pressure on these entities. As a result, they started outsourcing their non-core tasks including some safety sensitive activities. This has brought about some serious challenges for the existing regulatory systems and the NAAs. It is argued that the economic issues are influencing the safety outcomes. This has been explored by using an example of the international maritime industry. Other elements, such as privatisation of aeronautical activities of airports, professional standards of aeronautical personnel, airworthiness of aircraft, and airline operations are also discussed to examine the regulatory issues. It is found that the outcome based regulations look attractive on surface due to their inbuilt flexibility, but assessing the expected performance outcomes is a challenging task. Hence, a liberal performance standard under these regulations may affect the aviation safety adversely. Generally, it is believed that an outcome based aviation safety regulation is probably preferable to a prescriptive rule in most situations, but significant empirical evidence is not available to support this belief. Furthermore, an outcome-based regulatory regime will reduce government involvement eventually that may make certain sections of the aviation industry more vulnerable to safety risks. Thus, it leads to believe that an outcome or performance based regulatory framework for safety sensitive aviation activities may not be considered as a superior choice.

9.2 Conclusions

This study concludes as follows:

- A simple analytical expression involving three independent parameters known as modulus of subgrade reaction (k_s), contact pressure (p), and vertical component of aircraft velocity (v_v) prior to landing is proposed for predicting the dynamic deflection of the runway pavement at touchdown point caused by a gear load during aircraft landing.

- The dynamic deflection increases nonlinearly with an increase in vertical velocity of the aircraft for any value of contact pressure and the rate of increase of the dynamic deflection is greater for higher values of the vertical velocity. It also increases with an increase in contact pressure for any value of the velocity as expected.

- The impact factor increases with an increase in vertical velocity for any value of contact pressure. Irrespective of contact pressure values for the elastic runway pavement considered for this study the impact factor is 2 for 0 value of vertical velocity, but it becomes extremely large when contact pressure tends to zero or pavement is rigid with a high modulus of subgrade reaction.

- An illustrative example is presented to describe the application of proposed analytical expressions and graphical presentations for calculating the dynamic deflection and associated impact factor. It is observed that the load imposed on a runway pavement primarily depends upon the rate of descent and weight of the aircraft. Therefore, the runway pavement technical evaluation can be performed using the deflection model proposed by this study. Similarly, it is suggested that the load bearing strength of a runway pavement should be reported considering potential deflection that can be calculated using the deflection model developed by this study.

- Investigation of civil aviation safety regulation system suggests that the commercial pressure caused by liberalisation and privatisation of airport operations and the aviation industry influences the safety outcomes. Current regulatory framework and the NAAs are also experiencing challenges as a consequence. Evidences, indicate that outcome based aviation safety regulation system reduces the government involvement in the industry practices. This may expose the safety sensitive aviation operations to higher risks as compare to prescriptive regulations.

9.3 Recommendations for further study

Further studies to expand the analysis carried out in this thesis and also to include more runway profiles, both in number and variety are highly recommended. A diversity of data would add greatly to strengthen the accuracy of the developed deflection model.

The runway of an airport is normally a complex structure, because it has various instrumentation and equipment integrated with the structure. In traditional civil engineering structures, the conduits or buried pipes are being used in wide applications since ancient times for carrying water, oil, gas, sewage, slurry, and other materials from one location to another. Similarly, a buried conduit may be used to house the components of instrument landing system (ILS) under a runway or taxiway pavement. Therefore, an exploration is required into determining the feasibility of such conduit installation and load distribution model through the runway pavement. The wall thickness of a conduit is significantly depends on the load acting upon the conduit. In a field situation where a conduit of desired thickness is not available, the use of a geosynthetic-reinforced soil backfill can be a viable option to solve the problem. Hence, a methodology for the installation of a geosynthetic layer within the soil backfill over the conduit in a ditch for airport applications in order to reduce the vertical load may also be investigated. This can be a potential area for further research.

Review of literature on aeronautical aspects of airports reveals that the field data and studies are rather scarce in public domain and a number of possibilities remain under explored. It would be interesting to identify additional issues relating aeronautical activities at airports. This would pave a way to operate an airport based on contemporary aeronautical research instead of empirical practices and procedures.

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Declaration

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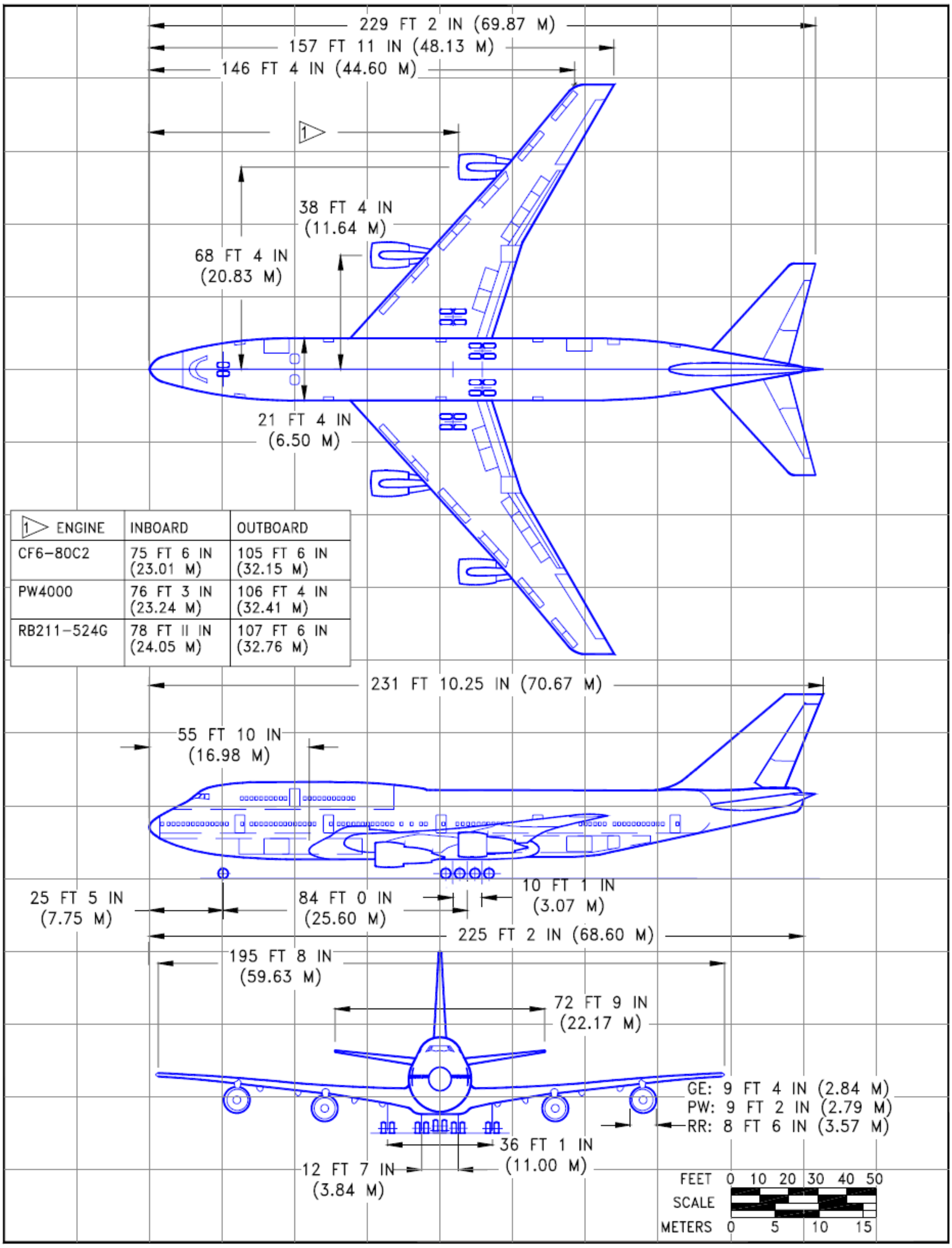
Appendix I: Boeing 747-400 characteristics



1 ENGINE	INBOARD	OUTBOARD
CF6-80C2	75 FT 6 IN (23.01 M)	105 FT 6 IN (32.15 M)
PW4000	76 FT 3 IN (23.24 M)	106 FT 4 IN (32.41 M)
RB211-524G	78 FT II IN (24.05 M)	107 FT 6 IN (32.76 M)

Fig.A1. General dimensions: B747-400 passenger aircraft

(After Boeing Commercial Airplanes, 2002)

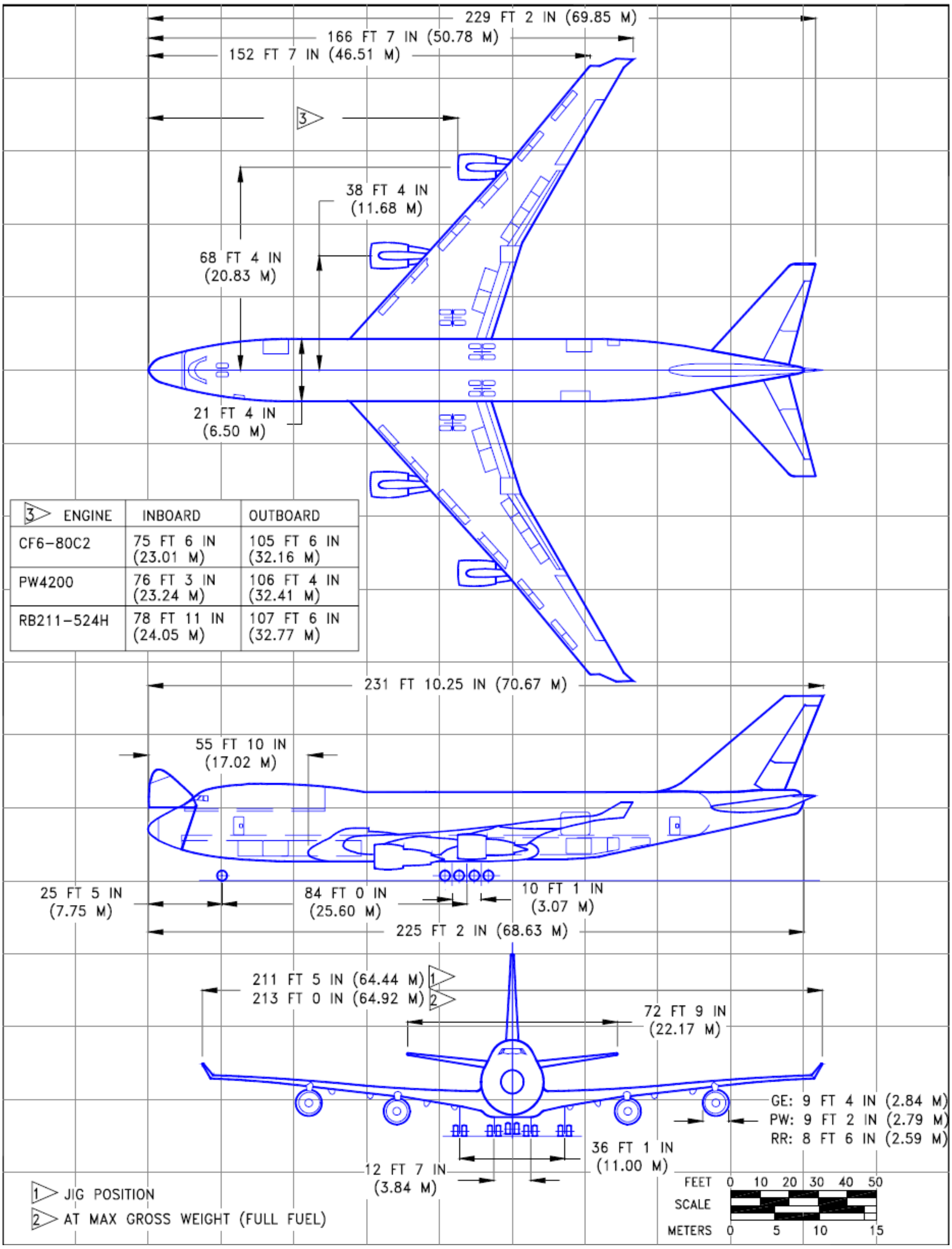


Fig.A2. General dimensions: B747-400 freighter aircraft

(After Boeing Commercial Airplanes, 2002)

CHARACTERISTICS	UNITS	CF6-80C2B1 ENGINES				
MAX DESIGN	POUNDS	803,000	836,000	853,000	873,000	877,000
TAXI WEIGHT	KILOGRAMS	364,235	379,204	386,915	395,987	397,801
MAX DESIGN	POUNDS	800,000	833,000	850,000	870,000	875,000
TAKEOFF WEIGHT	KILOGRAMS	362,874	377,843	385,554	394,626	396,894
MAX DESIGN	POUNDS	574,000	574,000	630,000	630,000	630,000
LANDING WEIGHT (1)	KILOGRAMS	260,362	260,362	285,764	285,764	285,764
MAX DESIGN	POUNDS	535,000	535,000	535,000	542,500	542,500
ZERO FUEL WEIGHT (2)	KILOGRAMS	242,672	242,672	242,672	246,074	246,074
SPEC OPERATING	POUNDS	394,088	394,088	394,088	394,088	394,088
EMPTY WEIGHT (3)	KILOGRAMS	178,756	178,756	178,756	178,756	178,756
MAX STRUCTURAL	POUNDS	140,912	140,912	140,912	148,412	148,412
PAYLOAD	KILOGRAMS	63,917	63,917	63,917	67,319	67,319
TYPICAL SEATING CAPACITY	UPPER DECK	42 BUSINESS CLASS				
(INCLUDES UPPER DECK)	MAIN DECK	24 FIRST, 32 BUSINESS, 302 ECONOMY				
MAX CARGO - LOWER DECK	CUBIC FEET	5,536	5,536	5,536	5,536	5,536
CONTAINERS (LD-1)	CUBIC METERS	157	157	157	157	157
MAX CARGO - LOWER DECK	CUBIC FEET	835	835	835	835	835
BULK CARGO	CUBIC METERS	24	24	24	24	24
USABLE FUEL CAPACITY (4)	U.S. GALLONS	53,765	53,763	53,765	57,065	57,065
	LITERS	203,501	203,493	203,501	215,991	215,991
	POUNDS	360,226	360,226	360,226	382,336	382,336
	KILOGRAMS	163,396	163,396	163,396	173,425	173,425

Fig.A3. General characteristics: B747-400 with General Electric engines
(After Boeing Commercial Airplanes, 2002)

CHARACTERISTICS	UNITS	PW 4056 ENGINES				
MAX DESIGN	POUNDS	803,000	836,000	853,000	873,000	877,000
TAXI WEIGHT	KILOGRAMS	364,235	379,204	386,915	395,987	397,801
MAX DESIGN	POUNDS	800,000	833,000	850,000	870,000	875,000
TAKEOFF WEIGHT	KILOGRAMS	362,874	377,843	385,554	394,626	396,894
MAX DESIGN	POUNDS	574,000	574,000	630,000	630,000	630,000
LANDING WEIGHT (1)	KILOGRAMS	260,362	260,362	285,764	285,764	285,764
MAX DESIGN	POUNDS	535,000	535,000	535,000	542,500	542,500
ZERO FUEL WEIGHT (2)	KILOGRAMS	242,672	242,672	242,672	246,074	246,074
SPEC OPERATING	POUNDS	394,660	394,660	394,660	394,660	394,660
EMPTY WEIGHT (3)	KILOGRAMS	179,015	179,015	179,015	179,015	179,015
MAX STRUCTURAL	POUNDS	140,340	140,340	140,340	147,840	147,840
PAYLOAD	KILOGRAMS	63,657	63,657	63,657	67,059	67,059
TYPICAL SEATING CAPACITY	UPPER DECK	42 BUSINESS CLASS				
(INCLUDES UPPER DECK)	MAIN DECK	24 FIRST, 32 BUSINESS, 302 ECONOMY				
MAX CARGO - LOWER DECK	CUBIC FEET	5,536	5,536	5,536	5,536	5,536
CONTAINERS (LD-1)	CUBIC METERS	157	157	157	157	157
MAX CARGO - LOWER DECK	CUBIC FEET	835	835	835	835	835
BULK CARGO	CUBIC METERS	24	24	24	24	24
USABLE FUEL CAPACITY (4)	U.S. GALLONS	53,985	53,985	53,985	57,285	57,285
	LITERS	204,333	204,333	204,333	216,824	216,824
	POUNDS	361,700	361,700	361,700	383,810	383,810
	KILOGRAMS	164,064	164,064	164,064	174,093	174,093

Fig.A4. General characteristics: B747-400 with Pratt & Whitney engines
(After Boeing Commercial Airplanes, 2002)

CHARACTERISTICS	UNITS	RB211-524G2 ENGINES				
MAX DESIGN TAXI WEIGHT	POUNDS	803,000	836,000	853,000	873,000	877,000
	KILOGRAMS	364,235	379,204	386,915	395,987	397,801
MAX DESIGN TAKEOFF WEIGHT	POUNDS	800,000	833,000	850,000	870,000	875,000
	KILOGRAMS	362,874	377,843	385,554	394,626	396,894
MAX DESIGN LANDING WEIGHT (1)	POUNDS	574,000	574,000	630,000	630,000	630,000
	KILOGRAMS	260,362	260,362	285,764	285,764	285,764
MAX DESIGN ZERO FUEL WEIGHT (2)	POUNDS	535,000	535,000	535,000	545,000	545,000
	KILOGRAMS	242,672	242,672	242,672	247,208	247,208
SPEC OPERATING EMPTY WEIGHT (3)	POUNDS	396,284	396,284	396,284	396,284	396,284
	KILOGRAMS	179,752	179,752	179,752	179,752	179,752
MAX STRUCTURAL PAYLOAD	POUNDS	138,716	138,716	138,716	148,716	148,716
	KILOGRAMS	62,921	62,921	62,921	67,457	67,457
TYPICAL SEATING CAPACITY (INCLUDES UPPER DECK)	UPPER DECK	42 BUSINESS CLASS				
	MAIN DECK	24 FIRST, 32 BUSINESS, 302 ECONOMY				
MAX CARGO - LOWER DECK CONTAINERS (LD-1)	CUBIC FEET	5,536	5,536	5,536	5,536	5,536
	CUBIC METERS	157	157	157	157	157
MAX CARGO - LOWER DECK BULK CARGO	CUBIC FEET	835	835	835	835	835
	CUBIC METERS	24	24	24	24	24
USABLE FUEL CAPACITY (4)	U.S. GALLONS	53,985	53,985	53,985	57,285	57,285
	LITERS	204,333	204,333	204,333	216,824	216,824
	POUNDS	361,700	361,700	361,700	383,810	383,810
	KILOGRAMS	164,064	164,064	164,064	174,093	174,093

Fig.A5. General characteristics: B747-400 with Rolls Royce Engines
(After Boeing Commercial Airplanes, 2002)

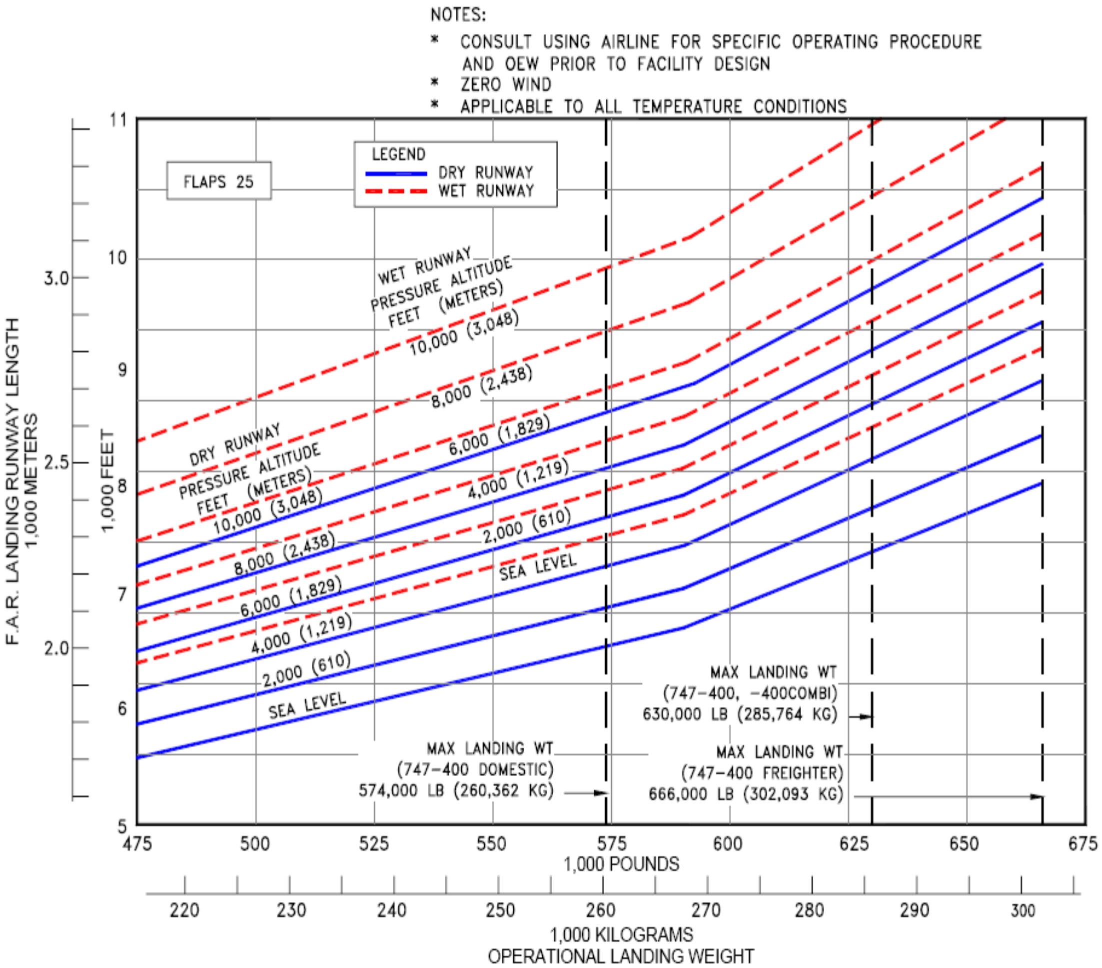


Fig.A6. B747-400 passenger aircraft:

Landing runway length requirements - Flap 25

(After Boeing Commercial Airplanes, 2002)

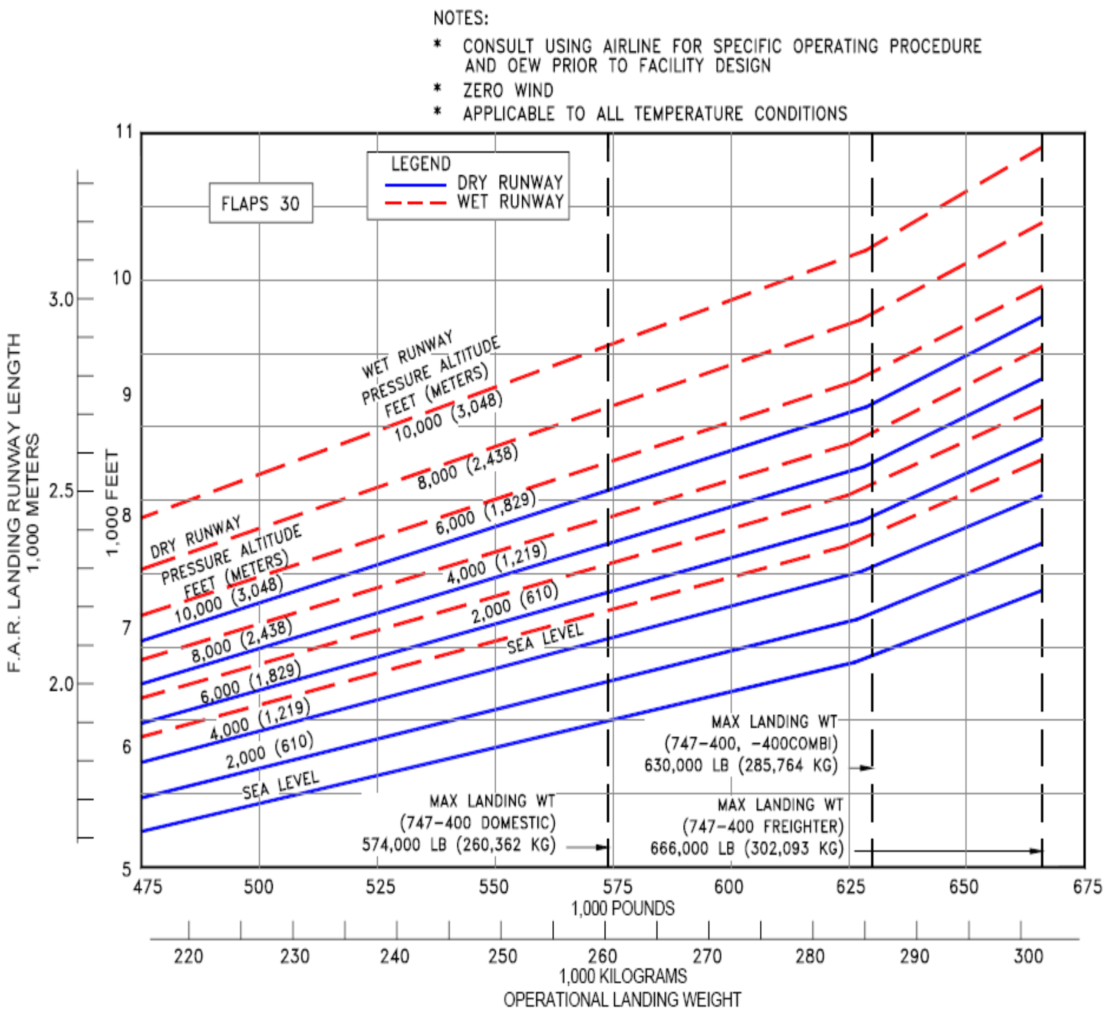


Fig.A7. B747-400 passenger aircraft:

Landing runway length requirements - Flap 30

(After Boeing Commercial Airplanes, 2002)

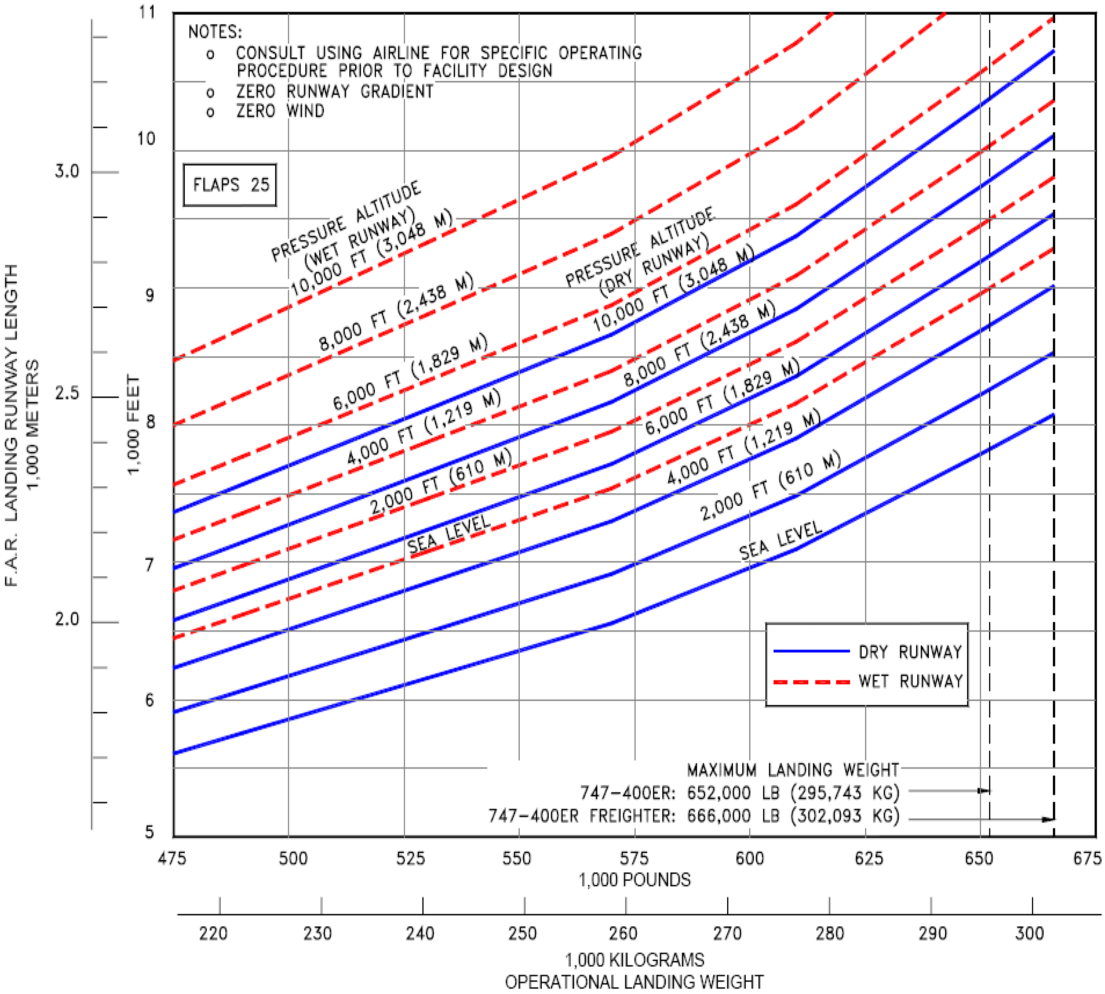


Fig.A8. B747-400 ER aircraft:

Landing runway length requirements - Flap 25

(After Boeing Commercial Airplanes, 2002)

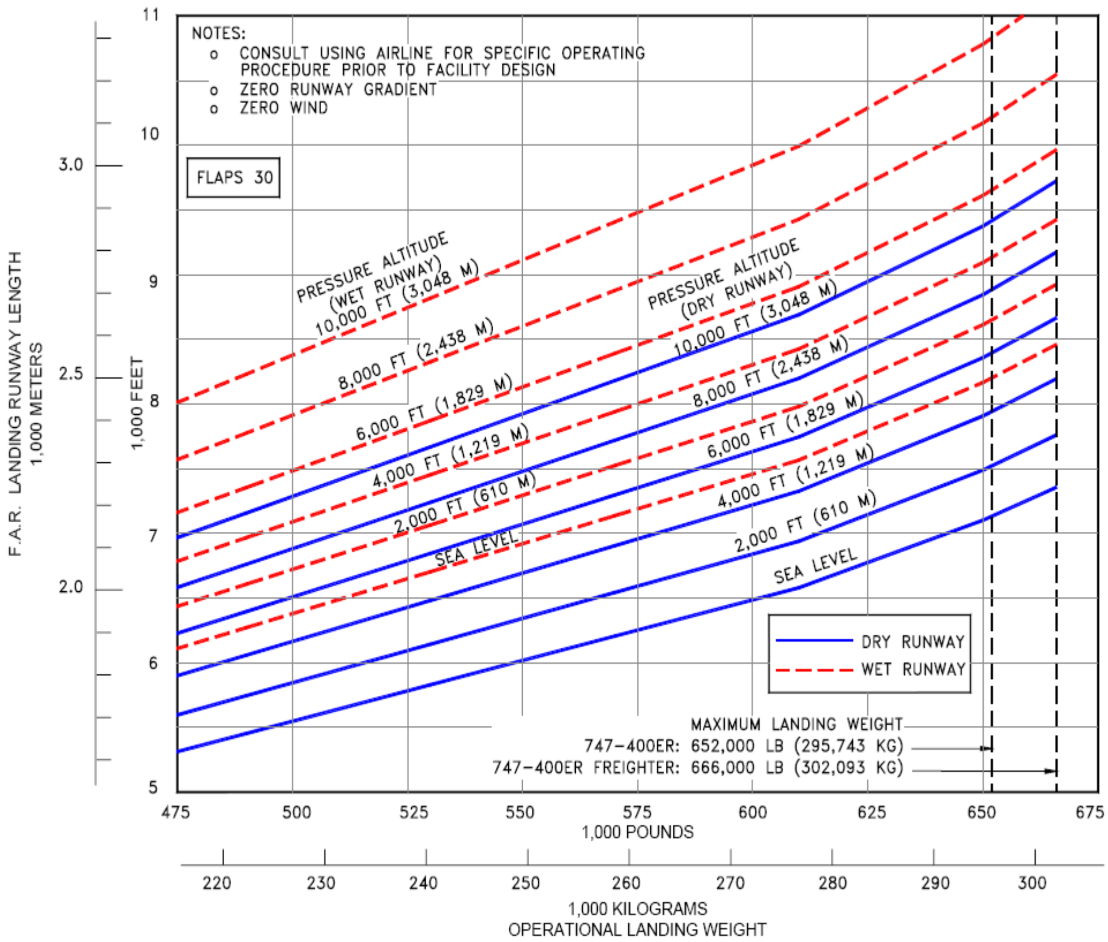


Fig.A9. B747-400 ER aircraft:

Landing runway length requirements - Flap 30

(After Boeing Commercial Airplanes, 2002)

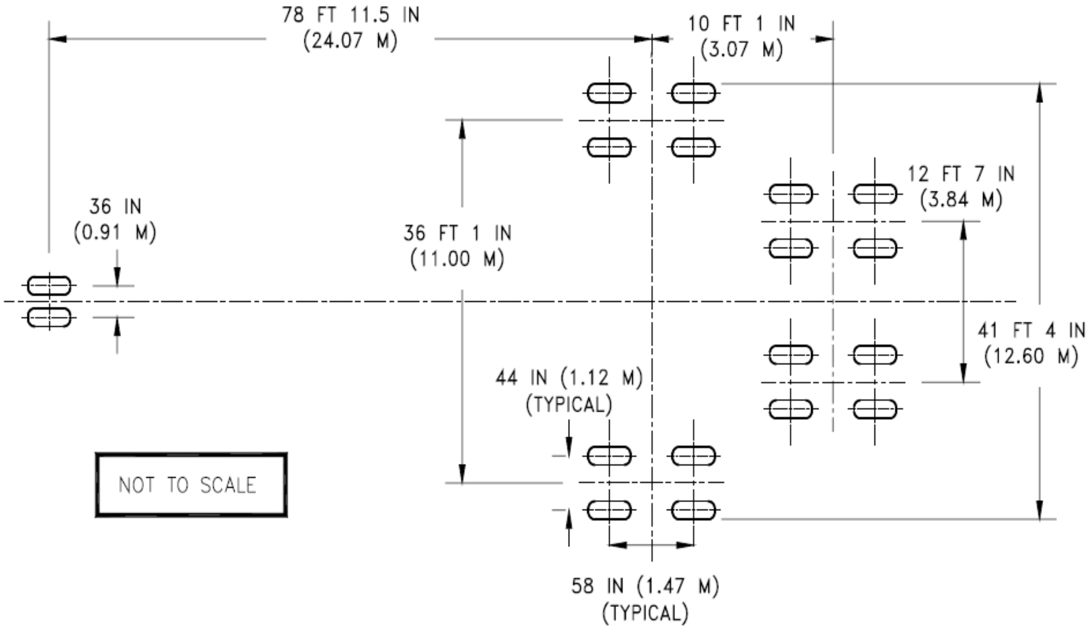


Fig.A10. B747-400 aircraft: Landing gear footprint
(After Boeing Commercial Airplanes, 2002)

Appendix II: Boeing 777 landing reports

LANDING EXCEEDANCE REPORT – WIND AND ACCELERATION 22 <11>

	FLT	FM	FLCT	DATE	UTC	FROM	TO	GWT	CODE
RH	A943	FL	100	19OCT09	072314	WADD	WSSS	187102	1102

	CAS	MACH	TAT	LAT	LON	THDG	VER
05	129.2	.196	34.88	1.355	103.993	–157.5	3167–BSM–812–02

WS	LATG MIN/MAX		VRTG MIN/MAX		SAT	REV		GLS	LOC
6	–0.013	0.039	0.948	1.024	31.1		1.1	.036	–.010
8	–0.044	0.021	0.941	1.026	31.1		1.1	.036	–.010
9	–0.055	0.006	0.938	1.051	31.3		0.6	.047	–.009
8	–0.019	0.027	0.951	1.033	31.1		1.1	.050	–.007
7	–0.021	0.003	0.936	0.994	31.3		0.8	.050	–.006
7	–0.026	0.024	0.894	0.962	31.3		0.8	.050	–.004
8	–0.010	0.020	0.938	1.000	31.3		1.1	.049	–.002
8	–0.025	0.021	0.926	1.016	31.4		0.8	.044	–.001
8	–0.014	0.017	0.949	1.026	31.4		0.8	.039	.000
8	–0.028	0.013	0.964	1.021	31.5		0.6	.032	.001
7	–0.022	0.008	0.994	1.044	31.6		1.0	.021	.001
8	–0.029	0.002	0.996	1.090	31.6		1.0	.018	.001
8	–0.030	0.011	0.974	1.112	31.6		1.0	.012	.001
9	–0.009	0.024	0.929	1.049	31.6		1.1	.015	.000
7	–0.029	0.013	0.923	1.085	31.6		1.1	.014	–.001
9	–0.016	0.016	0.926	1.025	31.6		1.0	.012	–.001
10	–0.013	0.031	0.978	1.045	31.6		1.3	.007	–.002
8	–0.015	0.030	0.937	1.048	31.6		0.6	.006	–.002
6	–0.017	0.022	0.962	1.030	31.9		1.3	.004	.000
7	–0.015	0.006	0.962	1.036	31.8		1.1	.002	–.001
9	–0.008	0.017	0.960	1.071	31.8		1.1	.002	–.001
8	–0.015	0.018	0.925	1.029	31.8		1.1	–.001	–.002
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]
7	–0.037	0.017	0.964	1.053	31.8		1.1	–.022	.000
9	–0.016	0.022	0.966	1.032	31.9		0.6	–.036	.000
7	–0.024	0.010	0.997	1.127	32.0		1.0	–.045	.000
6	–0.016	0.015	0.986	1.088	32.1		0.8	–.063	.002
4	–0.013	0.008	0.973	1.063	32.0		1.0	–.065	.002
4	–0.013	0.016	0.946	1.084	32.3		1.1	–.075	.000
6	–0.014	0.009	0.979	1.054	32.3		0.8	–.085	.001
9	–0.028	–0.005	1.021	1.084	32.1		1.3	–.084	–.001
7	–0.027	0.000	1.002	1.095	32.5		1.1	–.073	.001
7	–0.023	0.021	0.957	1.078	32.6		0.8	–.047	–.001
6	–0.022	0.035	0.976	1.051	32.4		1.0	.020	–.001
5	–0.012	0.033	0.989	1.094	32.5		1.1	.067	.000
4	–0.025	0.003	0.961	1.111	32.9		1.0	.134	–.002
4	–0.019	0.024	0.939	1.076	32.8		1.1	.202	–.003
3	–0.034	0.033	0.963	1.092	33.0		0.8	.075	–.004
5	–0.030	0.006	0.927	1.024	32.8		1.0	–.030	–.004
3	–0.011	0.022	1.000	1.101	32.9		1.1	–.018	–.004
3	–0.118	0.048	0.829	1.691	32.6		1.1	–.018	–.006

Profile.1. Indicating the value of lateral and vertical acceleration

(Singapore International Airline, 2009)

7 LANDING EXCEEDANCE REPORT – AIR AND ATTITUDE 22 <11>

D	FLT	FM	FLCT	DATE	UTC	FROM	TO	GWT	CODE
SRH	A943	FL	100	19OCT09	072314	WADD	WSSS	187102	1102

T	CAS	MACH	TAT	LAT	LON	THDG	VER
105	129.2	.196	34.88	1.355	103.993	–157.5	3167–BSM–812–02

P	LEF	LMLG	RMLG	NOSE
0.0	NOTUP	GND	GND	AIR

LT	RALT	CAS	MACH	MHDG	PTCH	ROLL	IVV	MSQT L	R	NSQT
584	455	134.4	.205	–159.6	1.3	–4.6	–551	AIR	AIR	AIR
574	444	138.0	.211	–160.0	1.3	–3.7	–565	AIR	AIR	AIR
565	434	138.4	.211	–159.6	1.1	–1.3	–599	AIR	AIR	AIR
554	423	137.3	.210	–159.2	1.0	1.0	–608	AIR	AIR	AIR
548	414	137.6	.210	–159.0	0.7	1.8	–682	AIR	AIR	AIR
537	397	137.1	.209	–158.6	0.2	2.0	–800	AIR	AIR	AIR
522	385	138.5	.211	–158.2	0.1	1.1	–858	AIR	AIR	AIR
506	302	138.6	.211	–158.1	0.3	0.4	–882	AIR	AIR	AIR
489	317	137.8	.210	–158.1	0.7	1.1	–890	AIR	AIR	AIR
475	311	137.4	.209	–158.2	0.8	2.2	–907	AIR	AIR	AIR
459	302	137.1	.209	–158.1	0.8	0.9	–912	AIR	AIR	AIR
444	252	137.4	.209	–157.9	1.0	0.3	–875	AIR	AIR	AIR
433	251	137.1	.209	–157.4	1.3	2.2	–809	AIR	AIR	AIR
424	239	138.4	.211	–156.9	1.4	2.8	–722	AIR	AIR	AIR
413	235	136.5	.208	–156.6	1.5	1.5	–721	AIR	AIR	AIR
400	220	138.3	.210	–156.2	1.4	0.4	–740	AIR	AIR	AIR
385	196	138.4	.211	–156.0	1.4	–0.8	–740	AIR	AIR	AIR
377	225	136.3	.207	–156.1	1.2	–0.2	–722	AIR	AIR	AIR
365	213	134.8	.205	–156.7	1.4	–0.5	–717	AIR	AIR	AIR
351	198	135.3	.206	–157.1	1.4	–2.1	–723	AIR	AIR	AIR
341	184	137.2	.209	–157.4	1.2	–2.3	–722	AIR	AIR	AIR
331	169	135.4	.206	–157.8	1.1	–0.6	–720	AIR	AIR	AIR
318	158	135.1	.205	–158.1	1.1	1.3	–821	AIR	AIR	AIR
300	142	134.1	.204	–158.2	1.5	1.5	–831	AIR	AIR	AIR
289	127	135.3	.206	–158.2	1.6	0.1	–801	AIR	AIR	AIR
275	114	134.0	.204	–158.3	2.0	0.6	–777	AIR	AIR	AIR
262	98	131.8	.200	–158.2	2.6	0.3	–719	AIR	AIR	AIR
252	85	130.6	.198	–158.1	2.8	0.1	–660	AIR	AIR	AIR
238	73	130.7	.198	–158.2	2.5	0.4	–672	AIR	AIR	AIR
228	64	132.9	.202	–158.2	2.3	–0.3	–636	AIR	AIR	AIR
220	53	137.4	.209	–158.3	2.2	–0.1	–600	AIR	AIR	AIR
212	43	137.2	.208	–157.9	2.0	–0.1	–521	AIR	AIR	AIR
196	34	137.2	.208	–157.6	1.9	1.7	–471	AIR	AIR	AIR
188	27	136.2	.207	–157.2	2.0	1.9	–440	AIR	AIR	AIR
168	20	136.4	.207	–157.4	2.8	–0.2	–408	AIR	AIR	AIR
156	15	134.7	.204	–157.7	3.1	0.3	–315	AIR	AIR	AIR
151	11	133.9	.203	–157.6	2.4	0.4	–275	AIR	AIR	AIR
130	7	131.7	.200	–157.7	2.3	–1.3	–270	AIR	AIR	AIR

Profile.2. Indicating the speed of main landing gears at touchdown

(Singapore International Airline, 2009)

'7 LANDING EXCEEDANCE REPORT – WIND AND ACCELERATION 20 <11>

D	FLT	FM	FLCT	DATE	UTC	FROM	TO	GWT	COD
·SRH	A979	FL	84	130CT09	133405	VTBS	WSSS	194784	110

.T	CAS	MACH	TAT	LAT	LON	THDG	VER
–16	129.9	.196	31.50	1.361	103.989	–160.0	3167–BSM–812–0

	WS	LATG MIN/MAX		VRTG MIN/MAX		SAT	REV	GLS	LOC
6	9	–0.015	0.006	0.968	1.082	27.9	0.6	–.012	.001
1	9	–0.024	0.010	0.974	1.082	27.9	0.6	–.005	.002
5	8	–0.023	0.012	0.969	1.015	27.9	1.3	–.007	.003
0	9	–0.017	0.008	0.967	1.087	27.9	1.3	–.012	.001
0	9	–0.036	0.021	0.979	1.058	28.0	0.5	–.005	.000
0	8	–0.027	0.006	0.962	1.030	28.0	1.3	–.006	–.001
7	8	–0.017	0.021	0.919	0.994	27.9	1.3	.000	.001
5	8	–0.012	0.012	0.905	1.054	27.9	1.4	–.006	.002
9	8	–0.019	0.019	0.977	1.055	27.8	0.6	–.001	.002
3	8	–0.031	0.002	0.972	1.074	27.9	0.6	–.009	.002
4	8	–0.029	0.016	0.929	1.063	28.0	1.4	–.005	.002
0	8	–0.021	–0.006	0.962	1.025	27.9	0.5	–.003	.002
4	8	–0.023	0.021	0.951	1.007	27.9	0.5	–.004	.002
3	8	–0.021	0.004	0.914	1.010	27.9	0.6	–.007	.004
3	7	–0.013	0.023	0.958	1.075	27.9	1.4	–.008	.004
5	7	–0.011	0.012	0.953	1.054	28.0	1.4	–.011	.004
1	6	–0.021	0.014	0.994	1.043	28.1	0.6	–.015	.004
5	6	–0.036	0.020	0.991	1.051	28.3	1.3	–.013	.004
7	7	–0.021	0.017	0.944	1.024	28.3	1.3	–.018	.002
3	6	–0.029	0.021	0.980	1.091	28.4	1.4	–.009	.003
2	5	–0.009	0.026	0.965	1.079	28.3	0.6	–.012	.003
9	5	–0.029	0.021	0.938	1.032	28.1	0.6	–.012	.004
2	6	–0.021	0.020	0.993	1.067	28.4	1.3	–.011	.003
2	6	–0.033	0.007	0.953	1.084	28.4	0.6	–.009	.002
9	6	–0.025	0.008	0.960	1.105	28.5	0.6	–.004	.002
9	5	–0.016	0.033	0.911	1.025	28.5	0.8	.009	.004
1	5	–0.021	0.007	0.951	1.105	28.5	0.6	.027	.002
1	5	–0.006	0.029	0.909	1.037	28.4	0.6	.056	.003
2	5	–0.020	0.005	0.965	1.072	28.5	0.6	.086	.003
8	5	–0.021	0.038	0.931	1.031	28.5	1.3	.125	.003
5	5	–0.014	0.030	0.960	1.094	28.6	1.3	.173	.002
2	5	–0.010	0.012	0.965	1.108	28.6	1.3	.253	.002
0	6	–0.033	–0.001	0.970	1.117	28.6	1.3	.320	.003
8	7	–0.012	0.029	0.925	1.181	28.6	1.3	.287	.002
6	7	–0.011	0.008	0.926	1.166	28.9	1.3	.215	.003
1	6	–0.035	0.027	0.864	1.076	29.0	0.6	.175	.003
6	6	–0.018	0.032	0.927	1.277	29.1	0.6	.159	.003
8	8	–0.020	0.015	0.844	1.193	29.4	1.3	–.173	.004
7	8	–0.018	0.041	0.879	1.014	29.1	0.6	.011	.004
9	10	–0.025	0.003	0.953	1.081	29.4	0.6	.128	.003
3	10	–0.170	0.076	0.729	1.507	27.3	0.6	.052	.001

Profile.3. Indicating the value of lateral and vertical acceleration

(Singapore International Airline, 2009)

7 LANDING EXCEEDANCE REPORT - AIR AND ATTITUDE 20 <11>

D	FLT	FM	FLCT	DATE	UTC	FROM	TO	GWT	CODE
SRH	A979	FL	84	13OCT09	133405	VTBS	WSSS	194784	1102

T	CAS	MACH	TAT	LAT	LON	THDG	VER
-16	129.9	.196	31.50	1.361	103.989	-160.0	3167-BSM-812-02

P	LEF	LMLG	RMLG	NOSE
0.0	NOTUP	GND	GND	AIR

LT	RALT	CAS	MACH	MHDG	PTCH	ROLL	IVV	MSQT L	R	NSQT
432	422	135.9	.207	-160.7	2.2	-2.0	-764	AIR	AIR	AIR
423	408	135.3	.206	-160.8	2.3	-1.9	-733	AIR	AIR	AIR
411	397	135.6	.206	-160.8	2.0	-0.7	-706	AIR	AIR	AIR
396	383	136.3	.208	-160.8	2.1	0.9	-709	AIR	AIR	AIR
384	371	135.6	.206	-160.8	2.4	0.8	-690	AIR	AIR	AIR
377	359	134.9	.205	-160.6	2.4	0.0	-636	AIR	AIR	AIR
374	343	136.8	.208	-160.5	1.8	0.1	-711	AIR	AIR	AIR
359	325	136.9	.208	-160.5	1.6	0.4	-748	AIR	AIR	AIR
341	338	137.6	.209	-160.8	2.2	-1.2	-732	AIR	AIR	AIR
330	312	137.7	.209	-160.9	2.5	-0.2	-717	AIR	AIR	AIR
318	306	136.1	.207	-160.9	2.1	-0.3	-693	AIR	AIR	AIR
313	290	139.5	.212	-160.8	1.6	1.1	-685	AIR	AIR	AIR
298	274	138.7	.211	-160.5	1.0	1.4	-734	AIR	AIR	AIR
284	259	138.6	.211	-160.3	0.9	0.5	-785	AIR	AIR	AIR
268	242	138.4	.210	-160.0	1.3	1.2	-792	AIR	AIR	AIR
251	225	138.9	.211	-159.8	2.2	0.8	-767	AIR	AIR	AIR
243	212	138.6	.211	-159.7	2.2	-0.5	-739	AIR	AIR	AIR
234	198	137.1	.208	-159.7	1.9	0.8	-705	AIR	AIR	AIR
221	181	134.8	.205	-159.5	1.8	1.3	-716	AIR	AIR	AIR
210	169	137.3	.208	-159.2	1.8	-0.1	-722	AIR	AIR	AIR
198	156	138.9	.211	-159.1	1.7	0.2	-693	AIR	AIR	AIR
187	144	139.3	.211	-159.1	1.4	-0.7	-705	AIR	AIR	AIR
177	132	137.3	.208	-159.5	1.5	-1.1	-705	AIR	AIR	AIR
162	119	136.8	.207	-159.7	1.7	-0.6	-691	AIR	AIR	AIR
143	107	138.0	.209	-159.6	2.1	0.9	-650	AIR	AIR	AIR
140	96	139.9	.212	-159.4	1.9	-0.2	-634	AIR	AIR	AIR
130	86	139.9	.212	-159.2	1.9	0.8	-622	AIR	AIR	AIR
119	76	139.2	.211	-159.0	1.9	1.3	-607	AIR	AIR	AIR
108	65	138.1	.209	-159.0	1.8	0.8	-612	AIR	AIR	AIR
97	54	139.0	.210	-158.8	1.7	0.6	-620	AIR	AIR	AIR
84	44	140.4	.212	-158.9	1.4	-0.5	-630	AIR	AIR	AIR
66	33	140.0	.212	-159.1	1.6	-1.6	-615	AIR	AIR	AIR
45	24	138.6	.210	-159.3	3.1	-0.8	-531	AIR	AIR	AIR
32	17	137.9	.209	-159.3	3.4	-0.1	-469	AIR	AIR	AIR
18	12	136.7	.207	-159.4	4.4	-0.2	-276	AIR	AIR	AIR
17	8	137.7	.208	-159.4	3.3	1.4	-278	AIR	AIR	AIR
1	4	137.6	.208	-159.4	2.7	-0.6	-320	AIR	AIR	AIR
-19	3	133.6	.202	-159.6	4.6	1.2	-144	AIR	AIR	AIR

Profile.4. Indicating the speed of main landing gears at touchdown

(Singapore International Airline, 2009)

7 LANDING EXCEEDANCE REPORT - WIND AND ACCELERATION 18 <11>

D	FLT	FM	FLCT	DATE	UTC	FROM	TO	GWT	CODE
[illegible]	[illegible]	FL	73	05OCT09	144410	WSSS	VRMM	[illegible]	[illegible]

T	CAS	MACH	TAT	LAT	LON	THDG	VER
-32	133.4	.202	32.00	4.196	73.532	-6.1	3167-BSM-812-02

	WS	LATG MIN/MAX		VRTG MIN/MAX		SAT	REV	GLS	LOC
0	10	-0.022	0.014	0.989	1.054	27.8	1.0	-.004	.005
0	9	-0.014	0.024	0.938	1.057	27.9	0.6	-.004	.003
9	9	-0.014	0.013	0.919	1.040	27.9	1.0	-.002	.003
3	9	-0.014	0.009	0.898	1.057	27.9	1.1	.000	.002
4	9	-0.021	0.010	0.927	1.084	28.0	1.0	.003	.002
4	10	-0.011	0.013	0.927	1.045	28.0	1.1	.003	.003
0	9	-0.017	0.016	0.961	1.108	28.1	1.1	.004	.003
8	9	-0.016	0.007	0.953	1.062	28.1	1.1	.005	.001
0	9	-0.013	0.018	0.976	1.048	28.1	1.0	.009	.001
5	9	-0.016	0.012	0.928	1.021	28.1	1.1	.012	.000
9	8	-0.012	0.003	0.939	1.025	28.0	1.1	.014	.001
2	9	0.001	0.021	0.923	1.028	28.1	1.1	.015	.002
9	9	-0.026	0.011	0.937	1.024	28.3	1.1	.016	.004
1	9	-0.014	0.015	0.980	1.055	28.3	1.0	.014	.004
9	9	-0.012	0.014	0.949	1.063	28.3	1.0	.017	.006
3	9	-0.026	0.009	0.981	1.034	28.5	1.0	.017	.007
1	9	-0.023	0.007	0.945	1.052	28.5	1.0	.016	.007
7	9	-0.010	0.011	0.926	1.035	28.5	1.3	.019	.004
1	9	-0.013	0.010	0.941	1.044	28.5	0.8	.018	.000
3	9	-0.016	0.009	0.935	1.017	28.5	0.3	.011	-.002
2	9	0.001	0.024	0.971	1.062	28.5	1.3	.007	-.002
5	9	-0.008	0.023	0.988	1.047	28.8	1.0	-.002	-.002
9	9	-0.020	0.007	0.948	1.071	28.8	1.1	-.015	-.001
5	9	-0.013	0.021	0.932	1.039	28.8	1.0	-.028	.003
5	9	-0.018	0.016	0.962	1.043	28.9	1.1	-.034	.004
4	9	-0.019	0.010	0.906	1.037	28.9	1.4	-.038	.002
0	9	-0.024	0.019	0.943	1.052	29.0	1.1	-.039	-.001
5	9	-0.028	0.002	0.994	1.061	29.0	1.3	-.057	-.001
1	9	-0.021	0.015	0.954	1.022	29.0	0.6	-.062	.002
2	8	-0.023	0.019	0.923	1.036	29.0	1.1	-.069	.007
1	8	-0.030	0.019	0.944	1.034	29.0	1.0	-.081	.007
0	8	-0.046	0.020	0.905	1.063	29.0	1.0	-.101	.011
8	8	-0.035	0.020	0.921	1.135	29.1	1.0	-.126	.003
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	9	-0.040	0.007	0.951	1.133	29.4	1.3	-.159	.010
9	9	-0.035	0.021	0.961	1.079	29.4	1.1	-.171	-.002
2	10	-0.018	0.023	0.975	1.067	29.4	0.5	-.162	.003
0	12	-0.016	0.026	0.915	1.131	29.5	1.1	-.149	-.001
6	13	-0.031	-0.006	1.032	1.163	29.5	1.1	-.072	-.003
2	16	-0.038	0.004	0.976	1.145	29.6	1.3	-.500	-.005
8	14	-0.428	0.074	0.819	1.857	29.6	1.1	-.297	.004

Profile.5. Indicating the value of lateral and vertical acceleration

(Singapore International Airline, 2009)

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D	FLT	FM	FLCT	DATE	UTC	FROM	TO	GWT	CODE
·SRH	A452	FL	73	05OCT09	164619	WSSS	VRMM	203373	1102

.T	CAS	MACH	TAT	LAT	LON	THDG	VER
−32	133.4	.202	32.00	4.196	73.532	−6.1	3167-BSM-812-02

.P	LEF	LMLG	RMLG	NOSE
0.0	NOTUP	GND	GND	AIR

LT	RALT	CAS	MACH	MHDG	PTCH	ROLL	IVV	MSQT L	MSQT R	NSQT
529	533	141.1	.215	−0.3	1.6	0.2	−735	AIR	AIR	AIR
518	521	141.3	.216	−0.3	1.4	0.1	−728	AIR	AIR	AIR
504	509	141.3	.216	−0.2	1.3	0.5	−725	AIR	AIR	AIR
492	496	140.8	.215	−0.2	1.4	−0.5	−754	AIR	AIR	AIR
478	484	140.8	.215	−0.3	1.6	0.2	−758	AIR	AIR	AIR
466	469	140.7	.214	−0.3	1.6	0.3	−768	AIR	AIR	AIR
457	456	141.4	.216	−0.2	1.4	−0.3	−755	AIR	AIR	AIR
444	443	141.8	.216	−0.2	1.4	−0.6	−734	AIR	AIR	AIR
433	430	141.9	.216	−0.1	1.2	−0.1	−731	AIR	AIR	AIR
419	416	140.9	.215	−0.2	1.1	−1.0	−761	AIR	AIR	AIR
406	401	141.6	.216	−0.2	0.8	−0.5	−780	AIR	AIR	AIR
392	389	142.2	.216	−0.4	1.1	−0.3	−830	AIR	AIR	AIR
378	373	141.8	.216	−0.6	1.3	−0.7	−862	AIR	AIR	AIR
362	357	141.6	.215	−0.6	1.3	0.3	−870	AIR	AIR	AIR
350	342	141.6	.215	−0.6	1.2	0.5	−843	AIR	AIR	AIR
335	332	141.3	.215	−0.6	0.9	1.3	−826	AIR	AIR	AIR
323	316	141.8	.216	−0.4	0.8	1.5	−801	AIR	AIR	AIR
312	299	142.2	.216	−0.1	0.5	0.7	−862	AIR	AIR	AIR
296	285	141.9	.216	0.0	0.7	0.1	−886	AIR	AIR	AIR
279	267	141.4	.215	0.1	1.0	1.5	−900	AIR	AIR	AIR
260	255	141.6	.215	0.2	1.4	1.3	−894	AIR	AIR	AIR
248	239	141.2	.214	0.1	1.3	−1.4	−887	AIR	AIR	AIR
234	223	142.1	.216	−0.2	1.0	−2.1	−875	AIR	AIR	AIR
224	209	141.5	.215	−0.5	0.8	−1.5	−833	AIR	AIR	AIR
208	195	141.4	.215	−0.7	0.7	−2.7	−840	AIR	AIR	AIR
189	182	141.4	.215	−0.8	1.0	−0.9	−849	AIR	AIR	AIR
177	164	142.5	.216	−0.9	1.2	0.7	−829	AIR	AIR	AIR
166	151	142.9	.217	−0.6	1.1	2.0	−811	AIR	AIR	AIR
154	135	143.2	.217	−0.2	0.6	2.6	−790	AIR	AIR	AIR
137	122	142.0	.215	0.1	0.7	1.2	−808	AIR	AIR	AIR
124	106	143.3	.217	0.3	0.6	−0.5	−829	AIR	AIR	AIR
105	86	141.6	.214	0.2	1.2	0.2	−827	AIR	AIR	AIR
93	72	141.5	.214	0.2	1.9	2.0	−850	AIR	AIR	AIR
71	59	140.9	.213	0.3	2.3	0.2	−769	AIR	AIR	AIR
63	47	139.9	.212	0.1	2.1	1.4	−723	AIR	AIR	AIR
47	36	139.0	.210	0.2	2.0	2.9	−650	AIR	AIR	AIR
32	25	138.6	.210	0.0	2.0	0.3	−644	AIR	AIR	AIR
14	15	136.9	.207	−0.6	2.0	−1.7	−631	AIR	AIR	AIR

Profile.6. Indicating the speed of main landing gears at touchdown

(Singapore International Airline, 2009)

Appendix III: Publications based on this research

As a result of this research, following papers have been submitted to relevant peer reviewed journals for publication:

Yadav, D. K., & Nikraz, H. (2012). An insight into bearing strength reporting methods of a runway pavement. *International Journal of Critical Infrastructures*, *8*(4), 326-335).

Yadav, D. K., & Nikraz, H. (2012). Technical evaluation of runway pavement using deflection method. *Aviation*, (Under review).

Yadav, D. K., & Nikraz, H. (2012). Implications of evolving civil aviation safety regulations on safety outcomes of air transport industry and airports. *Aviation*, (Paper accepted for publication).

Yadav, D. K., & Nikraz, H. (2012). An insight into professional registration of technical personnel in aeronautical engineering industry. *Aviation*, *16* (2), 51-55.

Yadav, D. K., & Shukla, S. K. (2012). An analytical model for deflection of the runway pavement at touchdown point caused by an aircraft during landing. *International Journal of Geomechanics*, *12* (2), 113-118.