Taylor & Francis
Taylor & Francis Group

AVIATION
ISSN 1648-7788 print / ISSN 1822-4180 online
2013 Volume 17(4): 150–160
doi:10.3846/16487788.2013.861647

TECHNICAL EVALUATION OF A RUNWAY USING THE DEFLECTION METHOD

Devinder K. Yadav, Hamid Nikraz

Curtin University, Bentley Campus, Kent Street, Bentley, WA 6102, Australia
E-mail: dkharyanvi@yahoo.com.au (corresponding author)

Received 14 September 2012; accepted 20 November 2013

Devinder K. YADAV
Education and affiliation: holds a doctorate degree in engineering and is associated with Curtin University, Australia. In addition to his academic qualifications, he also holds an aircraft engineer license with several ratings starting from Cessna 152 to wide-body Airbus and Boeing aircraft and a pilot license.
Research interests: aeronautical engineering, airport engineering, aviation regulations, multidisciplinary engineering, and aviation management.

Hamid NIKRAZ
Education and affiliation: holds a doctorate degree in engineering and is associated with Curtin University, Australia.
Research interests: civil engineering, pavement engineering, transportation and airport engineering, and multidisciplinary engineering topics.

Abstract. An aircraft imposes a heavy load on a runway during landing, resulting in deflection of the runway pavement. Therefore, runway performance is influenced by potential deflection levels. Estimating deflection at touchdown point is a challenging task, however. Generally, the applied load depends on the weight and vertical velocity of the aircraft before hitting the touchdown point. Similarly, performance of runway pavement is influenced by many factors such as number of landings, load factor, soil characteristics, etc. This study discusses landing practices, imposed load analysis, and runway pavement evaluation. The study is based on the idealisation of runway characteristics using mechanical elements, and it suggests that the mechanical modelling approach can be applied to estimate runway deflection. As a result, the analytically predicted deflection findings instead of the semi-empirical practices currently followed by various states of the International Civil Aviation Organisation (hereinafter – ICAO) can be used to carry out technical evaluation of a runway pavement.

Keywords: aircraft, deflection, engineering, flight, landing, pavement, regulations, runway.

1. Introduction

A stringent civil aviation regulatory framework regarding aerodromes and the runway structures administered by national governments dominates the airport engineering field. For determining the load-bearing capacity of a runway, empirical methods based on the aircraft classification number[1] (ACN) and pavement classification number (PCN) are still being used (International …

[1] 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. Similarly, the PCN is a number that expresses the relative load carrying capacity of a pavement in terms of a standard single-wheel load (Horonjeff, McKelvey 1994).

2004). In the past, aircraft were smaller and lighter, but with introduction of fast and heavy aircraft such as the Airbus 380, a new approach to runway evaluation is needed.

Evaluating a runway pavement is an indispensable tool for ensuring efficient utilisation of the runway and safety of aircraft. It primarily determines maintenance requirements to assess residual qualities of the pavement with a view that enables technical and economic solutions. It also ascertains type and mass of the aircraft that can use a particular runway. Similarly, the frequency of possible movements of aircraft on a runway can also be established by the evaluation. It is therefore imperative that the runway pavement evaluation task must involve both structural and functional characteristics of the pavement.

A typical flight includes various phases, but landing is considered the most crucial phase of the flight. An improper landing may result in serious implications for the safety of the aircraft and its occupants if the runway conditions or qualities are compromised. The aircraft imposes a tremendous load on the runway during landing, causing deflection of the runway. Consequently, the results of the technical evaluation of a runway are largely influenced by potential deflection, which primarily depends on the load-bearing characteristics of the layers of the runway pavement. Achieving an accurate estimation of the deflection in relation to landing loads is a fundamental difficulty in interaction analysis. This paper 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 a runway during landing, discusses the performance of runway pavement, and reviews the runway evaluation practices of various contracting states of the International Civil Aviation Organisation[2] (ICAO). Overall, this paper instigates a new approach for technical evaluation of a runway pavement using deflection-based analysis.

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

2. Runway pavement performance factors

An aerodrome runway pavement should be capable of withstanding intended traffic loads caused by the aircraft during landing, take-off, and taxi (Fig. 1). Runways should be constructed with minimum surface irregularities, and the load-bearing strength of the pavement must be suitable for the type and mass of the intended aircraft and other factors. Surface irregularities may adversely affect operation of the aircraft by creating excessive bouncing, pitching, and vibration and uncontrollability during take-off and landing. Similarly, the inappropriate load-bearing strength of the pavement may cause a significant deflection at the runway touchdown zone that could jeopardise the safety of the aircraft.

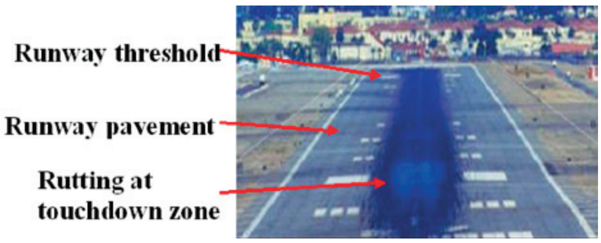

Fig. 1. Rutting at a runway touchdown zone (adapted from Fotosearch 2010)

Therefore, the bearing strength of a runway pavement must be reported in the Aeronautical Information Publication of the country concerned (International … 2004). The ICAO has adopted a pavement classification system for reporting airfield strength. This 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 tyre pressure. The bearing strength of the pavement is reported by indicating PCN, pavement type, subgrade category, allowable tyre pressure, and method of the evaluation.

Vertical velocity of an aircraft during landing causes a deflection of the runway pavement at the touchdown point. The effects of aircraft movement on a runway pavement vary with all-up mass (AUM), tyre pressure, number and spacing of wheels on the aircraft, and type and thickness of the pavement (Swatton 2008). An undesirable amount of movement of material from the

[2] The ICAO was formed in 1944 as a specialised 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.

runway pavement due to aircraft landing loads causes distresses in the pavement. As a result, the runway pavement deteriorates progressively and fails in the long run. Consequently, runway design requirements and pavement evaluation are largely affected by potential deflection, which primarily relates to California bearing ratio (CBR) or modulus of subgrade reaction of soil subgrade of the runway (Ashford, Wright 1992; Horonjeff, McKelvey 1994). Runways are therefore 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).

Performance operating limitations of an aircraft require a length of runway that is sufficient to ensure that the aircraft can either be brought safely to a stop or complete take-off safely after starting a take-off run. In order to discuss, it is supposed that the runway, stopway, and clearway lengths provided at an aerodrome are only just adequate for the aircraft requiring the longest take-off and accelerate-stop distances taking into account its take-off mass, runway characteristics, and ambient atmospheric conditions. According to the ICAO (International … 2004), a take-off must be abandoned or completed depending upon take-off decision speed if an engine fails during the take-off. A very long take-off run and take-off distance would be required to complete a take-off 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 the safety of the aircraft in these emergency situations.

Runway pavement performance is influenced by the frequency of loading. Consequently, stress and strain caused by loading lead a structure to irreversible damages and failure (Kulyk *et al.* 2011). The areas subjected to repeated loadings due to landing must therefore be designed to accommodate stresses. According to the ICAO (International … 1983), previous observations have shown a strong general correlation between deflection of a pavement under wheel load and repetitive landing applications of that wheel load resulting in severe deterioration and failure of the pavement. X. M. Zhang and Q. Dong (2012) calculated vertical displacements caused by loading, and they found that the loading area of the pavement was compressive, but regions of the pavement far away from the loading area were tensile. Loading data of a Boeing 737-800 aircraft were used as an example for the calculation. The researchers also noticed significant changes in vertical displacement depending on the positions of the wheels of the aircraft on the runway pavement. It can therefore be established that the performance of a runway pavement is directly related to the landing loads imposed by the aircraft at touchdown. It is however extremely difficult to precisely define the functional failure of pavement because it deteriorates gradually over a period of time.

3. International practices of evaluating runway pavement

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

Runway pavement evaluation starts with subgrade strength, thickness requirement, and quality of pavement structure, and it uses a design procedure pattern to determine the aircraft loading that a pavement can support (International … 1983). According to J. E. Wood (2008), one of the simplest methods for measuring the pavement profile is by using surveying equipment like an 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 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 concerning this issue use various indices developed for runway design and pavement evaluation (International … 1983). Though it is not within the scope of this paper to develop an additional index, this study uses those indices to discuss the possibility of deflection-based pavement evaluation.

Runway pavements may deteriorate by application of heavy loading, high frequency of loading, or both. These factors may 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 overloading is acceptable with only limited loss in pavement life expectancy. Hence the ICAO (International … 2004) has established certain standards and recommended practices to be followed by operators of aerodromes. The evaluation can be carried out by representing a specific study of the pavement characteristics and applying pavement behaviour technology or using an aircraft representing 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 of the reported PCN are acceptable for flexible pavement. Similarly, occasional movements by aircraft with ACN not exceeding five percent of the reported PCN are accepted as standard practices. However, if the pavement structure is unknown, the five percent limitation applies and the annual number of overload movements should not exceed approximately five percent of the total annual aircraft movements. Additionally, overload movements are not normally permitted on pavements with indications of deterioration or weakened subgrade. The ACNs of various types of aircraft are linked with rigid and flexible pavements according to soil subgrade categories for the purpose of reporting pavement bearing strength. Furthermore, civil aviation regulations require that the runway must be inspected for surface friction, slipperiness, roughness, cracks, and rutting at a predetermined interval (Civil … 2007).

Bearing strength of the pavement is reported by indicating a PCN, pavement type, subgrade category, allowable tyre pressure, and method of technical evaluation (International … 2004). However, in some unavoidable situations such as heavy landings, pavement deflection may become extremely high. This is an undesirable situation for the service life of the runway pavement. Most pavement designs for deflection are based on prescriptive standards and empirical knowledge gained through long experience of the runway history (International … 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 aircraft loading as a function of the bearing modulus of the surface on which the slab rests. Working stresses are used for design and evaluation of pavement, and results of pavement research affirm that the effects of tyre pressure are secondary to load (International … 1983).

Currently, two mathematical models are used in the ACN-PCN method and are 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 … 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, various researchers have developed computer programmes using these mathematical models (International … 1983). However, the computer programs were replaced later by reference tables for field use. Similarly, the aircraft for which pavement thickness requirement charts have been published by aircraft manufacturers can also be evaluated using graphical procedures.

According to the ICAO (International … 1983), a rigid pavement evaluation procedure uses conversion charts (Fig. 2) and pavement thickness requirement charts published by respective aircraft manufacturers. Figure 2 relates the derived single wheel load (DSWL) at a constant tyre 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. Figure 2 also includes an ACN scale, which permits the ACN to be read directly. It may be noted that tyre pressure corrections are not required in this procedure. Likewise, the flexible pavement procedure uses conversion charts (Fig. 3) and pavement thickness requirement charts published by aircraft manufacturers. The reason for using the manufacturer's charts is to obtain equivalency between the effects of a group of landing gear wheels to a DSWL mean of Boussinesq deflection factors.

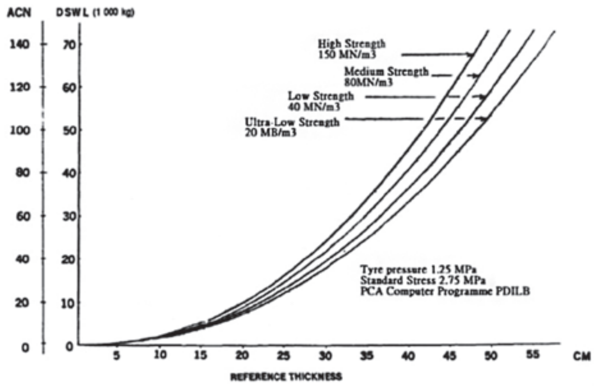

Fig. 2. ACN rigid pavement conversion chart (International … 1983)

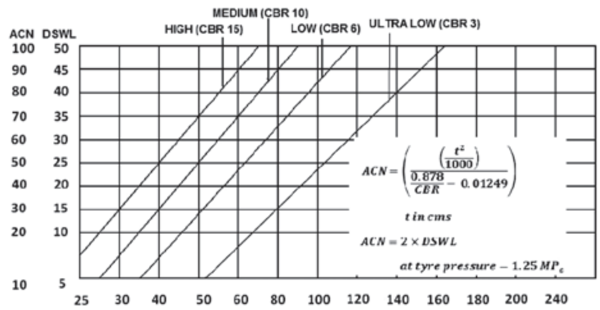

Fig. 3. ACN flexible pavement conversion chart (International … 1983)

4. Runway pavement evaluation practices of major states of the ICAO

The evaluation of a runway pavement structure for aircraft loading requires accurate information about the thickness of layers within the structure and the physical properties of the materials in these layers. ICAO (International … 1983) mentions that a borehole survey is required 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. Equivalent granular thickness is computed using granular equivalency factors for pavement construction materials listed in table. The granular equivalency factor of a material is the depth of the granular base in centimetres considered equivalent to one centimetre 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 of the material in the layer. The pavement equivalent granular thickness is the sum of these converted layer thicknesses.

ICAO (International … 1983) further confirms that it is necessary to conduct measurements of bearing strength on the surface of flexible pavements under Canadian practice. However, the testing is not required until at least two years after construction of the pavement to permit subgrade moisture condition to reach equilibrium. Conversely, the bearing strength of a rigid pavement is not normally measured because the strength calculated on the basis of slab thickness and estimated bearing modulus is considered sufficiently accurate. The standard measure of bearing strength is the load in kilonewtons (kN) that will produce a deflection of 12.5 millimetres for ten repetitions of loading when the load is applied through a rigid circular plate 762 millimetres in diameter. This definition applies for subgrade bearing strength and 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 variety of bearing plate sizes may be used.

Table. Granular equivalency factor (International … 1983)

S. No.	Pavement Material	Granular Equivalency Factor
1	Selected granular sub-base	1
2	Crushed gravel or stone base	1
3	Water-bound Macadam base	1 – ½
4	Bituminous-stabilised base	1 – ½
5	Cement stabilised 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. Subgrade bearing strengths are normally established at existing airports through the bearing strength measurement programme, and subgrade bearing strength derived from measurements are used when designing new pavement facilities at the airport provided the subgrade soil conditions are similar throughout the site (International … 1983). When evaluating pavements at an airport where strength measurements have not been made, a subgrade bearing strength is selected on the basis of the subgrade classification. In addition to the evaluation of pavement bearing strength, airport pavements are also subject to the evaluation of surface conditions under Canadian practice (International Civil Aviation Organisation 1983). The evaluation of surface condition consists of a visually based structural condition survey and quantitative measurements of roughness and friction levels on runway surfaces.

According to the French practice of evaluating runway pavement, two approaches known as reverse design method (RDM) and non-destructive (NDT) plate-loading tests are used (International … 1983). The RDM uses the subgrade data to determine a pavement structure that can bear a given amount of traffic over a certain life provided normal maintenance of the pavement is performed. Conversely, once the characteristics of the subgrade and pavement structure are known, this method enables traffic that can be accepted during a given time to be determined. According to the ICAO (International … 1983), the foregoing is the basis for evaluating the bearing strength of a runway pavement by means of the RDM. Considerable difficulties are however 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 pavement construction, maintenance, past reinforcement work, and accepted traffic are available, this method requires many trial borings and much testing of the pavement. Moreover, the difficulties in obtaining some required parameters results in uncertainties when using 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, ICAO (International … 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 corners of the slabs in case of a rigid pavement. These tests are therefore insufficient to determine the allowable load for an aircraft with multiple wheel undercarriages.

Currently, a number of computer programs based on the plate test theory, multilayer elastic theory, and finite element analysis are available to obtained tabulated data for pavement evaluation. ICAO (International … 1983) indicates that a reference construction classification (RCC) system has been developed in the 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 analysed by Westergaard centre case theory to establish 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 an 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 relative strengths of indigenous construction materials is adopted to convert theoretical model reference construction depths into actual pavement thickness. Consequently, the practical problems of 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.

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

5. Runway pavement evaluation using deflection analysis

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

The aircraft landing phase is one of the most crucial parts of any typical flight, and it commences when the aeroplane reaches 1,000 feet above ground level (AGL) and ends at the point where the aeroplane reaches a full-stop after landing on the runway (Swatton 2008). According to G. Kopecki (2006), aircraft disasters are much more frequent during approach and landing than during other phases of flight. A typical landing begins with the aircraft in approach mode and starts descending from 50 feet AGL as shown in figure 4 (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 a rest.

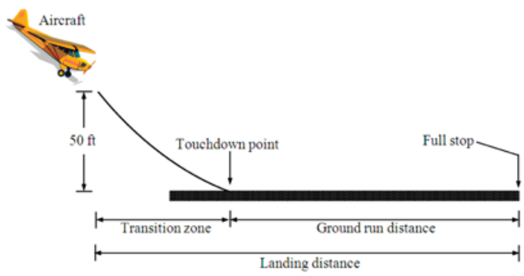

Fig. 4. Aircraft in approach phase of landing

In figure 5, the weight is resolved into two components that act in the same rectangular coordinate system as lift and drag forces. The aircraft approach path makes 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 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 equilibrium again, the force equations become:

$$L = W\cos\theta; \quad (1)$$

$$D = T + W\sin\theta. \quad (2)$$

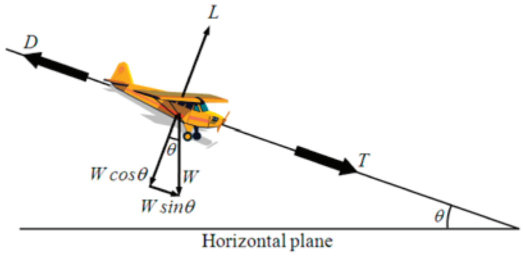

Fig. 5. Forces acting on the aircraft during descent [Note: T = thrust, D = drag, L = lift, W = weight of aircraft, θ = angle between the aircraft flight path to the horizontal plane]

Under standard aeronautical practices, the landing approaches made at a glideslope angle of 3° or less are classified as normal landing approaches (Federal … 2007). Various approach paths with respect to touchdown points as shown in Figure 6 are possible for a typical landing. 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, path (c) indicates an overly flattened path and aircraft requires a high thrust component to reach the touchdown point.

Aeroplanes are aerodynamically designed for a high lift-to-drag ratio and the lift coefficient decreases as this ratio decreases. As a result, the stalling speed[3] of the aircraft increases. Touchdown speed must therefore be greater than the stalling speed of the aeroplane. According to Hull (2007), this is expressed as:

$$V_{TD} = 1.2 V_{stall}, \quad (3)$$

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

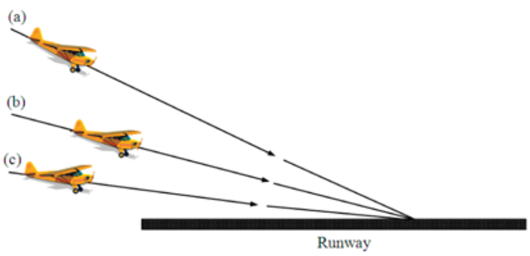

Fig. 6. Various approach paths during landing

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 (Mechanics … 2006):

$$L = C_L \frac{1}{2} \rho V^2 S, \quad (4)$$

where L, ρ, V, S are the lift, air density, speed of the aeroplane, and the surface area of the wings, respectively. When an aeroplane is in equilibrium in straight and level flight ($\boldsymbol{\theta}$ = 0°), equation (1) reduces to:

$$L = W. \quad (5)$$

From equation (4) and (5):

$$W = C_L \frac{1}{2} \rho V^2 S. \quad (6)$$

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

$$W \propto C_L \frac{1}{2} \rho V^2 S. \quad (7)$$

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

$$\frac{L}{D} = \tan\theta. \quad (8)$$

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

Accumulated periods of overstress can create a very detrimental effect on the useful service life of any runway pavement structure. Due to the ultimate factor of safety in aviation, the limit load condition is rarely used as the critical design point and the structure usually possesses a large positive margin of strength. This fact alone implies that the structure must be grossly overstressed to produce easily detectable damage. Similarly, the gross weight of the aircraft and the ROD at touchdown are considered 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 damage to the aircraft structure, including landing gear, and it also contributes to runway rutting.

The most significant function of the landing gear and the runway is to absorb the vertical energy of the aircraft at touchdown. An aircraft at a given weight and ROD at touchdown has a certain kinetic energy that must be dissipated by the landing gear and the runway. The impact of falling weights on the earth generates dynamic stresses that attenuate away from the point of impact (Mayne, 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). Aircraft

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

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, vertical acceleration can also be calculated mathematically, and it varies in accordance with the aircraft weight, centre of gravity, pitch, and roll (Guillaume 2012). 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). The landing load factor n for touchdown at a constant rate of descent is therefore expressed as a ratio of the load in landing gear shock strut, F, to aircraft weight, W, as given below:

$$n = \frac{F}{W} . \tag{9}$$

The landing load factor, n, can also be expressed as:

$$n = \frac{(rate\ of\ descent\ of\ aircraft)^2}{2gS} , \tag{10}$$

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, and the gross weight of the aircraft at the time of touchdown. Therefore:

$$F_{total} = W + n \times W = (1 + n)W . \tag{11}$$

According to equation (11), the total force is directly proportional to the gross weight of the aircraft. So, a higher gross weight produces a greater force depending upon the load factor. However, S will be influenced by factors such as the internal friction forces within the shock absorber, the aircraft approach profile during landing, landing techniques, and the direction and velocity of the wind 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 the runway. According to the (International … 1983), 5% and of the gross weight of a conventional aeroplane is carried by the nose leg (maximum forward load distribution), and 95% is carried by the main undercarriage legs (maximum rearward load distribution. Runway pavement design and evaluation are therefore carried out using these figures of load distribution. However, the effect of braking action is not taken into account in the evaluation of pavement. It plays a role only in specific studies, such as investigating the behaviour of structures underneath the runway. Therefore, stresses caused by the main undercarriage legs of the aircraft are generally taken into consideration for pavement evaluation practices.

ICAO (International … 1983) reveals that the theories applied earlier to pavement behaviour have indicated proportionality between load and deflection. Thus deflection should be an indicator of the capacity of a pavement to support load. This also implies that pavement deflection determined for a particular applied load could be adjusted proportionately to predict the deflection that 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 … 1983). Runway pavement can be idealised by a 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 V. Sawant (2009) for deflection analysis of runway pavement. It was observed that maximum deflection decreased with increasing soil modulus and the velocity of a moving load significantly influenced the pavement responses. Fig. 7 shows the earliest and simplest model proposed by E. 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, that is:

$$q(x) = k_s w(x) , \tag{12}$$

for two-dimensional problems, where k_s is known as the modulus of subgrade reaction.

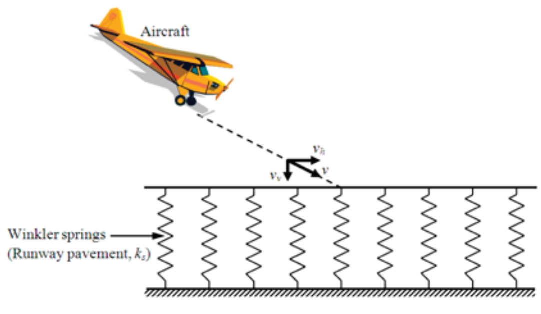

Fig. 7. Landing stage of an aircraft on an idealised runway pavement (adopted from Yadav, Shukla 2012)

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. Equation (12) usually denotes response function for the Winkler model. A. P. S. Selvadurai (1979) argues that the Winkler model represents an accurate idealisation of operating conditions in many engineering applications.

Figure 7 shows the landing stage of an aircraft on a runway, where v is velocity of the aircraft prior to landing at the touchdown point, and it has horizontal and vertical components v_h and v_v. Due to the vertical component of velocity, v, the aircraft applies an impact load on the runway pavement. The aircraft load is transmitted to the pavement through the landing gears of the aircraft. According to the ICAO (International … 1983), the number of wheels, their spacing, tyre pressure, and tyre size determine the distribution of aircraft load on 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 paved 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 subgrade strength category, the relative effects of two aircraft types on pavements can be uniquely stated with good accuracy.

ICAO (International … 1983) argues that it is not sufficient to consider the magnitude of loading alone. There is a fatigue or repetition of load factor that should also be considered. Thus magnitude and repetition must be treated together, and a pavement that 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 a mixture of aircraft using a pavement. According to D. K. Yadav and S. K. Shukla (2012), deflection estimation can be done by considering the aircraft landing a free fall of a body from a known height. If m is the mass of the aircraft causing the load on one main landing gear leg, h is the height of free fall and g is the acceleration due gravity, then:

$$\frac{1}{2}mv_v^2 = mgh\,, \tag{13}$$

or

$$h = \frac{v_v^2}{2g}\,. \tag{14}$$

Therefore, if w is the deflection of the runway caused by the impact load, k_s is the modulus of subgrade reaction of the runway pavement, and p is the equivalent static contact pressure exerted by landing gear wheels on the runway pavement surface, the following general expression derived by D. K. Yadav and S. K. Shukla (2012) can be used to estimate the runway deflection at touchdown point for the purpose of runway pavement technical evaluation:

$$w = \frac{p}{k_s} + \sqrt{\left(\frac{p}{k_s}\right)^2 + \left(\frac{pv_v^2}{gk_s}\right)}\,. \tag{15}$$

Equation (14) can be represented in non-dimensional form as:

$$w^* = p^* + \sqrt{\left(p^*\right)^2 + p^* v_v^{2*}}\,, \tag{16}$$

where $w^*(= w/a)$ is non-dimensional dynamic deflection; $p^*\,(=\frac{p}{k_s a})$ is non-dimensional equivalent static contact pressure exerted by landing gear wheels on the runway pavement surface; a is the radius of the equivalent circular area (related to m); and $v_v^*(=\frac{v_v^2}{ga})$ is the non-dimensional vertical velocity of the aircraft at runway touchdown point during landing.

Though D. K. Yadav and S. K. Shukla (2012) specify that equations (15) and (16) are based on idealisations, the overall model may be used by runway maintenance engineers for routine technical evaluation of runway pavement instead of using the empirical practices recommended by the ICAO. Many other secondary factors such as spacing of the aircraft wheels and aircraft taxiing loads also influence the life of a runway pavement, however. 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 take-off or is taxiing fast after a landing 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 minimal effects on the accuracy of the evaluation results because the deflection caused by landing impact is a primary factor for major deterioration of a runway pavement. Consequently, a maximum allowed deflection threshold, similar to the deflection limits set for highways, can be set to reduce the risk factor caused by the secondary factors.

X. M. Zhang and Q. Dong (2012) discovered that significant influences of vertical displacements of loads caused by landing gear occur within 15 metres of the aircraft taxiing direction and 45 metres of entire width of the runway pavement. The touchdown zone of the runway pavement is the area with the highest stresses due to landing forces and experiences the maximum displacement. As a result, the deflection in this zone will also be the highest, causing severe deterioration of the pavement. This indicates that the deflection caused by aircraft loading is the main factor that influences the condition of a runway pavement. Considering the vertical velocity of an aircraft during landing as 2.6 m/s, Y. Dai *et al.* (2003) found that dynamic load caused by the impact of landing was more than twice of total weight of the aircraft. The researchers also observed that the deflection caused by impact is higher than that caused by a moving load and that the landing impact induces higher stresses on the pavement. They further argued that the maximum deflection and stresses under a landing impact load are much higher than those under a taxiing load. It can therefore be established that the deflection caused by aircraft landings should be considered the primary indication of a pavement's physical conditions when assessing deterioration of the pavement. Consequently, the aircraft-runway interaction model projecting deflection as the key indicator can be used for technical evaluation of a runway pavement. However, friction characteristics of a runway pavement may still be determined using Grip Tester suggested by the ICAO-Doc.9137-AN/898 (De Luca, Dell'Acqua 2013).

6. Conclusions

Impact load imposed by an aircraft landing is the primary contributory factor causing deflection in a runway pavement. Consequently, it is important to consider the physical and operational characteristics of the pavement and related structures while carrying out technical evaluation of the pavement. The pavement deforms in the touchdown zone due to static and dynamic loads exerted by aircraft landings. This deformation in a wheel path at the touchdown point is the primary failure criterion when determining the functional capabilities of an airfield pavement. It therefore 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 should be reported using the ACN-PCN system indicating the information about the pavement type for ACN-PCN determination, subgrade strength category, and the maximum allowable tyre pressure category. Similarly, the pavement evaluation practices followed by various states of the 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 the modern aviation industry. Hence, new approaches are required to deal with routine airfield pavement evaluation tasks.

This study has observed that the load imposed on a runway pavement during landing primarily depends upon the ROD and weight of the aircraft. Furthermore, runway pavement performance is influenced by various factors such as frequency of loading, load factor, and the modulus of the subgrade reaction. Therefore, the technical evaluation of a runway pavement can be carried out using the deflection profiles and predictions projected by the analytical deflection model discussed in this study instead of the empirical practices currently followed by the major states of the ICAO. The model can be used for both rigid and flexible pavements. However, this model may not produce accurate results for complex runway pavement systems.

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 on the pavement and determine pavement response in terms of deflection to the aircraft loading. It would have been impractical to carry out pavement evaluation for each type of aircraft, however. 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 the deflection method.

References

Ashford, N.; Wright, P. H. 1992. *Airport Engineering.* 3rd ed. New York: John Wiley & Sons Inc. http://dx.doi.org/10.1002/9780470172896

Mechanics of Flight. 2006. Barnard, R. H.; Philpott, D. R. (Eds.). 11th ed. London: Pearson Education Limited.

Civil Aviation Safety Authority. 2007. *Advisory Circular AC 139-09(0): Aerodrome safety inspections at registered and certain other aerodromes*. Canberra: Civil Aviation Safety Authority of Australia.

Dai, Y.; Zhong, Z.; Tong, P. 2003. Transient response of airport runway, *Key Engineering Materials* (243–244): 135–40. http://dx.doi.org/10.4028/www.scientific.net/KEM.243-244.135

De Luca, M.; Dell'Acqua, G. 2013. Runway surface friction characteristics assessment for Lamezia Terme airfield pavement management system, *Journal of Air Transport Management* 34(2014): 1–5. http://dx.doi.org/10.1016/j.jairtraman.2013.06.015

Federal Aviation Administration. 2007. *Instrument Flying Handbook.* Washington D. C.: Federal Aviation Administration.

Fotosearch. 2010. *Stock photo: Airplane Landing on Runway* [online], [cited 10 November 2012]. Available from Internet: http://www.fotosearch.com/DGT066/trn008/, accessed November 2010

Guillaume, A. 2012. Characterising hard landings, in *Proceedings of 2012 European Operators Flight Data Monitoring Conference*, Cologne, Germany.

Horonjeff, R.; McKelvey, F. X. 1994. *Planning and Design of Airports*. 4th ed. New York: McGraw Hill Inc.

Hull, D. H. 2007. *Fundamentals of Airplane Flight Mechanics.* New York: Springer.

Hurt, H. H. J. 1965. *Aerodynamics for Naval Aviators*. 1st ed. United States Navy, California: Naval Air System Command.

International Civil Aviation Organisation. 2004. *Annex 14 to the Convention on International Civil Aviation: Aerodrome Design and Operations*. 4th ed. Montreal: International Civil Aviation Organisation.

International Civil Aviation Organisation. 1983. *Aerodrome Design Manual: Part 3. Pavements*. 2nd ed. Montreal: International Civil Aviation Organisation.

Kulyk, M.; Kucher, O.; Miltsov, V. 2011. Mathematical models of the calculation of aircraft structural reliability, *Aviation* 15(1): 11–20. http://dx.doi.org/10.3846/16487788.2011.566311

Kopecki, G. 2006. Analysis of control quality of aircraft lateral motion during approach with the use of different control laws, *Aviation* 10(3): 21–29.

Mayne, P. W.; Jones, S. J. J. 1983. Impact stress during dynamic compaction, *Journal of Geotechnical Engineering* 109(10): 1342–1346. http://dx.doi.org/10.1061/(ASCE)0733-9410(1983)109:10(1342)

Rozelle, R.; Lacagnina, M.; Rosenkrans, W., *et al.* 2004. Stabilized approach and flare are keys to avoiding hard landings, *Flight Safety Digest* 23(8): 1–25.

Sawant, V. 2009. Dynamic analysis of rigid pavement with vehicle-pavement interaction, *International Journal of Pavement Engineering* 10(1): 63–72. http://dx.doi.org/10.1080/10298430802342716

Selvadurai, A. P. S. 1979. *Elastic Analysis of Soil-foundation Interaction*. 1st ed. 17. Amsterdam: Elsevier Scientific Publishing Company.

Swatton, P. J. 2008. *Aircraft Performance Theory and Practice for Pilots*. 2nd ed. West Sussex: John Wiley & Sons Ltd.

Winkler, E. 1867. *Die Lehre von der Elastizitat und Festigkeit*. Prague: Dominicus.

Wood, J. E. 2008. *A Study of Airport Pavement-Aircraft Interaction Using Wavelet Analysis*. San Antonio: University of Texas.

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. http://dx.doi.org/10.1061/(ASCE)GM.1943-5622.0000118

Zhang, X. M.; Dong, Q 2012. Displacement field study on the full width of rigid airport pavement to aircraft loadings, *Applied Mechanics and Materials* 178–181 (2012): 1611–1614. http://dx.doi.org/10.4028/www.scientific.net/AMM.178-181.1611