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Improving safety of runway overrun through the correct numerical evaluation of rutting in Cleared and Graded Areas

A. Benedetto *, F. D'Amico, F. Tosti

Department of Engineering, University Roma Tre, Via Vito Volterra 62, 00146 Rome, Italy

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ABSTRACT

Aircraft overrun is potentially very dangerous to human life. Statistics show that overrun is mainly due to human errors causing loss of control in wheel alignment, high approach speed, and long touchdown. To prevent such disastrous consequences, advanced material arresting systems are currently being used in the main international airports for construction of Runway Safety Areas (RSAs). Many predictive models have been developed for controlling overrun events: the early reliable numerical models, on the basis of theoretical streamlined assumptions, were gradually replaced. More rigorous models based on Multibody System (MBS) and Finite Element Method (FEM) theories are nowadays much more preferred. These are characterized by high levels of reliability, even though the large number of data required does not always allow an exhaustive description of the domain of analysis. The paper presents an alternative method for predicting rut depths induced by aircraft overrunning. Such method is based on a numerical streamlined model, integrated with measurements from Light Falling Weight Deflectometer (LFWD), to define, section by section, the mechanical properties of soils in Cleared and Graded Areas (CGAs). The method has been validated through in situ tests, showing its high effectiveness and efficiency.

1. Introduction

In the past decade air transportation traffic has recorded a significant growth, due to new carriers of commercial airlines, competition processes, and technological enhancement. Moreover, a deep increase of low-cost carriers has been observed all over the world. In the case of U.S. airports, such aspect has focused in a first step on the largest airports, moving to second tier airports, once the best opportunities for growth at the largest hubs began to dwindle (Belobaba et al., 2012). In general, the increasing of the number of operations has caused a large number of further problems particularly related to environmental issues, mostly in secondary airports, and safety aspects. In that respect, aircraft overrun is one of the most potentially damaging events. An overrun by definition occurs any time an aircraft passes beyond the end of a runway during an aborted take-off or while landing.

Many accidents related to overrun events have been recorded in international plane crash databases, sometimes with devastating results (PlaneCrashInfo.com Database, 2012). On the 17th of July 2007, an Airbus A-320-233 skidded off the end of the runway at Congonhas Airport (Brasil), across a major roadway and struck a gas station and building, bursting into flames: 187 people, crew including, lost their lives. More recently, on the 22th of May 2010, a Boeing 737–800 crashed while attempting to land in heavy rain at Mangalore-Bajpe (India). The aircraft overran the runway, slid down a ravine into a wooded valley, and burst into flames: 158 people died.

Concerning aircraft overruns and undershoots in Runway Safety Areas (RSAs), 459 international accidents and incidents occurred between 1978 and 2006 have been analyzed (Hall et al., 2008). It is shown that landing overrun events (60%) occur more frequently than landing undershoots (20%) or take-off overruns (20%). Within these critical events, anomalies during accidents and incidents are mostly related to human error, weather, runway conditions, approach procedures, or any number of other conditions or combinations thereof. Information concerning the dynamics of overrun events indicate that in 90% of cases, the aircraft exits the runway at 36 m/s (118 ft/s) (70 knots) or less.

Moreover, from the analysis of the final resting locations of aircraft after an overrun, it can be noted that most of the overruns (88%) stop within a lateral distance of 30.5 m (100 ft) from the runway centerline, and 304.8 m (1000 ft) longitudinally from the end of the runway (David, 1990; White and Agrawal, 1993; Wong et al., 2009). Such statistics have been confirmed by further analyses carried out by the Ascend World Aircraft Accident Summary between 1998 and 2007 (e.g., Taylor et al., 2008a; Taylor and Godley, 2008b): a set of 120 runway excursions on landing involving commercial jet aircrafts has been investigated to map the distance that aircraft overran or veered off the runway. Most of the aircrafts

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* Corresponding author. Tel.: +39 06 57333543; fax: +39 06 57333441.
E-mail address: andrea.benedetto@uniroma3.it (A. Benedetto).

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stopped within 304.8 m (1000 ft) the runway end, and within the extended runway area.

Safety overrun areas are designed by regulation to provide an additional 304.8 m (1000 ft) of length to stop overrunning aircrafts. Anyhow, such additional areas are not available in many airports. In these cases, soft ground arresting systems can be employed to decelerate or stop an overrunning aircraft (White and Agrawal, 1993).

In that respect, many efforts have been devoted. In 1975, the Royal Aircraft Establishment experimented the use of urea formaldehyde foam in full-scale tests (Bade, 1969; Barnes, 1974) according to preliminary theoretical studies (Gwynne, 1975). Due to the large costs of such materials, the experiments were untimely left. In 1984, following a landing overrun of a Scandinavian Airlines DC-10 at John Fitzgerald Kennedy International Airport, testing on arresting materials were resumed. Ten years later, the first soft ground arrester was realized (White and Agrawal, 1993).

Nowadays, to minimize the hazards of overruns, the Federal Aviation Administration (FAA) provides the use of soft ground arresters at different bearing capacities whereas the existing pavement length is not suitable to meet runway safety area standards. In most cases, the pavement structure is therefore composed of an arresting layer, protected with a covering material, and placed above a subgrade. During overruns, it is also required to be resistant to deterioration due to aircraft fuels and oils leakage in case of accident (Bennett, 2005).

Arrestor beds can be manufactured with different materials. Cellular concrete is a type of lightweight concrete formed by entraining air into the cement slurry, so that the crushable pre-cast cellular concrete blocks have compressive strengths as the normal weight concrete, even though with lower densities (Marisetty et al., 2008). The effectiveness of gravel beds was assessed by the Royal Aircraft Establishment using the physical similarity and dimensional analysis techniques. Results allowed to accurately predict the distance required to stop aircrafts at a given entry speed (Barnes, 1974). Urea formaldehyde foam is a non-transparent thermosetting resin or plastic, with a chemical structure classified as polymethylene (Jiang et al., 2010; Randall, 1970). Due to its high tensile strength, heat distortion temperature, elongation at break, and volume resistance, good properties in aircrafts arresting have been demonstrated (Gwynne, 1975). Phenolic foam has significant properties such as an excellent fire resistance, no dripping during combustion, and both a low smoke density and toxicity. Moreover, it has high resistance to chemical and solvents (Desai et al., 2007). A phenolic foam bed 207.26 m (680 ft) long, by 14.63 m (48 ft) wide, and 0.4572 m (18 in.) deep was used to check the effectiveness of safely stopping a Boeing 727 aircraft while entering the bed at different runway exit speeds. Results were positive: at 25.7 m/s (84.4 ft/s) (50 knots) the aircraft was stopped in 128.02 m (420 ft), and at 30.9 m/s (101 ft/s) (60 knots) in 164.59 m (540 ft). No structural damages were registered and the foam was successfully repaired (White and Agrawal, 1993). The Engineered Material Arresting System (EMAS) is characterized by a readily and reliably deformation under the weight of an overrunning aircraft (O'Donnell, 2005). The resulting displacement drag forces are generated as the landing gear burrows through this material, and applied through the traveled distance, as they are friction forces. The resulting work dissipates the kinetic energy of the aircraft until it eventually comes to decelerate the aircraft to a safe stop (Deloach et al., 2009; Lang, 2004). In the past decade, further studies have been developed by the FAA in cooperation with the Engineered Systems, Co. (ESCO) of Logan Township, NJ, to optimize an EMAS design for the specific needs of airfields (Heymsfield and Halsey, 2007).

Arrestor beds are characterized by high costs of construction and maintenance requiring to be improved in order for this type of safety system to be more widely used. Ho and Romero (2009) evaluated the costs of EMAS as used in three U.S. airports: construction costs ranged from 3037 dollar/m^3 (86 dollar/ft^3) to 3885 dollar/m^3 (110 dollar/ft^3). FAA further studies have confirmed such estimates, with 3249 dollar/m^3 (92 dollar/ft^3) both for site preparation and bed installation (Lang, 2004). Due to such high costs of construction, the use of arresting materials in Cleared and Graded Areas (CGAs) has proved to be not cost-effective. Therefore, natural soil is nowadays considered as the most efficient material for CGA in most of the airports.

Kirkland et al. (2004) proposed a probabilistic methodology to assess the risk of runway overrun. Moreover, many predictive models for tire-soil interaction and evaluation of the sinkage of aircrafts wheels in soil landing fields have been developed to check the effectiveness of the bearing capacities of CGA subgrades, as well as the bearing characteristics required to decelerate the aircraft in a safe stop distance.

Richmond et al. (1968) proposed a mathematical model validated through experimental results on the basis of four primary factors causing soil rutting and drag. Such factors consist of a tire spring rate, a soil load deflection relation, a drag inertia force, and a lift inertia force. Information about active and reactive forces, soil properties, in terms of CBR index and HRB-AASHTO classification category, and tire characteristics are required. The model has been further refined (Coutermarsh, 2007; Crenshaw, 1972; Shoop et al., 2001). The growth of computational resources allowed the development of more rigorous mathematical models. The Multibody System (MBS) simulation tools allow to investigate the dynamic behavior of the vehicle, tire, and soil system (Gibbesch, 2002). The simulation of tire-soil interaction by means of multibody tools is based on analytical modeling, and specific measurable parameters are required to describe the physical soil behavior. The tire-soil contact area is represented by analytical approaches. This allows to to reach a relatively good approximation of the real contact conditions. Anyhow, the description of physical soil behavior is affected by many problems due to its non-deterministic properties.

Other approaches treated the problem of tire–soil interaction with the method of finite elements (FEM) (Liu and Wong, 1996). These models allow a very fine discretization and an accurate simulation of the deformations of either tire or soil. In any case, this modeling approach generally needs a large amount of computation time, thereby making the MBS mainly used in the modeling of tire–soil interaction. The Institute of Robotics and Mechatronics also demonstrated a high effectiveness in the combined use of such two approaches. In particular, MBS was used for modeling the landing gear and fuselage, and the FE method additionally calculated the tire and soil deformations (Liu and Wong, 1996).

Within these numerical models, soils mechanical properties can be modeled using different survey instruments and methods. The California Bearing Ratio (*CBR*) is a strength parameter arising from punctual and destructive tests. This requires a large number of samples and several days for testing (American Society for Testing and Materials, 2009). In that respect, non-destructive technologies are nowadays increasingly being used. The light falling weight deflectometer (LFWD) is an instrument widespreadly used both for construction quality control and road construction. It was developed in Germany as an alternative in situ device to the plate load test (Kavussi et al., 2010; Lee et al., 2004). Basically, the LFWD consists of a loading device that produces a defined load pulse, a loading plate, and a set of geophone sensors to measure the deflections. The LFWD elastic modulus can be therefore calculated from the applied load pulse and the recorded deflection. Several studies have been carried out in the last few years to assess the LFWD measurements and evaluate as these can be affected by some relevant parameters such as moisture content, temperature,