Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Evaluation Methods for longitudinal evenness of runway pavements

An overview of recent Dutch experiences

Problem area

Safe aircraft operations may be jeopardized when runway pavements are not smooth or even. Un-evenness may not only cause excessive accelerations and loads on aircraft tyres, landing gear and structure, but also discomfort for passengers and pilots, leading to degraded controllability during take-off and landing, tyre burst and structural damage of the aircraft. Therefore smooth runways are of vital importance.
The problem is how to determine whether a runway is smooth or rough. In order to do this several procedures and methods are available for the classification of the smoothness or roughness.

In the Netherlands, runway roughness testing or monitoring is the responsibility of the individual airport authority. This is not mandatory, but can be initiated for instance after pilot complaints when using (part of) a particular runway.

Description of work

In the paper different procedures for measuring and evaluating runway roughness are described. Special attention is given to the development of a rather straightforward procedure based on the 'Boeing Method' and a proposal under discussion in the Aerodrome Panel of ICAO. This procedure enables the assessment, identification and classification of surface roughness problems in a simple and cost effective manner.

Results and conclusions

An overview of the applied methods has been presented and results are discussed for the 'classical' test-case, San Francisco runway SFO 28R, before and after repair.

Applicability

The applicability of the obtained results is quite general, since the qualification criteria that are used in the Boeing/ICAO method have been obtained from experience with aircraft responses from a wide range of airfields.

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Summary

According to ICAO's Annex 14 (Ref. 8), the roughness of newly constructed airport pavements is acceptable when it is constructed within the limit of 3 mm deviation from a 3 m straight-edge. Another approach, which is more related to the user's perspective (e.g. ride comfort), is an assessment via the simulation of aircraft response behaviour due to the roughness (un-evenness) of the measured longitudinal runway profile. The generally accepted standard for admissible accelerations is the ±0,4g vibration criterion. Response simulation however requires specialized software, which makes this approach less feasible for small(er) airports for instance.
In the Netherlands a CROW[1]-working group developed a Means-of-Compliance for evaluating runway roughness, based on predicting the aircraft's response (in accelerations) at the aircraft's centre of gravity as well as at the pilot's seat.
The working group also looked into various other methods, a.o. IRI, PSD and the Boeing Method in order to get a quick yet sound impression of the surface roughness.
It is noted, that a revised version of the Boeing Method is currently under discussion in the Aerodrome Panel of ICAO (Ref. 9), and may become part of ICAO Annex 14 (Ref. 8).

Based on the Boeing Method, the working group developed a relatively simple and cost-effective routine for assessing, identifying and classifying possible surface roughness problems within the boundaries of the Boeing Method.

The paper gives an overview of the methods considered, discusses the benefits and drawbacks of these methods and in particular the experience with the proposed revised version of the Boeing method. The paper also presents a worked-out example of San Francisco runway SFO 28R before and after repair, as described in advisory circular AC-25.491-1 (Ref. 5).

[1] CROW is the Technology Platform for Transport, Infrastructure and Public Space in The Netherlands

Contents

Abbreviations

AC	Advisory Circular
APRas	Airport Pavement Roughness assessment software
BH	Bump Height
BL	Bump Length
CAA	Civil Aviation Authority
CGA	Centre of Gravity Acceleration
CROW	Technology Platform for Transport, Infrastructure and Public Space
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
IRI	International Roughness Index
NLR	Nationaal Lucht en Ruimtevaartlaboratorium (National Aerospace Laboratory)
PROFAA	Aircraft Pavement Rideability assessment software (by FAA)
PSA	Pilot Station Acceleration
PSD	Power Spectral Density
SE	Straight Edge

1 Introduction

Surface roughness of runways, together with the pavement's bearing capacity and runway's friction level constitutes an essential part of air safety. Airfield pavement surfaces must be smooth and free of any irregularities that could be detrimental to aircraft operations. Surface smoothness, or sometimes termed roughness (the opposite of smoothness), is critical for safe operation of aircraft during takeoff and landing runs. An uneven runway can lead to discomfort for pilot and passengers, higher user costs, a longer brake-path when landing and/or an aborted take-off and to an increasing chance of a tire-burst. A rough runway surface can lead to additional maintenance of the pavement.

The responsibility for runway roughness monitoring in the Netherlands lies with each individual airport authority. At present, roughness testing is not mandatory but is a discrete activity that can be undertaken in response to known roughness problems or complaints received from pilots or airlines. ICAO's International Standards and Recommended Practices, Aerodromes Annex 14 contains only very general information respecting airfield pavement surface roughness (Ref. 8). There is ample direction provided on acceptance criteria for new pavement surfaces in Annex 14, Volume 1, Attachment A, paragraphs 5.1 through 5.3. The longitudinal slope change criteria is specified in Annex 14, Volume I, Sections 3.1.14 and 3.1.15. Airport Authorities however, generally lack the means by which to easily assess the ride quality of their runways. They typically do not know how to address the point beyond which further aircraft operations should not be sustained, unless corrective measures can be taken immediately to repair the runway surface.

At the instigation of CROWs Committee on Airfield Pavements, a research project on pavement roughness and smoothness classification started in 2005. The first stage of the project resulted in CROW-report D06-01 'Survey on Airport Pavement Roughness Assessment', over viewing potentially available measurement devices and methods for accurate profile measurement and classification (Ref. 2). The second stage consisted of drawing up guidelines or Means of Compliance for the Evaluation of Airport Pavement Roughness. CROW Report D07-03 contains a method, accepted by Dutch airport representatives, to be used in compliance to ICAO procedures. It may ultimately lead to a standard method for classifying the runway pavement roughness for usage in the Netherlands (Ref. 3). The document contains recommendations for indicative, exploratory or detailed surface roughness evaluation.
In 2008 the study was completed with a further analysis of the PSD-method and a review of the Boeing Bump method (Ref. 4). The Power Spectral Density (PSD) focuses on measurement of roughness in the form of power spectra, which indicates the relative amplitude of roughness

corresponding to wavelength. It gives an indication of average roughness of the runway, but does not distinguish between many bumps of small amplitude and a few bumps of large magnitude at a given wavelength. The Boeing Method (Ref. 10) has been most widely circulated and used worldwide for a number of years, and is proposed to amend the existing guidance material contained in Attachment A to Annex 14. The Boeing Bump criterion addresses single event roughness, however without long wave length harmonic effects or the effect of repetitive surface undulations.

This paper overviews the CROW state-of-the-practice and discusses the potential of a modified Boeing/ICAO Bump method as a complementary method for the indicative method presented in CROW-report D07-03 (Ref. 3).

2 Means of compliance for the evaluation of airport pavement roughness

The Means of Compliance (Ref. 3) presents procedures for measurement, analysis and evaluation of longitudinal pavement roughness. It is a method accepted by the Dutch industry to be used complementary to ICAO procedures. Depending on the importance, an airport may decide to undertake an indicative, exploratory or detailed surface roughness evaluation. All evaluations are based on profile measurement and analysis.

2.1 Profile Measurement

Airport runways are "busy places" and obtaining the required access time to complete the survey measurements may be difficult. The profile survey method must be quick, economical, detailed and accurate. A pavement’s profile can be measured by a variety of devices. Each device produces only one of two types of profile data; relative profile or true profile.
Relative profile can be defined as the variation in elevation from one data point to the next. Relative profile is often generated by an inertial profiler. The procedure is known as a Class II survey. Examples of devices to be used for Class II surveys are portable laser profilers and multi-laser instrumented vehicles. An inertial profiler measures the pavement’s elevation profile by establishing an initial reference and by measuring the pavement’s elevations in relative to the external reference. Specifically, the inertial reference is established by using a height-sensing device to measure the distance between the vehicle and the pavement’s surface. An accelerometer, mounted above the height sensor, records the vertical accelerations experienced by the vehicle while measuring the pavement’s profile. The accelerations are then mathematically converted into vertical displacement of the vehicle. This data is then merged

with the elevation data measured with the height sensor. The vertical displacement values are then subtracted out of the elevation data in order to calculate the relative elevation of the pavement. Laser profilometers developed for measurement of pavement roughness or serviceability index calculation in highway pavements may be adapted for evaluation of airport pavements. However, most laser profilometers catch wavelengths up to 45 meters only, whereas an aircraft responds to wavelengths up to about 120 meters. In adapting those profilometers consideration should be given to removing or setting filters to permit the longest wavelength roughness to be measured.

Table 1 Class I and II Profiler systems

Class I: True profile	**Class II: Relative profile**
Characteristics: - Absolute measurement of elevation (relative to an external level) - Relatively slow method of measurement (4 hours per section) - Suitable for assessing surface roughness, and suitable for re-profiling - Accuracy of measurements ± 1 mm - Intervals: 0.25 m	Charcteristics: - Relative measurement of elevation (**not** with respect to an external level) - Fast method of measurement (15 minutes per section) - Suitable for assessing surface roughness, **not** suitable for re-profiling - Wavelength at least 120 m - Intervals: ± 5 mm
Examples: 1 Face Dipstick 2 Automated Rod and Level (ARL) 3 Walking Profiler G2 4 Digital Profilite 300 5 CS8800 walkable profiling system	Examples: 1 High-speed roughness profilometer (ARAN) 2 Non-contact lightweight profiler 3 Portable laser profiler systems 4 Multi-laser profiler vehicle 5 LaserProf (Laser/SPD)
Note: a. conventional rod and level survey is useful in combination with Class II profile measurements *b. conventional closed loop rod and level surveys minimize the level error of Class I measurements*	

A "true elevation" profile is highly desirable. These are known as Class I surveys for their high accuracy and usually require some type of "static" profiling device. The method requires that the longitudinal surface profile of the runway be measured - this takes longer and costs more but it makes a more detailed analysis possible. A runway profile can be analyzed using a computer for a variety of short bump length roughness indicators and also for long bump length roughness up to and exceeding the wheelbase length of the aircraft nose/main landing gear. Individual bumps and depressions which may be rough to an aircraft can also be located. These methods

require measurement of the longitudinal surface profile with a sufficient degree of vertical accuracy (0.1 mm) and a sufficiently close sampling intervals (0.3 m).
Profiles measured by conventional rod and level survey can still be useful and can be analyzed quite successfully depending on the type of roughness problem in the surface. However, rod and level survey shots (sampling intervals) should not exceed a 5.0 meter interval spacing. Since rod and level profiles can not be analyzed for short bump length roughness indices, combining them with the data of inertial profilers is a useful means. Rod and level data can also be used to minimize the level error by means of a closed loop survey, improving the accuracy of the topographical data derived with walking profilers.

Class II surveys are mainly used for pavement quality assurance and quality control. Profilographs and Straight Edge meters check the pavement against profile based specifications. Tender documents specify the allowable "built-in" deviation during construction.

2.2 Procedure for measuring roughness

Depending on the use of a runway with certain types of aircraft at least two and maximal four lines of survey are measured. The lanes for runways with general aviation and narrow bodied aircraft is located at 3 meters to the centreline. In case of use by wide bodied aircraft the 5 m lane is measured as well. If the runway also serves new generation aircraft, such as A380-800 and B777, lanes located at 6,5 meters from the centre line marking are measured for roughness too.

2.3 Procedures for evaluating roughness

Depending on the motive and the purpose for the surface roughness evaluation, three types of assessments are recommended:

Indicative Survey: When an airport authority wants a quick and simple impression of the surface roughness in the short wavelength area, a Straight Edge-analysis can be made.
For this purpose a straight edge with a length of 3.0 m can be used, but when a (fictitious) length of 30 m with an allowable deviation of 25 mm is used, problem areas are quickly identified. The length of the straight edge is about the same as the wheelbase of a narrow body aircraft such as the B737. This aircraft is known for its sensitivity for points of unevenness. This kind of evaluation can be executed with both relative and absolute longitudinal profiles (no preference);
An example of the determination of the deviation with a “Virtual Straight Edge” is depicted in the next figure.

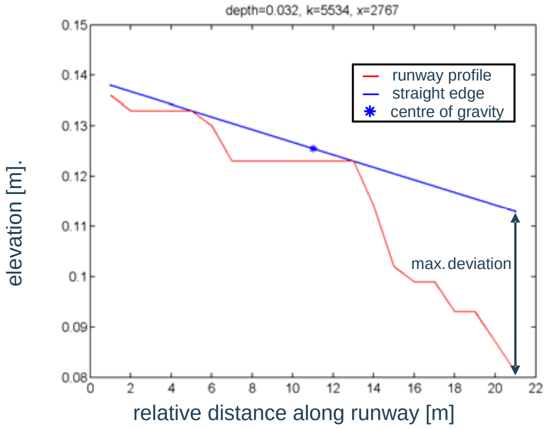


Figure 1 Definition of deviation by using a “Virtual Straight Edge”

Exploratory Survey: Aircraft simulation could be considered the next best method (the best being an instrumented aircraft to record its response to the pavement’s profile). By predicting the aircraft’s response to the measured pavement profile, areas of roughness can be precisely located and the ride quality can be accurately quantified.

When an airport authority wants to have an indication of possible surface roughness problems in a relatively simple and cost-effective manner, a PROFAA-analysis of *taxiing aircraft* can give a good impression of the condition of the runway. According to FAA’s own website:

"ProFAA" is the Federal Aviation Administration's computer program for computing pavement elevation profile roughness indexes. Data analysis performed by the program includes the simulation of the following devices or procedure and the calculation of, Straight Edge, Boeing Bump, International Roughness Index (IRI), California Profilograph (PI), and RMS Bandpass Indexes.

The straight edge length can be varied from 1.5 to 76.2 meters. PROFAA (Ref. 6) only simulates taxi operations, whereas APRas simulates takeoff and landing operation too. PROFAA simulates B727 an B747 taxiing on the pavement (profile) at a speed of 20 knots for taxiways and 100 knots is used for runways. Other aircraft in the database are DC-9 and DC-10. It is important to recognise that by simulating aircraft with long and short wheelbase (e.g. B747 vs. B727), different areas of roughness can be detected.

An exploratory assessment can be made with both absolute and relative longitudinal profiles.

Elaborate Survey: When complaints are made or problems arise, a more detailed method of analysis using aircraft simulation technology is to be used. Simulations can be made of takeoff, landing or constant speed taxi operations using a variety of aircraft types. This technology predicts the aircraft’s response (in accelerations) at the aircraft’s centre of gravity as well as the pilot’s station. Although standard criteria are not yet available for evaluating the results of aircraft roughness simulations, keeping the peak vertical acceleration experienced by the aircraft landing gear below 0.35 to 0.40 g's (acceleration due to gravity) is generally considered an achievable and acceptable objective. The advantage of aircraft simulation is that it accounts for the response of the whole vehicle; how the main gear response drives the nose gear response. Because it is a response-based technique, the location of the event creating a ride quality problem is clearly identified (as seen in Figure 2).

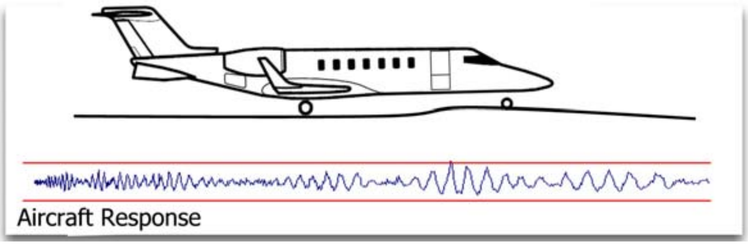


Figure 2 Aircraft response to measured pavement profile.

The calculation of take-off and landing requires the use of APRas software (Ref. 7), which is commercially available as a consultancy service. APRas (Airport Pavement Roughness assessment software) has been widely accepted internationally. The tool is capable of simulating the response of modern aircraft. The aircraft database contains approximations of Cessna Citation II, B707, B727-200, B737-200, B737-800, B747-100, B747-400, DC-8, DC-9, DC-10, L-1011 and MD-11.

The index variables (deviation from straight edge or aircraft vertical acceleration, for example), when plotted over the full length of a runway or taxiway, provide a convenient means of identifying possible rough areas and evaluating strategies for remediation. After execution of the Straight Edge (SE) analysis or the aircraft simulation the results can be compared against the surface roughness standards in force and the ± 0.4g criterion. Corrective design adjustments can then be made to smooth out the rough profile sections and the resulting effect on alleviating aircraft roughness response can be checked by repeating the simulations using the new smoothed profile. The method can also be used to engineer runway crossings.

3 Boeing Bump method

The Boeing Company submitted a working paper to the Aerodromes Panel of the ICAO presenting presents the proposed specifications and guidance regarding runway surfaces tolerances (Ref. 9). The panel was invited to note the contents of the paper, to review and agree with the proposed amendment to Annex 14 - Volume 1, “Attachment A. Supplementary

Guidance Material (Pages ATT A-3 and ATT A-5)". For the Netherlands, this working paper was analyzed and discussed by the CROW working committee.

3.1 Runway Roughness Measurement, Quantification and Application

The Boeing Company developed an easy-to-use method on which roughness in a longitudinal profile surface roughness can be easily detected and repaired. The method is fully documented in Boeing document (D6-81746),"Runway Roughness Measurement, Quantification and Application – The Boeing Method" (Ref. 10). The document presents a full description of the development of the method, which is based on aircraft responsiveness to known surface irregularities, and features a description of how the method can be used by any airport to self-assess their characteristic surface roughness (or ride quality). The content of the document has been supported by other major manufacturers and has been used in one form or another since the late 1970's.

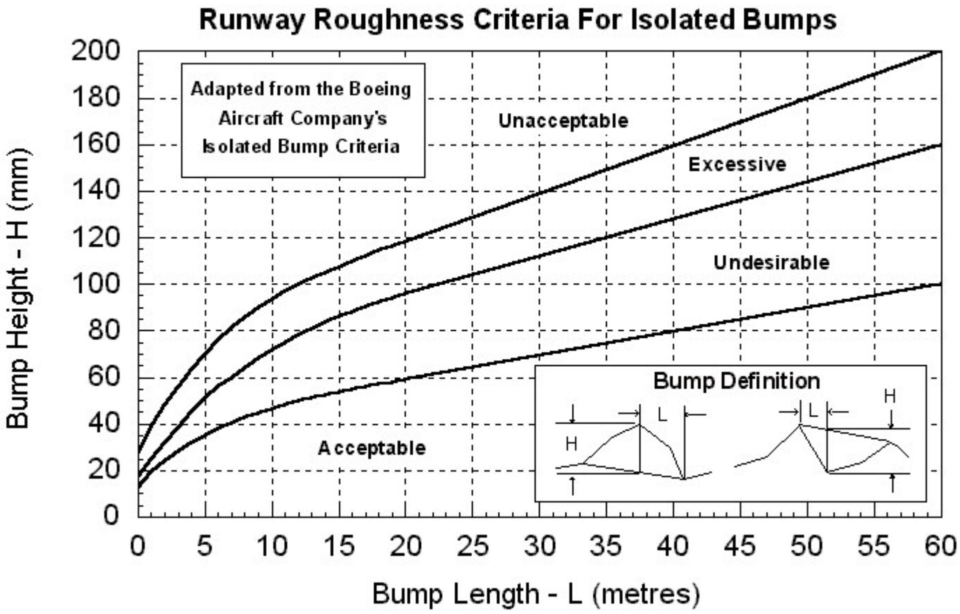


Figure 3 The Boeing Roughness Criteria for single event condition (Ref. 10)

The method that has been most widely circulated and used worldwide for a number of years has been what is known as "the Boeing Bump" criteria (Figure 3). The criteria is based on data relating to large commercial jet aircraft. It is easy to use in that it allows for surface measurements to be made via a standard rod-and-level technique, or a laser rod, or travelling lasers, or even string lines. Boeing has developed several criteria for the seriousness and extent (amplitude versus wavelength) of a local unevenness by dividing them in terms of 'acceptable', 'excessive' and 'unacceptable'. In principle the effect of consecutive irregularities is not taken into account. This method is simple and convenient for all airports to use in determining the riding quality of their airport pavements.

3.2 Proposed Amendment to Annex 14 (Boeing/ICAO method)

The proposed amendment presents boundaries for surface irregularities, defining ´Surface Irregularity´ as isolated surface elevation deviations that do not lie along a uniform slope through any given section of a runway. In this amendment, a section of a runway is understood to be from 30 to 60 meters in length (or longer) and for this section a continuing general uphill, downhill or flat slope is prevalent. The amendment recognizes that exact information on maximum acceptable deviations cannot be given, as it varies with the type and speed of an aircraft, however, surface irregularities can be estimated to a reasonable extent. The following chart describes acceptable, temporarily acceptable and excessive limits (Figure 4). When rated acceptable the Bump height/length combinations falling in this region should not adversely affect the majority of aircraft operations. If the temporarily acceptable limits are exceeded, corrective action should be undertaken in a timely fashion to improve the ride quality. If the excessive limits are exceeded, the portions of the runway that exhibit such roughness should have corrective measures taken immediately if continued aircraft operations are to be maintained.

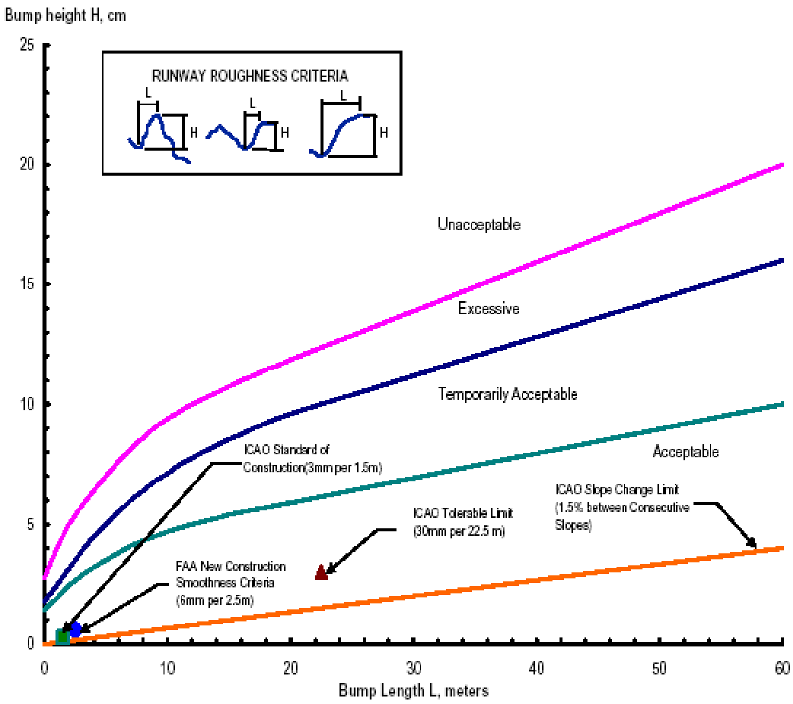


Figure 4 Revised Boeing Curve proposed to ICAO's Aerodromes Panel for adoption in Annex 14 (Ref. 9)

3.3 Modified Boeing-ICAO approach

Based on the Boeing-ICAO, the CROW-working group developed a complementary method to survey a runway longitudinal profile for irregularities. As the definition of Bump height vs Bump length allows several interpretations, Mr Edward Gervais was contacted to come to a common definition (Ref. 12). The Bump height / Bump length definition according to Figure 5 has been used in the study of CROW.
The method recommended is complementary to the Boeing Method & ICAO Bump Method and sweeps the pavement's true profile for straight edge irregularities at distances of max. 120 meters. The procedure enables to localize the problem areas for further inspection and qualify the area in terms of acceptable- temporarily acceptable, excessive and un-acceptable. Furthermore, the effect of repair can be studied prior to carrying out actual repair measures.

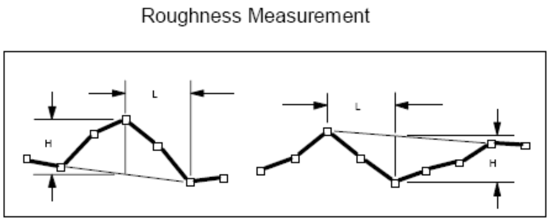


Figure 5 Bump height / Bump length definition

The basic steps of the method comprise of:

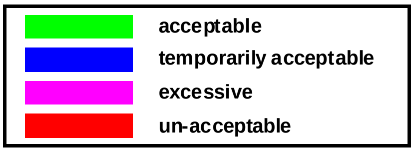
- Measurement of elevation profiles of geodesic quality ('true profile');
- Sweep the longitudinal profile for ICAO/Boeing-Bump covering bump-lengths of 30 to 60 meters (i.e. wave-lengths of 60 – 120 meter) and record the maximum deviation for the particular location under consideration
- Plot the result as bump-length versus bump height in the graph recommended in the ICAO state-letter, and qualify the unevenness event in term of ICAO singular events:
  * Acceptable
  * Temporary acceptable
  * Excessive
  * Unacceptable

Prior to repair, problem areas can be localized for further analysis

The method can be used by any airport to self-assess their characteristic surface roughness (or ride quality). The method does not require the use of specific aircraft simulation software.

The results are then presented in a graphical way, showing the (coloured) classification code:

1	green	acceptable
2	blue	temporarily acceptable
3	magenta	excessive
4	red	un-acceptable



The assessment comprises a search for the maximum deviation for a certain section of runway pavement (wave length) for each (discretized) point of the runway profile, and determines the maximum bump-height for bump-lengths from 3 up to 60 meter (in forward direction of the reference point and a step size equal to the runway-profile interval distance). Each of these maximum values is are stored and categorized according to the Boeing/ICAO-classification model (see Figure 5). The highest code (worst situation) is retained to categorize the situation for that given point. The results (deviation from straight edge) are plotted over the full length of a runway.

3.4 Application to San Francisco SFO 28R

The suggested procedure was applied to San Francisco - 28R runway profile (Ref. 5). This runway had some worse irregularities and was measured before and after repair. The longitudinal profile is presented in Figure 6. Please note that the length of runway SFO-28R is approximately 3,500 m. Hence, the profile in the referenced Advisory-Circular represents only a (small) part of the total runway.

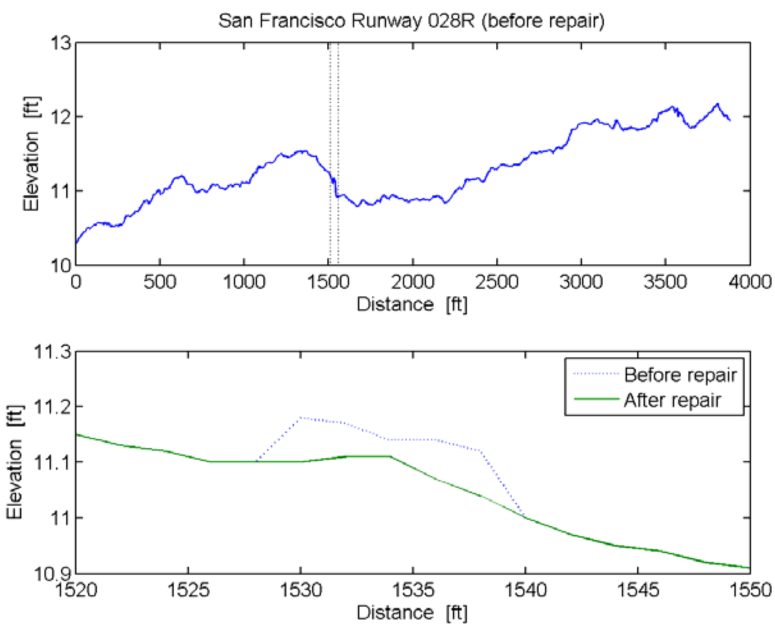
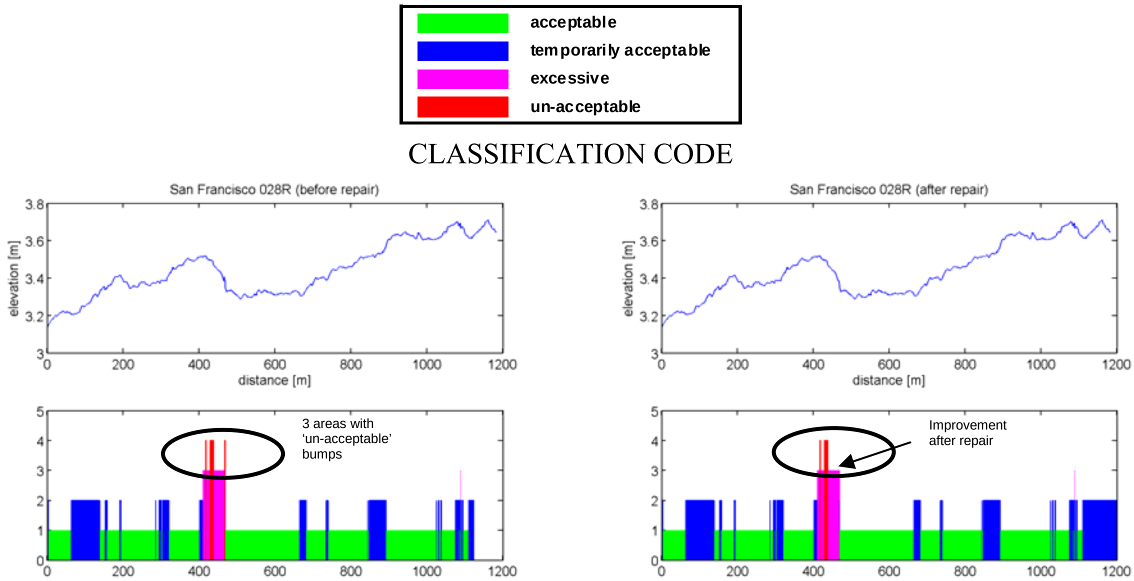


Figure 6 San Francisco 28R, runway profile

For the analyses, the runway profile has been converted to metric units and re-sampled at 0.5m intervals (instead of 2 ft). An analysis of the runway before repair shows three areas (coloured red) with bumps in the ‘un-acceptable’ zone (see Figure 7). The ‘problem’ areas are located at the following positions: x = 416.5 – 419.5 m (833 – 839 ft), x = 428 – 438m (856 – 876 ft) and x = 467 – 469m (934 – 938 ft).

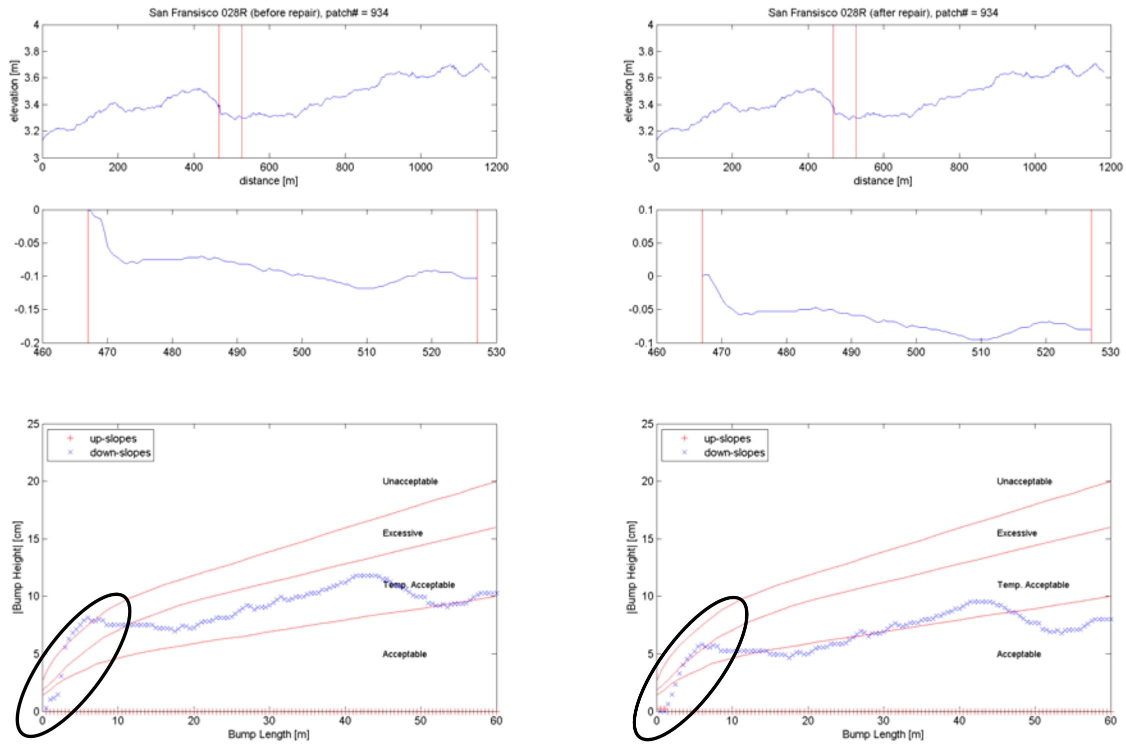


a) original profile BEFORE repair *b) original profile AFTER repair*

Figure 7 Overall result of classification applied to San Francisco 28R

Figure 7 shows that only one of the three ‘unacceptable’ rated locations were repaired. The area rated ‘unacceptable’ is rated ‘excessive’ after the repair, which is an improvement with respect to the previous situation (see Figure 8).

A similar (simple) repair operation to the other two area’s would most likely not be possible, as the problem in these areas is related to bumps with long wave lengths. In order to improve these situations, the repair would have had to involve a much greater length of runway-pavement then applied to the repair under consideration, which has a length of only 13 ft (≈ 4.0 m).



a) runway before repair *b) runway after repair*

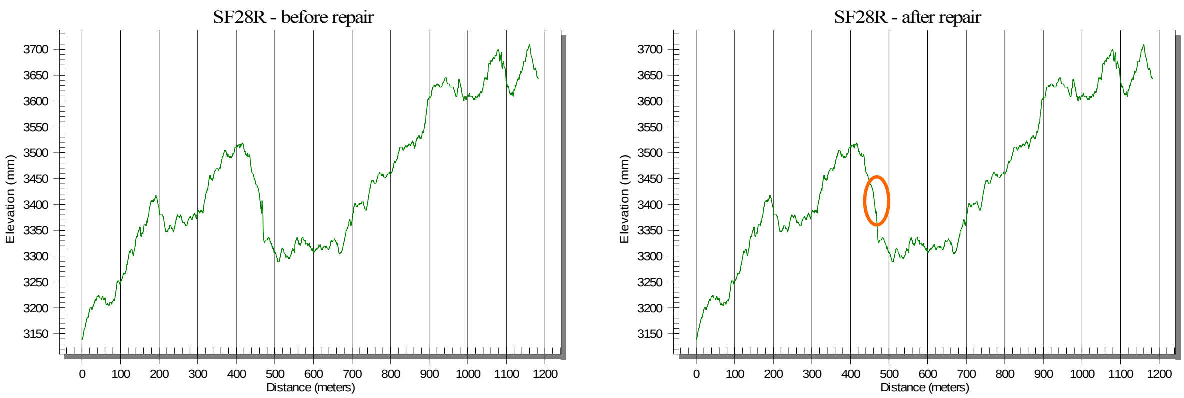
Figure 8 Intermediate result for current Boeing/ICAO analysis for the 3rd critical area of the SFO 28R runway profile, at the location where the repair has been applied

3.5 Validation of Boeing/ICAO method with response model

For validation, the results from the Boeing/ICAO method for the San Francisco runway 28R are compared the with aircraft response using APR Assessment Software APRas. Figure 9 shows the profile before and after execution of the small, local repair. APRas calculates the response of aircraft taking off, landing and taxiing on a measured longitudinal profile in the shape of occurring vertical accelerations (G-forces).

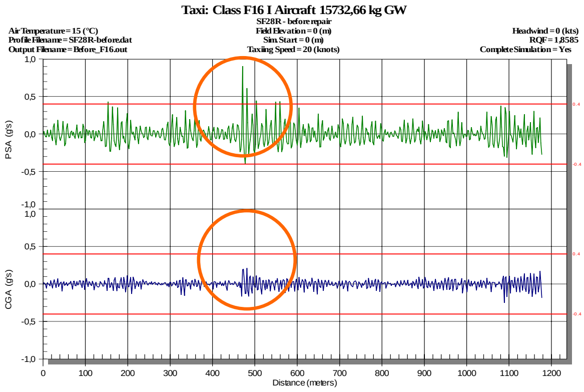
The PSA and CGA for a F16 aircraft during taxi at 20 knots on San Francisco runway 28R are plotted in Figure 10. It can be depicted that due to the local repair, the vertical acceleration at the pilot station (cock-pit) is reduced, although not completely disappeared. This finding fully complies with the findings of the Boeing/ICAO procedure applied to the San Francisco 28R case presented in the previous section.

When looking at the responses (in particular accelerations at the Pilot Station PSA exceeding 0.4 g) from the B737 APRas-model to the SFO-28R runway, seem to be qualitatively well in line with what was found from the ICAO procedure, i.e. “bump-sensitive” area’s between x≈400-450 m and at x ≈ 1100 m. Responses from an F-16 aircraft taxiing at 20 knots do give a noticeable peak in PSA at x≈450 m, while also the Centre of Gravity acceleration CGA shows larger responses at x≈400-450 m and at x ≈ 1100 m, which is in line with the classifications found from the Boeing/ICAO procedure.

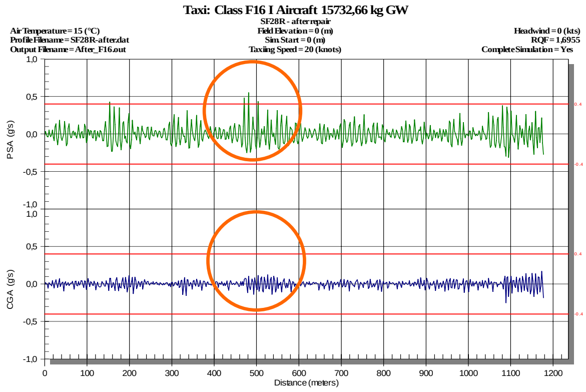


a) original profile SFO 28R before repair *b) profile SFO 28R after repair @ 466–469 m*

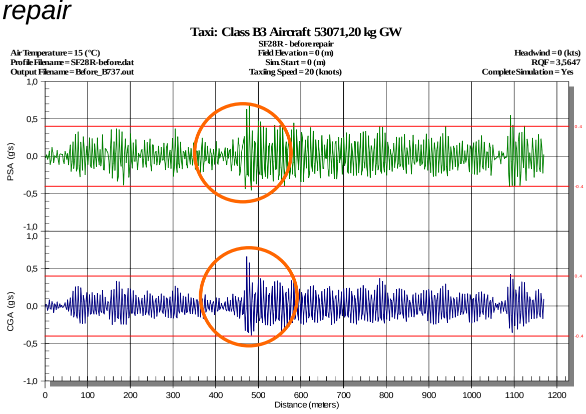
Figure 9 Original profile and profile with local repair from 466 to 469 m.



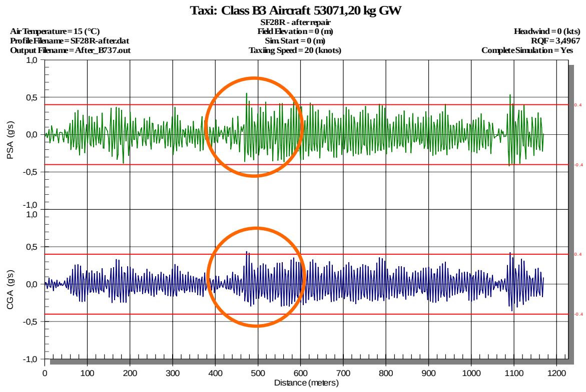
a) response of F16 on profile SFO 28R before repair



b) response of F16 after repair @ 466–469 m



c) response of B737 on profile SFO 28R before repair



d) response of B737 after repair @ 466–469 m

Figure 10 Effect of local repair: peak vertical acceleration at pilot station (green line)and center of gravity of aircraft (blue line) is reduced (although not completely vanished).

4 Findings

The Boeing Method & ICAO Bump Method sweeps the pavement's true profile for straight edge irregularities at distances of max. 120 meters. The basic steps of the method comprise:

1. Measurement of elevation profiles of geodesic quality ('true profile');
2. Sweep the longitudinal profile for ICAO/Boeing-Bump covering wavelengths of 30 to 60 meters (i.e. length of 60 – 120 meter) and record the maximum deviation for the particular location under consideration
3. Plot the result as bump-length versus bump height in the graph recommended in the ICAO state-letter, and qualify the unevenness event in term of ICAO singular events:
   a. Acceptable
   b. Temporary acceptable

c. Excessive
d. Unacceptable
4. Prior to repair, problem areas can be localized for further analysis

The procedure enables to localize the problem areas for further inspection and qualify the area in terms of acceptable, temporarily acceptable, excessive and un-acceptable. Furthermore, the effect of repair can be studied prior to carrying out actual repair measures.

- Application of the Boeing/ICAO-method is rather straight-forward and should in principle be applied to 'true' runway profiles. However, in some cases simple (linear) de-trending could be allowed in order to remove 'obvious' effects (e.g. an overall up- or down-slope of the runway).
  On the other hand runways with a pronounced up- or down-hill character should be treated cautiously for other reasons (Aircraft take-off and landing performance).
- One of the advantages of the Boeing/ICAO method is, is that it directly points out where critical bumps are located.
- When used for assessing the effect on local runway repair or reconstruction, the Boeing/ICAO procedure gives good results when compared with the results of aircraft simulation. Results become better (for the aircraft types under consideration i.e. B737 and F 16) when only bumps with a maximum length of BL=30 m are considered.
- The aircraft simulation does have greater potential in analyzing the effects on aircraft and pavement and there is not always a complete match with the Boeing-ICAO-method. However, the latter is recommended as a first step for use in case of pilot complaints to identify singular roughness events.

5 Conclusions

- The Boeing/ICAO method is rather straightforward and should be applied to 'true' runway profiles (no detrending, except in some cases).
- The Boeing/ICAO method gives a direct indication of (critical) bump locations.
- Results comply with response simulation calculations, for (smaller) aircraft even better when also smaller Bump Lengths are considered.
- Results from the Boeing-ICAO method are complementary to the methods described in CROW-report D07-03.

6 Disclaimer

This paper represents the best professional opinion of the authors and the CROW working group on runway roughness. Members of the committee are Melvin Bakker (Schiphol Airport), Harry van Dijk (CAA), Peter van Gelder (NLR, co-reporter), Ad van Leest (CROW, chairman), Bart van Pelt (Rotterdam Airport), Marc Stet (VIA Aperta, co-reporter), and JanPiet Verbeek (Ministry of Defense). Every effort has been made to ensure that the results are accurate and reliable.

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[2] Note: D07-03 (Dutch version), D07-03a (English version)