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TITLE **RUNWAY ROUGHNESS MEASUREMENT, QUANTIFICATION, AND APPLICATION - THE BOEING METHOD**

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Summary

Often an indication that a runway is beginning to fail is when it starts to become intolerably rough during airline operations. Many attempts have been made to quantify the effects of roughness on aircraft fatigue and on passenger comfort. While research has been able to determine how rough a runway might be in terms of power spectral density, it has not been able to propose a satisfactory methodology in which to quickly and simply alleviate the roughness that is of most concern to pilots - an isolated single bump or a series of bumps.

The Boeing method has been able to help both airports and airlines make rational decisions over the last 20 years as to the best course of action when roughness is reported. This approach applies to all jet transport aircraft and can be utilized easily without requiring extensive technical analysis. It is a criteria that describes roughness based on a single event condition, and in doing so, allows for ease of runway repair through the use of profile surveys. These surveys are very valuable in indicating whether a particular depression or high spot can be repaired, either by patching or milling of the surface.
The Boeing roughness criteria has been developed for what is considered the most critical condition for runway roughness - a heavily loaded aircraft approaching takeoff speed. Aircraft moving at taxi speeds or operating a relatively light weight would not likely experience as severe of a g-loading as at the takeoff condition. These other conditions are best served by consideration of the “excessive” region of the Boeing criteria between the “acceptable” and “unacceptable” areas. Upper bounds of the “excessive” region designate the beginnings of critical landing gear fatigue, while the lower bounds are the limits of comfort for both passengers and pilots. Thus, excessive pavement maintenance is not required from too low a criteria, yet the airplane is protected by its upper limits.

An application of this criteria is shown for temporary ramping which could occur during surface overlay construction, allowing for repair of entire runways with minimal interruption of traffic.

KEY WORDS

acceptable roughness
bump
cockpit acceleration
depression
excessive roughness
fatigue life
frost heave
“g” loading
landing gear fatigue
power spectral density
ramping
roughness criteria
runway profile
runway roughness
runway testing
survey interval
unacceptable roughness

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References

1. Morris, G. J. and Hall, A. W., “Recent Studies of Runway Roughness.”, NASA SP-83, Conference on Aircraft Operating Problems, May 1965.
2. Hall, A. W., Hunter, P. A., and Morris, G. J., “Status of Research on Runway Roughness,” Langley Research Center, NASA SP-270, May 1971.
3. Lee, Harry R. and Scheffel, James L., “Runway Roughness Effects of New Aircraft Types,” Journal of the Aero-Space Transport Division, ASCE, AT 1, November 1968.
4. McCullough, B. F. and Steitle, D. C., “Criteria Development to Evaluate Runway Roughness,” Journal of Transportation Engineering Division, ASCE, Vol. 101 TE-2, May 1975.
5. Spangler, E. B. and Gerardi, T., “Airport Runway Roughness, Runway Rehabilitation and Aircraft Fatigue,” DOT/FAA/RD-90/23, July 1990.
6. “Runway Roughness Criteria”, Boeing Coordination Sheet 707-LD-29, July 30, 1968.
7. “Criteria for Runway Roughness”, Boeing Coordination Sheet 727-PD-131, June 10, 1968.
8. Richmond, L. D., Brueske, N. W., DeBord, K. J., et al, “Aircraft Dynamic Loads From Substandard Landing Sites,” Technical Report AFFDL-TR-67-145. The Boeing Company, September 1968.
9. “Runway Roughness Levels for Fatigue Life Study”, Boeing Coordination Sheet 737-LD-326, May 2, 1974.
10. “Fatigue Loads as a Function of Runway Roughness”, Boeing Coordination Sheet 737-LD-327, July 26, 1974.
11. Tung, C. C, Penzien, J., and Horonjeff, R., “The Effect of Runway Unevenness on the Dynamic Response of Supersonic Transports”, NASA Report CR-119, October 1964.
12. “Airline Operational Data from Unusual Events Recording System in 707, 727, and 737 Aircraft.”, FAA-RO-71-69, 1971.

13. “Model 737 Landing Gear Fatigue Life versus Runway Roughness”, Boeing Coordination Sheet S-707/727/737-LG-49, October 25, 1974.
14. “Effects of Operating the 737 on Rough Runways”, Boeing Coordination Sheet S-707/727/737-LG-53, February 25, 1975.
15. “Evaluation of the Effect of Rough Field Operation on Model 737 Airplane Fatigue Life”, Boeing SEWA NO. 497, May 1, 1975.
16. DeBord, K. J. and Gervais, E. L., “How Rough is Your Runway?”, Boeing Airliner, January-March 1989.
17. Runway Roughness Criteria, Boeing Structures Engineering Concurrence, May 12, 1994.
18. United States Air Force, MIL-A-008862A, March 31, 1971.
19. “International Standards and Recommended Practices, Aerodromes”, International Civil Aviation Organization, Annex 14, March 1983.
20. FAA Advisory Circular, AC 150/5370-13, “Off-peak Construction of Airport Pavements Using Hot-Mix Asphalt”, August 27, 1990.
21. Gervais, E. L., “Nighttime Paving, Repair and Rehabilitation of Major Airport Runways”, Boeing Airliner, April-June, 1991.

Section 1
Introduction

The Boeing Company Airport Technology Group has long been involved in the assessment of runway strength capabilities and the inspection of runway conditions of both paved and unpaved runways for customer airlines. These activities have often allowed the introduction of Boeing jet service into areas not previously thought possible. Evaluation for pavement strength is an issue that is most related to runway longevity, while another type of evaluation, runway roughness, is more related to aircraft safety and aircraft structural fatigue. Although evaluation for strength is all that is required in many situations, runway roughness is an important concern of the Company in its determination to build aircraft that will deliver acceptable airframe life to its customer airlines.

Roughness has long been considered a difficult and evasive issue among the many elements of consequence in airport pavement administration and in aircraft operations. Whether considered at best an inconvenience or at worst an issue affecting airfield and aircraft safety, roughness has not been uniformly considered, measured, or understood by the industry.

The kinds of roughness of typical concern are:

1) that which causes on-board vibration, preventing pilots from accurately reading instruments during takeoff.
2) long-wave undulations, which may be so severe that the nose and main gear oleos compress to the limit.
3) not so noticeable, but still critical enough to affect the fatigue life of the landing gear or related structure.

Few airlines have the necessary resources available to analyze the severity of the roughness, nor can they easily quantify the effect that it has on the airplane. The airline might communicate with the airport authority or the appropriate governmental agency about a roughness problem, but these agencies are not usually in a position to make a judgment as to the impact of the roughness on the airplane. Neither the airline nor the airport authority is usually equipped to repair nor improve the situation quickly, unless they can get precise detailed information that both locates and quantifies the roughness on a given runway.

The problem that has been encountered at this point, historically, is that no one knows quite what to do, once intolerable roughness has been subjectively detected. A determination of how rough a runway really is and where the roughness exists is not always readily available. Pilot comments are usually the first indications of rough runway conditions, but the understanding and isolation of the roughness itself can only be understood by a surface profile survey. Even a high-speed run over the runway in an automobile is less than an ideal indicator because of the differences in wheel base, mass, speed, and suspension between the car and the airplane. Visual observance will normally not reveal a runway roughness problem either, because the bumps are often too long in length or shallow in depth to appear to the eye. Statistical measurements have been used to determine whether or not a runway is rough, but cannot determine the location of distinct roughness points.

This report will detail early investigations into runway roughness, including brief summaries of proposed standards of roughness measurements. Efforts by Boeing to develop a criteria are outlined, including the 1968 Boeing - Air Force study that formed the basis for current Boeing recommended roughness standards. Although roughness effects on an airplane were considered in establishing the method, Boeing criteria to quantify runway roughness is related to a single-event describing a condition of the runway. This allows a criteria that relates to nearly all jet transport aircraft without regard to physical configuration. An additional advantage is that describing roughness as a single event allows for easy location and repair of the distressed location. Other research has attempted to relate roughness to aircraft resonance frequencies or runway profile statistical measurements with several inherent disadvantages, as will be discussed herein.

The Boeing method of roughness analysis has been able to help both airports and airlines make rational decisions over the last 20 years as to the best course of action when runway roughness is reported. Recommended profile adjustments from these surveys, when made according the Boeing criteria, have been very successful in alleviating the reported roughness. Case history examples of these applications to existing roughness measurement are presented in detail, including one each of:

- Long wave, undulating roughness.
- Shorter amplitude frost heave roughness.
- Temporary ramping during an overlay project.

Section 2

Development of Roughness Criteria

2.1 Early Investigations

There has been considerable relevant research into the area of runway roughness effects, and beginning with the advent of the jet transport in the late 1950's, this subject became substantially more critical. It was found that runways that had been satisfactory for propeller transport traffic were unacceptable for jet transport traffic.

Many of these early investigations have centered on measurement of roughness in the form of power spectra, which indicates the relative amplitude of roughness corresponding to wavelength. It is a convenient statistical measure of roughness over the entire runway or portion in question. Power Spectral Density (PSD) 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. It is useful in the analysis of aircraft loads and fatigue problems, but it does not furnish information on the location of roughness along the runway.

It had been established by 1967, through NASA's published studies by Morris and Hall (1), that the response of aircraft to runways required tentative limits on the vertical acceleration at the cockpit location. It was concluded that roughness was not only a function of the aircraft response frequency, but that proper runway design and construction was paramount to the reduction of roughness effects on the aircraft. In practice, a runway could be judged as rough by some pilots and satisfactory by others, even with the same power spectral levels. It became, therefore, necessary to relate roughness to cockpit acceleration and concentrate repair efforts on those sections of the runway producing undesirable acceleration responses. Based on the NASA investigations reported in reference (1) and later confirmed by Hall, Hunter, and Morris (2), an acceptable maximum incremental cockpit acceleration from a pilot's viewpoint was established at +/- 0.4 g. This was considered to be the dividing line between satisfactory and unsatisfactory runways, and any greater acceleration could cause loss of precise control of the aircraft and subsequent pilot difficulties.

Other studies have focused on the causes of runway roughness. Lee and Scheffel (3) studied the effects of critical bump spacing on the aircraft and the effects the aircraft could have in reshaping the roughness. It was observed at Anchorage International Airport that pilot roughness complaints began shortly after introduction of intercontinental class jet transports in the early 1960's. Although some of the roughness was caused by frost heave effects, other non-related runway undulations were reported. Detailed investigation of the bump patterns indicated an apparent migration of the undulations longitudinally along the runway, indicating that aircraft were affecting the runway structure. Thus it was concluded that a major non-variable cause of runway roughness was the aircraft moving over a semi-elastic pavement structure. Variable factors influencing roughness intensity were stated to be foundation soil structure, climate, size of aircraft, pavement composition and the number of aircraft using the runway. Of primary importance in prevention of roughness were proper design of the runway structure in relation to the area soil conditions, in addition to the other factors mentioned.

Lee and Scheffel also concluded that a runway that had been satisfactory for piston aircraft could cause undesirable cockpit accelerations in jet transports. Furthermore, not all aircraft are affected similarly by a given roughness pattern. That is, for a given velocity over a given runway roughness pattern, aircraft of different sizes will respond in different ways. This response is dependent on the natural frequency of the aircraft rigid body and elastic response, such that resonant patterns can be created between the aircraft and the runway unevenness pattern. The predominant rigid body response frequency is lower for heavier aircraft, making the range of bump spacing of importance. They also found that irregularities in the runway can magnify or dampen accelerations.

McCullough and Steitle (4) attempted to apply a highway system of roughness evaluation to airport runways. This was accomplished by providing rating form checklists to pilots of a variety of aircraft. Their proposed procedure was to relate pilot comments with runway profile measurements in order to develop a new summary statistic that was closely related to runway roughness. They studied the effect of wavelengths on airplane resonant response for selected aircraft and profile patterns. It was found that while pilot responses to runway acceptability in terms of roughness depended on the pilot's opinion, accurate roughness measurement could not be obtained without a corresponding field survey to measure the runway surface profile. For example, of two pilot reports with identical aircraft, one considered the runway acceptable while the other considered it unacceptable.

There have been many other worthwhile studies, both national and international, conducted since the early 1970's on this subject, including those by NASA and other governmental agencies, aircraft companies, and consultants. Among the most notable was that by Spangler and Gerardi (5), in which a method was developed to determine the dynamic response of a flexible aircraft to roughness during takeoff or taxi.

While not discounting these methods and techniques that have been developed, in practice many of the analytical suggestions can be exhaustive to employ and require copious amounts of data collection and analysis. They often do no more than confirm that a runway is indeed rough and do not specifically identify where the roughness exists, nor how to correct the roughness. Some of these methods of evaluation depend on subjective pilot reports, while others rely on accurate modeling of aircraft to determine response to series of events. Most methods employ statistical measures to report roughness magnitudes. These uncertainties, especially at the costs involved for data collection and analysis tend to render these methods restrictive to both the airport owner/operator and the airline. It would seem imprudent to repair an entire runway that has been determined to have unacceptable roughness for the sake of one or two exceptionally rough locations. Likewise, it would not be effective to ignore one or two intolerably rough locations on a runway when the measurement technique utilized has indicated satisfactory roughness for the overall runway. It is for these reasons that the Boeing method, as described in the next sections, has been useful to both airline operators and airport authorities in their efforts to keep runway roughness under control in a cost-effective manner.

2.2 Boeing Studies

Interest of the Boeing Company in runway roughness became significant due to the many requests from customer airlines and airport authorities to comment on this subject. Major emphasis on developing a roughness criteria was initiated from a request in 1968 by Ethiopian Airlines to comment on the condition of the runway at Addis Ababa, which was a representative example of a runway subjectively felt to be too rough by experienced pilots (6). According to the pilot reports, in a typical operation certain isolated bumps on the runway felt extremely hard during takeoff and landing, and the airplane resounded with sharp jolts that seemed much more severe than a hard landing. It was determined that the severity of the jolt varied with speed and the wavelength of the bump, leading Boeing investigators to believe that an objective criteria should be developed based on single bump height and spacing limits.

Although absolute roughness limits could probably not be precisely defined, a criteria was needed which had some defensible rationale related to airplane structural loads as imposed by roughness. Initially, however, a more subjective approach was suggested to provide a general indication of the amount of allowable roughness in order to alleviate passenger and crew discomfort. This would require that an acceptable level of fatigue loading and human acceleration be established. Because of the difficulty in establishing such limits, it was decided to base the roughness criteria on data previously obtained from taxi experience (7). This was done from original Boeing investigations, begun in the early to mid 1960's by Richmond, et.al. (8), in which a preliminary single-event bump criteria was established.

One purpose of the reference (8) effort was to examine the taxi response characteristics of large military aircraft on substandard surfaces. Preliminary roughness characteristics, in terms of bump height vs. wavelength, were established for three classes of runway sites, paved, semi-prepared, and unprepared. A plot of the bands of paved and semi-prepared data is seen in Figure 1. The unprepared site data is not shown in that it has no relevance to commercial airport runway roughness. Definitions of each runway type or classification are as follows:

- Paved: Surfaced with asphalt or concrete.
- Semi-prepared: An existing assault field that may have required a considerable construction effort. This type of field may be unsurfaced or surfaced with landing mat or a protective membrane. For commercial applications, most gravel runways would fit into this definition.
- Unprepared (data not shown): An unsurfaced natural ground area suitable for operation of military cargo-type aircraft with little or no preparation. There are probably no commercial aircraft operations today on runways with this type of preparation, and roughness of this magnitude was not considered in criteria development.

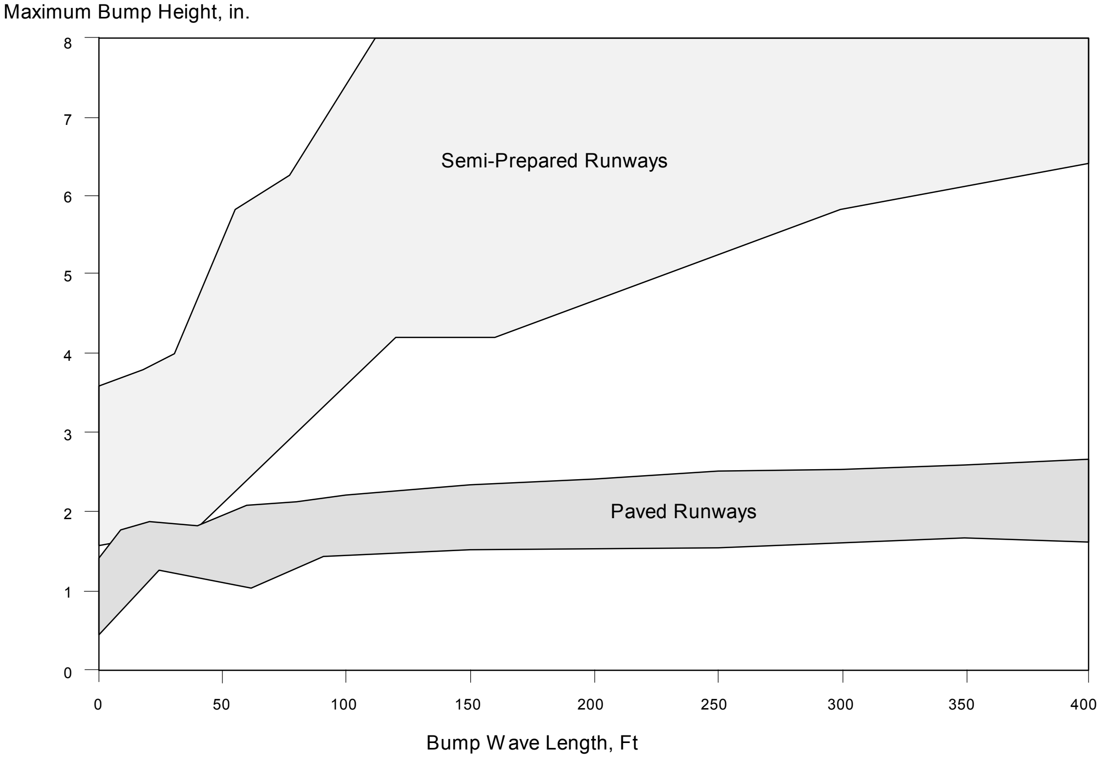

Figure 1. Comparison of Maximum Bump Height Bands for Paved and Semi-prepared Runways

The maximum bump height was defined in reference (8) as the maximum positive or negative deviation from a straightedge whose end points lie on the profile. The deviation is calculated as the perpendicular distance from the straightedge to the profile surface, as illustrated in Figure 2. The largest deviation is then recorded and plotted against the selected wavelength. Wavelengths above 400 feet (120 meters) had previously been demonstrated to not contribute to the dynamic airplane response and were not considered.

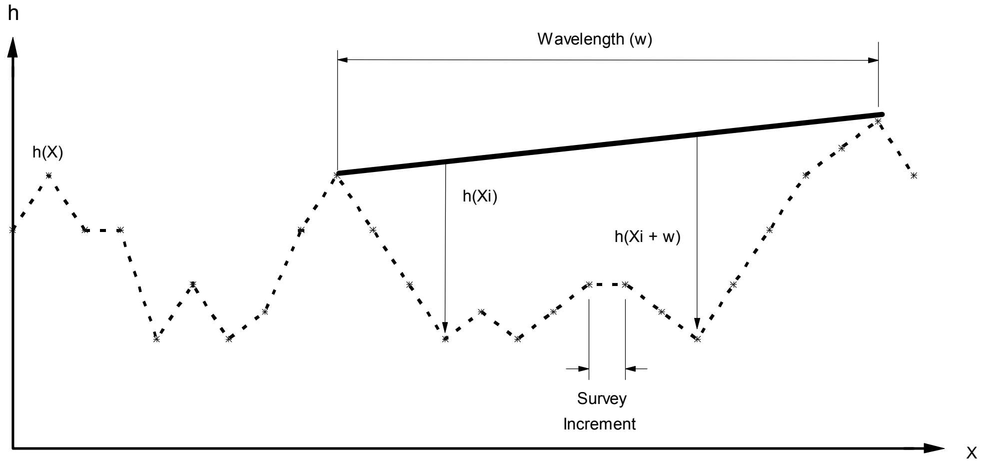

Figure 2. Schematic of Bump-Height Measurement

Initial development of Boeing roughness limits approximated the paved runway data of Figure 1. It was selected as the acceptable runway criteria model based on generally acceptable response characteristics and lack of complaints about operations on the runways used in generating the bump height-wavelength data. Furthermore, no structural damage had been attributed to operations on these runways.

A comparison of the criteria from Figure 1 with the Addis Ababa runway profile is shown in Figure 3. As previously indicated, the Addis Ababa runway roughness was reported to far exceed a desirable level. However, the runway profile did show that the extreme roughness was confined to two or three areas only and could be eliminated with a minimum of rebuilding. It was concluded that improvement of any existing runway to meet the criteria could be accomplished by modifying the original profile until the criteria is satisfied. This could be done by either removing or adding material from the runway surface in specific locations rather than the entire runway (6).

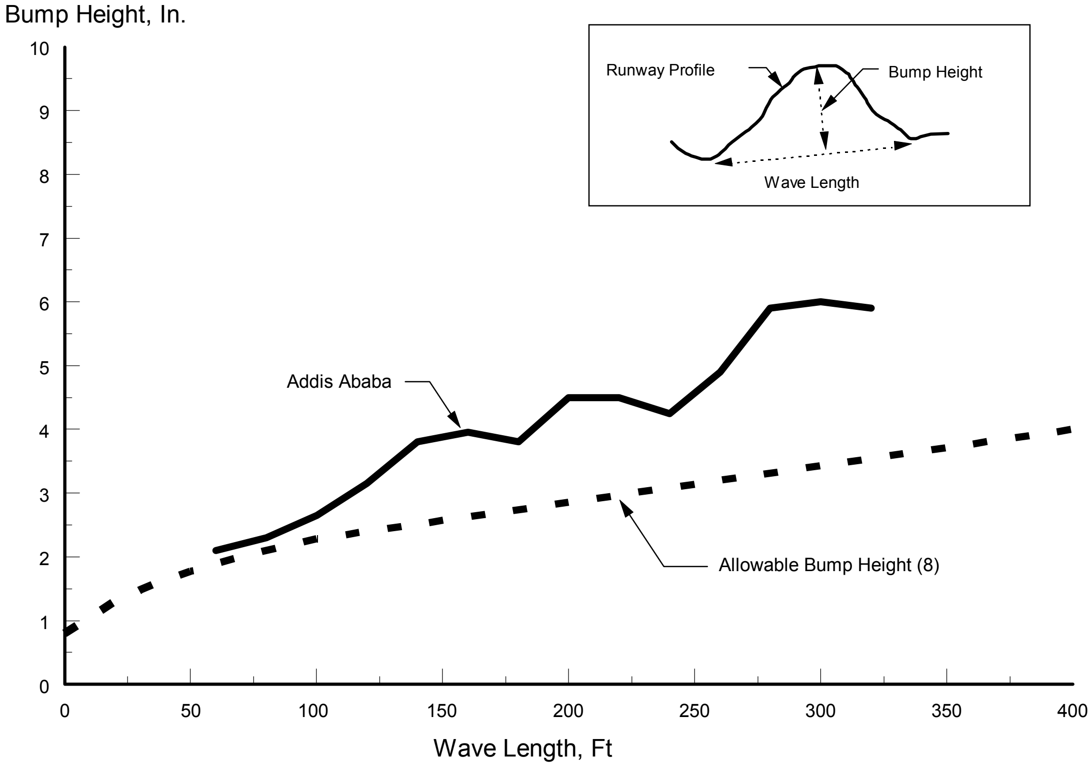

Figure 3. Runway Roughness Criteria as Applied to Addis Ababa Runway

Additional studies (9) that computed taxi fatigue life for a 737 were initiated in 1973. Three levels of roughness were selected for initial investigation in which to compute taxi fatigue life, as shown in Figure 4:

- Level 1: An "average" magnitude of roughness for either an existing or a newly constructed paved runway. This is also defined as 50 percent of the Level 2 magnitude.
- Level 2: A level equal to the allowable bump height of Figure 3 which also includes data from Boeing Field in Seattle, Washington. This base level has been shown to be acceptable by virtue of continuous safe operation from sample runways and without complaints of excessive crew discomfort or known

structural damage attributable to those operations. It is generally at the upper band of the paved runways.

- Level 3: A level of roughness that is at the approximate lower band of the semi-prepared runways. It is also defined as 150 percent of the Level 2 magnitude.

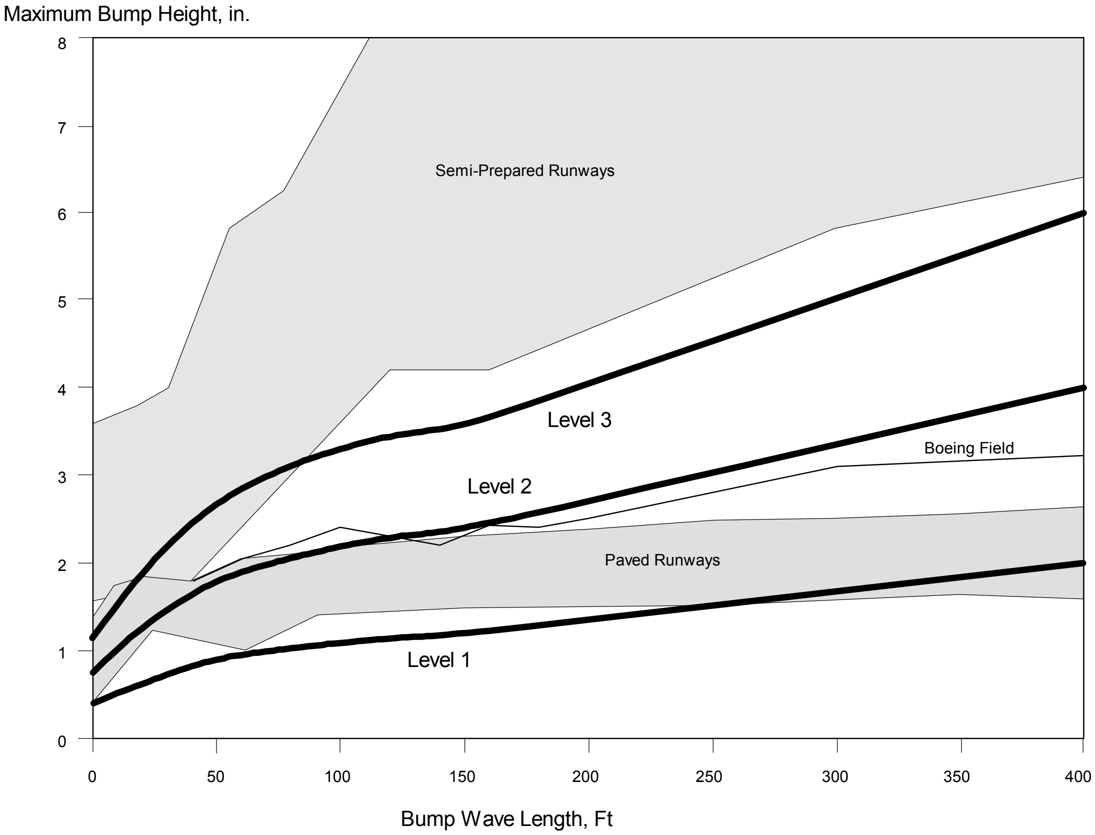

Figure 4. Runway Roughness Levels for Taxi Fatigue Life Study

Figure 5 shows the results of a study comparing computed 737 airplane load factor exceedances for taxi fatigue life at each of the three roughness levels with other in-service roughness observations (10). These roughness levels are shown in terms of cumulative frequency per 1,000 flight cycles and load factor at the airplane center of gravity. Load factors exceedance points combined with runways of known roughness show the relationship of roughness level and acceleration. The Level 2 roughness condition was simulated by rolling a computer model of the 737 over an older measured profile of San Francisco International Airport runway 28R (10 and 11). This runway was selected for analysis because its overall roughness level closely approximated the Level 2 roughness curve of Figure 4. The San Francisco profile was uniformly scaled up and down to achieve roughness Levels 1 and 3. All runs were made at the maximum taxi gross weight with an aft c.g. and represented constant acceleration taxi to takeoff speeds. Preliminary results from these simulations indicated that the main gear axles were the structure most sensitive to rough runways while other gear components and structure were most sensitive to ground-air-ground cycles. It was also determined that proper gear servicing was essential to alleviating roughness effects on the airplane.

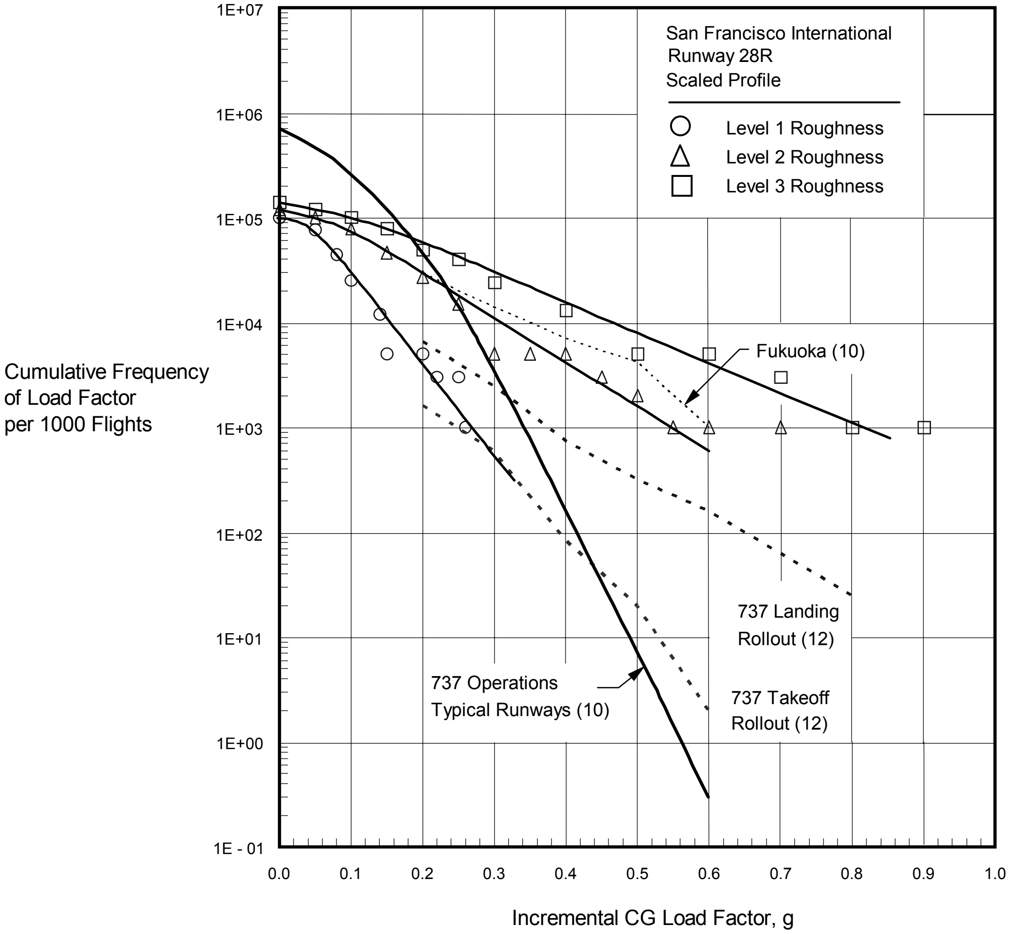

Figure 5. Airplane Load Factor Exceedances for Taxi Fatigue Life Study

The load factor service data was measured from 727 airplanes operating out of Fukuoka International Airport, Japan, in 1974. At the time this airport was known to be a relatively rough paved field. This experience data correlates with Level 2 roughness computations from the San Francisco runway. Plots of 737 fatigue design load level experience curves are included from an FAA study in which it was established that 727 and 737 taxi response characteristics are similar, and that criteria established for one airplane could be applied to the other (12).

For 1,000 load factor exceedances per 1,000 operations (i.e., one per operation), the maximum observed load factor is dependent on the level of roughness. At Level 1, a maximum incremental c.g. load factor of about 0.25 g can be expected. The maximum incremental c.g. load factor at Level 2 is about 0.55 g, and at Level 3 about 0.80 g. The curve labeled “737 Operations, Typical Runways” was compiled as representative fit of a number of runways, with the relationship of load factor exceedances at the airplane center of gravity and the cumulative frequency of the loading shown. This line is not meant to approximate or fit the other data shown on the chart. It shows the variability of load factors with the level of roughness in Figure 5, and it is repeated in Figure 6 as a comparison to NASA studies (2) in which center of gravity load factor exceedances of a variety of two and four engine jet transport airplanes were compiled. The NASA runway load exceedances represent an average of the runways that an airline might encounter in its route structure. Given that there is data scatter (not shown), the Boeing line and the NASA lines are seen to be very similar. Figure 6 demonstrates that for a wide variety of aircraft and runways, the expected airplane c.g. load factor can be consistently plotted as a function of operational frequency.

The limit at which roughness becomes unsatisfactory from the pilot’s viewpoint or passenger comfort has been judged to be an incremental acceleration of +/- 0.4 g (1). This is a ride quality limitation rather than an airplane gear fatigue problem. It can be seen from Figure 6 that on a typical series of runways and a variety of jet transport aircraft, one incremental load factor of about 0.35 g will occur once per flight. The overall effect is that as roughness increases the vertical acceleration at the airplane c.g. increases, and the number of occurrences required to encounter a critical load factor for structural fatigue life decreases. Thus it is essential that accelerations from runway roughness be limited to a practical level so as to minimize cumulative effects on the airplane.

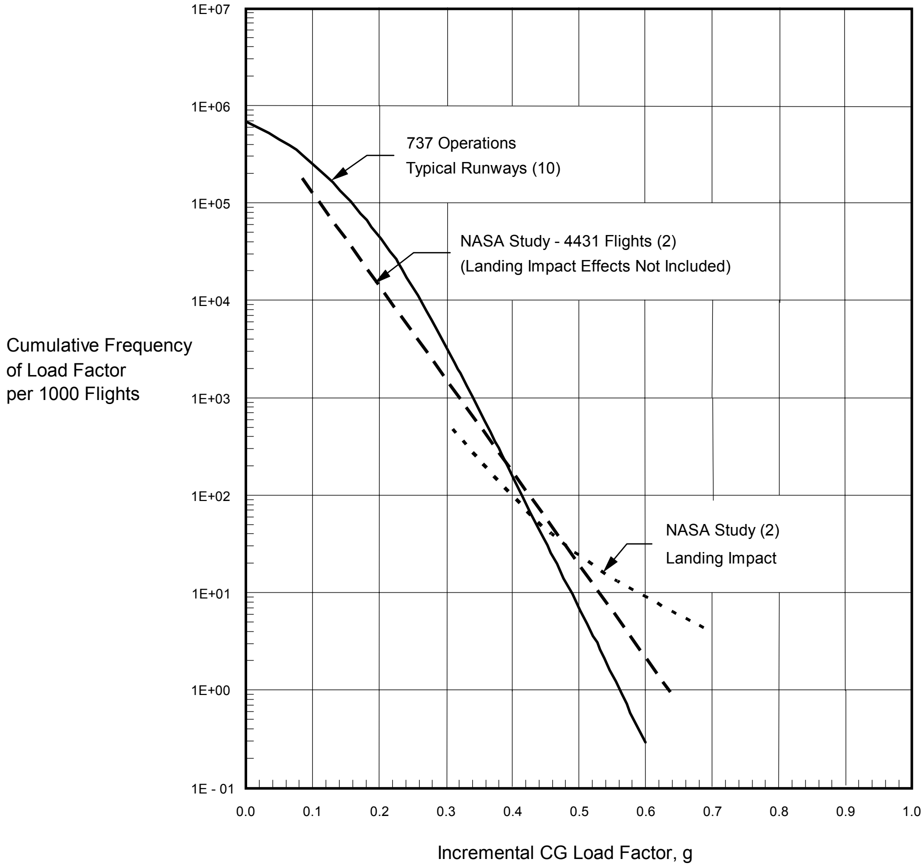

Figure 6. Roughness Occurrence Frequency of Typical Runways

As a result of these findings, Boeing follow-on studies (13 and 14) showed a computed relationship between landing gear life and runway roughness level. The main gear and nose gear axles were analyzed since they were previously found to be the gear items most sensitive to runway roughness. The main gear showed adequate fatigue life for a moderately high gross weight operation on runways at roughness Level 2, and the nose gear fatigue life was computed to be greater than the main gear. This investigation confirmed earlier work which had recommended that the maximum allowable runway roughness criteria, Level 2, continue to be utilized. However, a suggestion was made that Level 3 could be the upper maximum of roughness allowed for acceptable service, but it was not implemented until 1994, as discussed later in this report.

The plot relating main gear life with roughness level developed in reference (14) is shown in Figure 7. Extremes of this chart indicate that if 100 percent of operations were conducted on Level 2 runways, then the gear fatigue life goal would be met. If, however, 100 percent of the operations were on Level 3 runways, then the life of the main gear would be seriously reduced. This seems to indicate that the airplane operator should avoid any runways of roughness level greater than 2. However, there are two mitigating factors that should be considered which indicated that the Level 2 criteria was conservative:

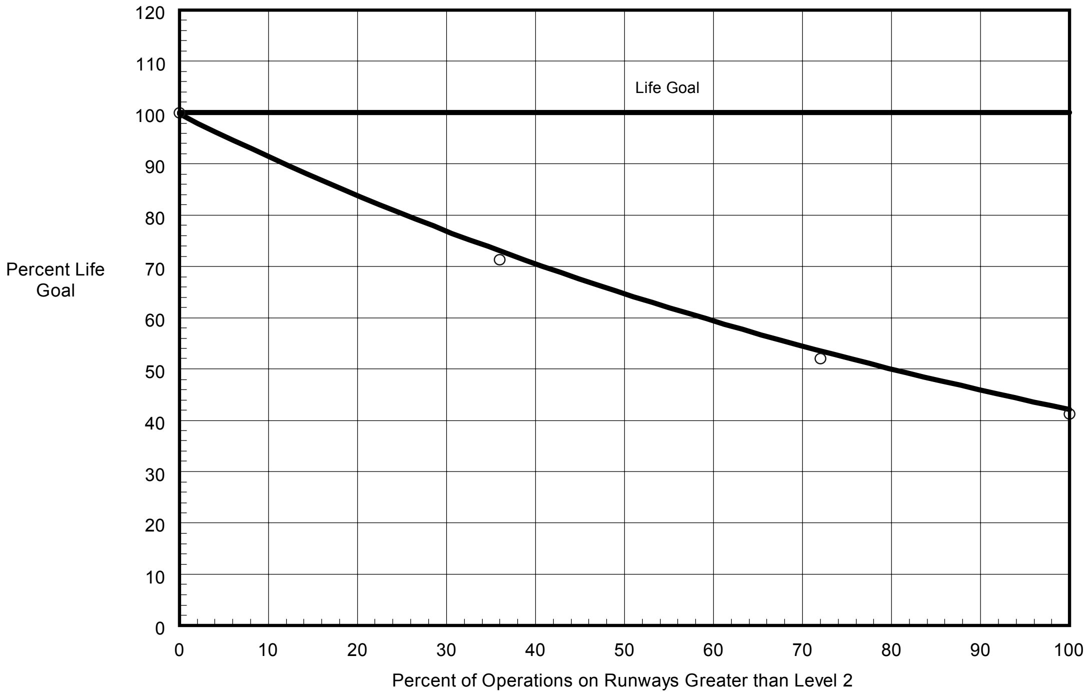

Figure 7. Main Landing Gear Axle Fatigue Life

1. The data of Figure 7 is for operations on runways that are entirely at the indicated level. In actuality, most runways that are considered rough may have only limited areas of exceedances. Therefore, fatigue life will rarely be affected materially unless there are a significant number of rough runway operations at the indicated level.

2. The fatigue tests used to determine life were conducted using computer simulations and on test stands, and they have later proven in operational experience to be conservative.

These studies were concluded with the development of the Boeing runway roughness criteria (15) (Figure 8), which has been used by Boeing for runway roughness evaluations from 1975 until mid 1994 and published in 1989 (16).

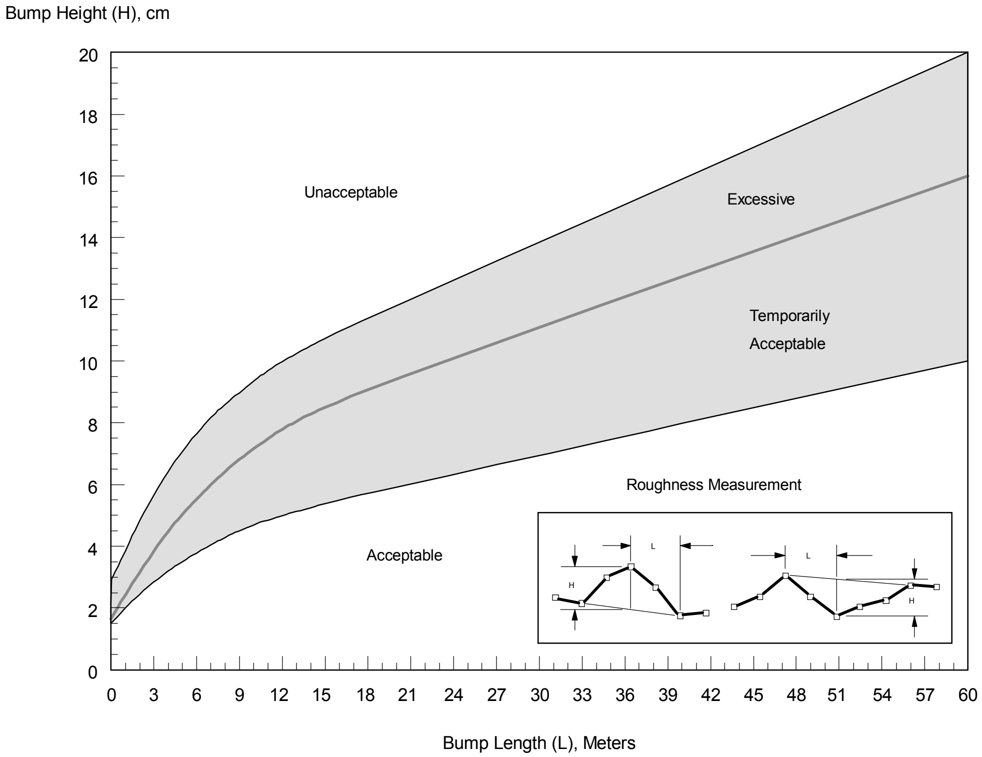

Figure 8. 1975 - 1994 Boeing Runway Roughness Criteria

Note that the definition of *bump length* has been introduced on this chart to replace that of *wavelength*. Bump length is defined as the shortest distance to a bump maximum or minimum from either point of measurement of the total wavelength. The maximum bump length is therefore 200 feet (60 meters), rather than the previously used 400-foot (120-meter) wavelength. However, the criteria is not altered by the definition change. Descriptive bump examples on the chart show how bump height and depth are measured.

The labeled regions on the Figure 8 criteria are defined as:

- Acceptable --Any roughness in this area is acceptable. Most new construction would be evaluated at the lower level of this region, while runways that have been in service for some time will tend towards the upper bounds.
- Temporarily Acceptable -- A band with an upper limit approximating the midpoint of the “excessive” region. It was used to determine the limits of temporary construction ramps that were placed during surface overlays.
- Excessive -- Bumps in this area are cause for the runway to require immediate repair. Roughness at this level is extreme, and represents the upper limit of acceptable surface gradients for short-term aircraft usage.
- Unacceptable -- Any roughness found in this region must result in the closure of the runway to high-speed aircraft usage, since immediate structural damage may occur.

Figure 9 shows a comparison of the 1975-1994 Boeing criteria and the levels of roughness. Level 1 roughness is seen at the midpoint of the acceptable region. The upper bound of the acceptable region is at or near Level 2. The temporarily acceptable band is located between Levels 2 and approximately Level 3. Roughness that is excessive or unacceptable is just above the Level 3 line.

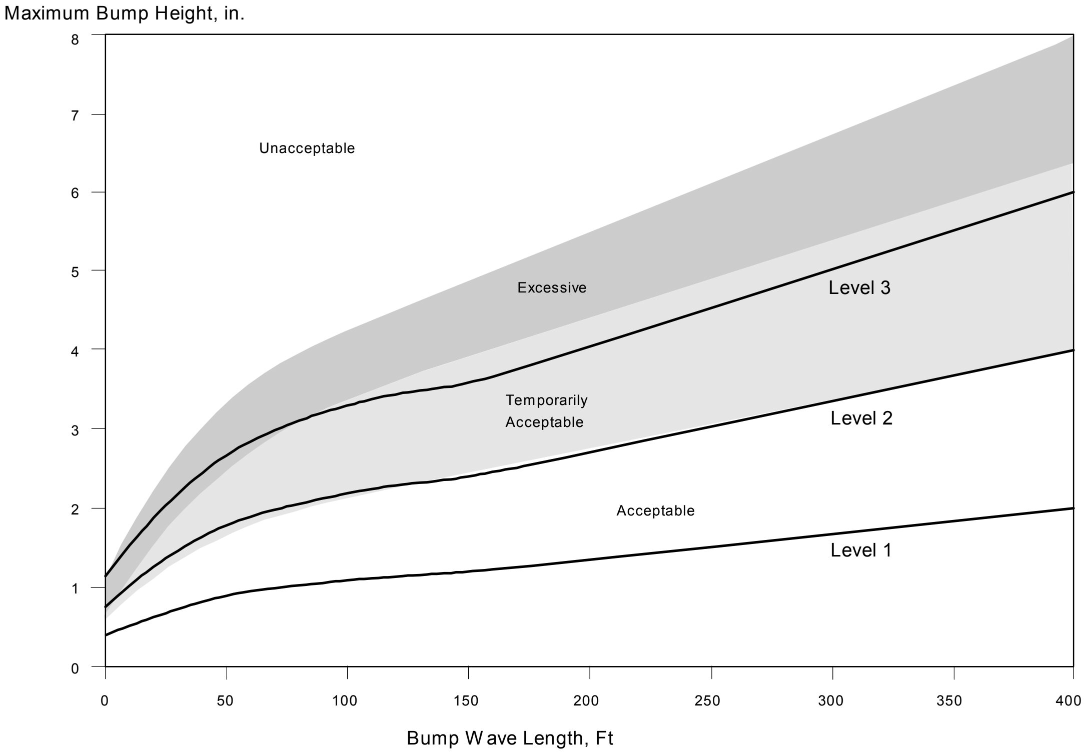

Figure 9. Roughness Levels versus 1975-1994 Boeing Criteria

Operational experience has lately been used to further refine the acceptable limits of roughness. There have been no recorded cases of airplane structural damage occurring at or below Level 3, giving further indication that the criteria line of Level 2 was conservative. Thus, in 1994 the region somewhat above the Level 3 line was adopted by the Boeing Commercial Airplane Group Structures Staff as the upper level of acceptability (17). The levels of acceptability are shown in Figure 10, which is the criteria version in use by Boeing since that date.

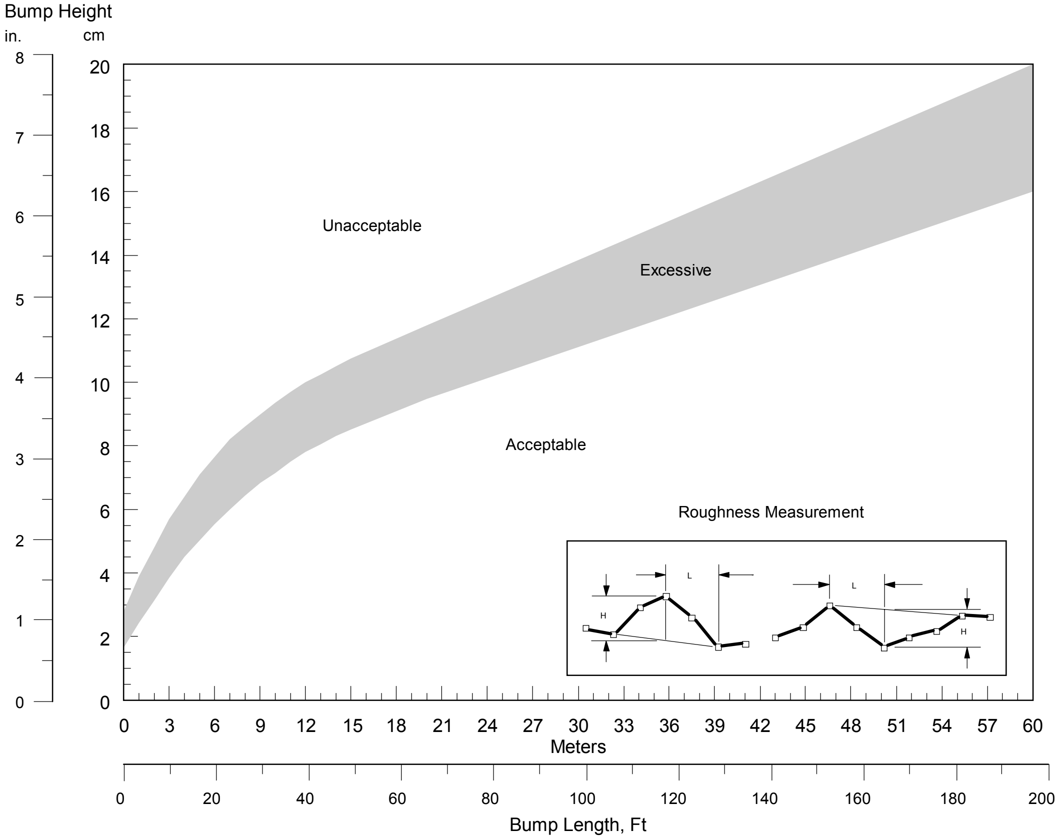

Figure 10. 1995 Boeing Runway Roughness Criteria

It should be emphasized that although the computer analysis of effects of roughness on an airplane and operational experience were used in the formulating this criteria, this is a single-event criteria describing the general condition of a runway rather than an analysis of an airplane. It does not address the problem of root-mean-square roughness (measured through power spectral density techniques) nor the effects of a series of long-wave undulations in which airplane frequency response could be important. This effect is accounted for by supplementary analyses using surface profiles at airports known to be rough, such as San Francisco 28R. By eliminating the root-mean-square and frequency response factors from consideration, this simplified criteria can be applied to all jet transport aircraft without regard to structural design or physical characteristics. This new criteria has as its basis a technical analysis, and it has been verified by in-service experience.

As a summary of roughness tolerance limits, pilot reports of rough runway conditions tend to emerge as the runway bumps approach the line designating the “acceptable” limitation, which is an indication of runway deterioration with age and usage. As the bumps get nearer to the peak of the “excessive” range, roughness becomes noticeably intolerable, both to the pilots and passengers. When roughness of this magnitude occurs, air crews and passengers alike will experience acute discomfort, and induced instrument interference on the flight deck can be severe. There is additionally a potential for a short term loss of aircraft steerage, as well as excessive nose and main gear loading.

Whenever roughness is above the “acceptable” range, airplane gear fatigue life rather than passenger cabin comfort or cockpit acceleration limitations is the more critical. Maximum roughness for passenger comfort and instrument interference should not exceed the “acceptable” upper limits, while maximum roughness for airplane gear fatigue should not be located in the “unacceptable” region. Roughness that occurs in the “unacceptable” range will require immediate runway closure in the affected locations, while roughness in the “excessive” range will require immediate repairs, but not closure.

2.3 Comparison of Roughness Criteria

The Boeing criteria has been shown to be applicable to commercial passenger jet transports. Other criteria lines developed by various agencies such as the United States Airforce (USAF) (18), the International Civil Aviation Organization (ICAO) (19), and the United States Federal Aviation Administration (FAA) (20) are shown in relation to Boeing criteria in Figure 11.

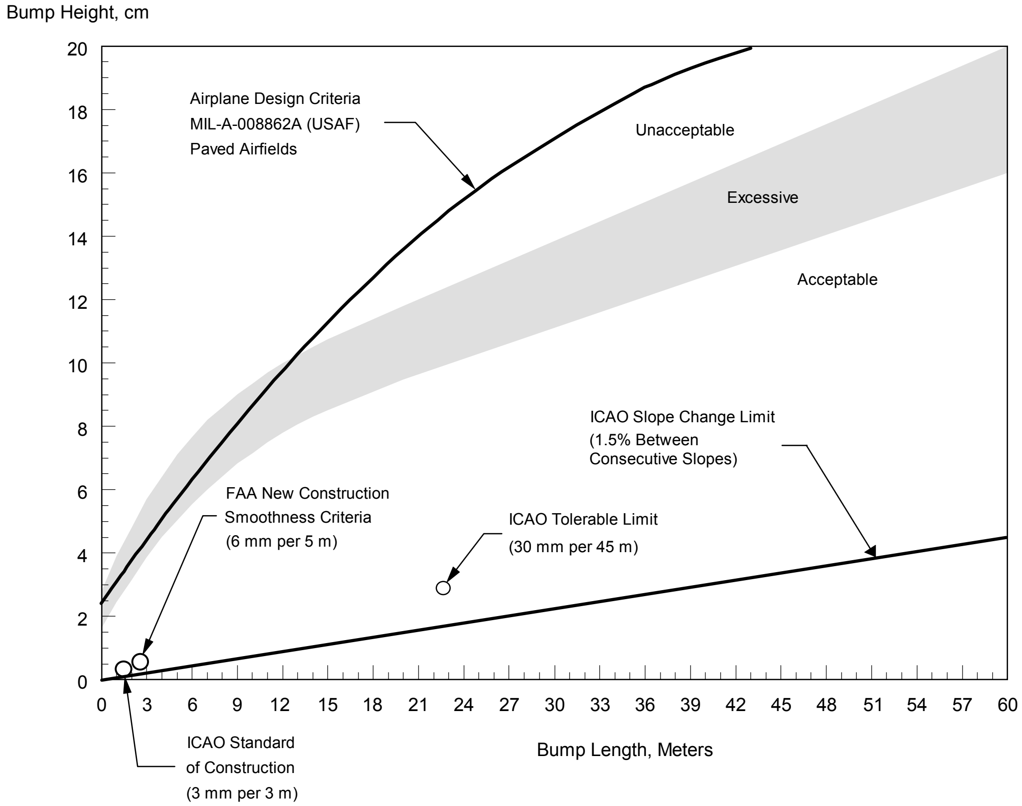

Figure 11. Comparison of Roughness Criteria

The FAA smoothness criteria and the ICAO standard of construction criteria of Figure 11 are intended as guides for new runway construction. The FAA allows a 1/4 inch deviation over 16 feet (6 mm over 5 meters), while the ICAO standard is 3 mm over 3 meters.

The ICAO tolerable limit recognizes that runways deteriorate with aircraft operations and differential settlement. In general, isolated irregularities on the order of 2.5 to 3 cm over a 45 m distance will not seriously hamper aircraft operations, according to ICAO. However, it was recognized by ICAO that exact information of the maximum acceptable deviation cannot be given, as it varies with the type an speed of the aircraft. ICAO also lists a criteria for the maximum change in consecutive longitudinal slopes that should not exceed 1.5 percent.

The central portion of this figure shows that commercial airplanes can tolerate some runway deterioration above the new construction roughness level, but are clearly not intended for military battle conditions or airplane design criteria appropriate to military applications. Because of differing airplane requirements, the USAF criteria line was developed to more stringent standards than for commercial applications. The USAF line, shown here for comparison purposes, is an airplane design criteria, while FAA and ICAO standards are runway roughness criteria. The Boeing criteria should be considered to be an airplane design based criteria.

Section 3

Evaluation of Roughness

3.1 Measurement and Analysis Techniques

A practical roughness evaluation requires that the location of the roughness first be determined. Usually pilot reports or local knowledge are sufficient to determine the location to be surveyed. Visual observations or high-speed car runs generally cannot verify roughness due to the long-wave nature of the bumps. If the location cannot be determined precisely, then a profile elevation survey over the entire high-speed portion of the runway is recommended.

As a minimum, the profile survey should be conducted along the centerline of the runway over the reported rough areas. Survey lines along the track where the main gear would normally be are very helpful in determining the full extent of the roughness and airplane response. The main gear tracks are normally about 3 to 3.5 meters (10 to 12 feet) either side of the centerline. Optionally, an additional survey track to accommodate the 747 wing gear may be necessary. It is recommended that the longitudinal surface measurement interval be on a maximum of 3 meter (10 foot) stations. A typical survey map plan view is shown in Figure 12.

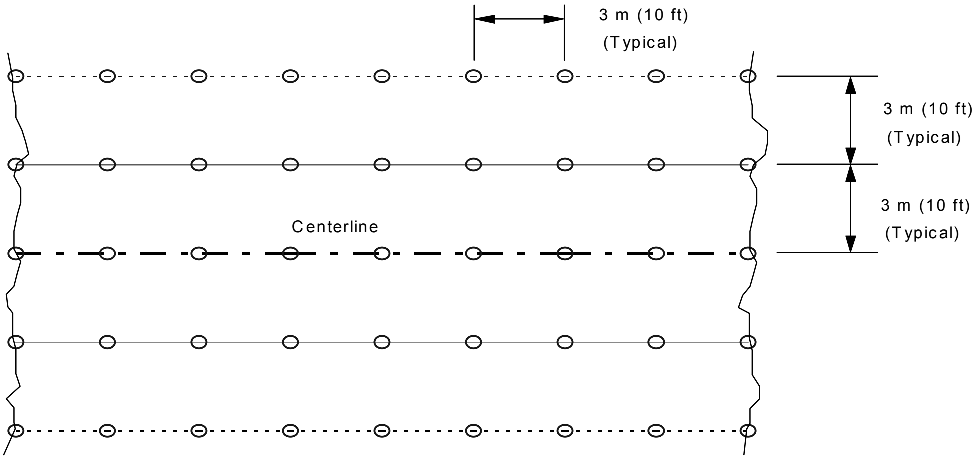

Figure 12. Typical Roughness Survey Points, Plan View

Many surveys, such as have been provided by airport authorities or airlines, are often done on 10 to 20 meter (33 to 66 foot) stations. These broader surveys generally do not reveal the true roughness of the runway, hence requiring the more detailed survey. For example, the profile of Figure 13 shows the difference in detected roughness between a 3 meter and a 12 meter survey measurement. Although this example is somewhat of an exaggeration, it is apparent that the broader survey would have missed many of the bump peaks and valleys that contribute to the roughness felt by the airplane.

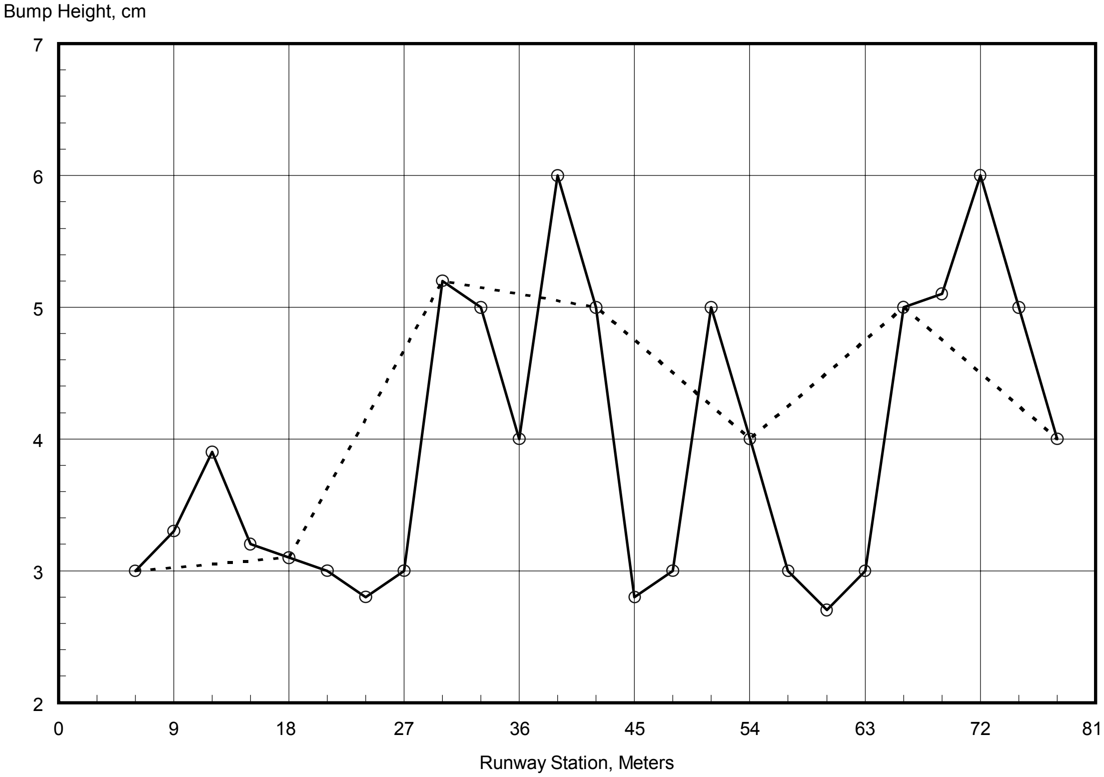

Figure 13. Effect of Survey Interval on Roughness Detection

The profile survey can be performed with an ordinary surveyor's level and rod or by the use of a laser instrument and a rod that detects the laser beams. A three-member crew is suggested for a rod and level survey, and they can complete about 150 feet per hour of measurements over three tracks. A crew of two is normally required to operate the laser and laser rod, along with a source of 12-volt power (such as car battery) for the laser. This method is about three times as fast as can be done with the surveyor’s instruments.

Other profile measuring devices are available that are self contained and will do up to three survey tracks on a 9000-foot runway in about three to four hours.

It is apparent that the self-contained profile measuring device is the most proficient in measuring the profile quickly. It has the added advantage that the data is recorded automatically for rapid transfer to graphic representations. However, it is also the most expensive to purchase, and transportation is somewhat cumbersome. The laser rod and level has been used by Boeing due to the lower initial cost of equipment and the ease of transportation. It is normally taken as checked luggage on an airline. It has been found to be more than adequate timewise for short profile surveys, which are the kinds most often encountered.

Upon completion, the survey data can be entered into a spreadsheet program on a personal computer for examination. The data can be then analyzed graphically or analytically by means of a computer program. One advantage of a graphical analysis is that a visual indication of the best means of repair is rendered. For example, the extent of depressions that need to be filled or the location of high sections that need to be milled can be readily seen on the graphical portrayal of the profile.

3.2 Application to a Typical Runway - Frost Heaves

The profile of Figure 14 is a plot of runway elevation versus runway station, showing the effect of localized frost heave action. The elevations on the vertical axis are exaggerated and offset for ease of evaluation. Note that the precise runway elevation is not required to enable calculation of the roughness magnitude. Accordingly, the elevations shown are relative to an arbitrary starting point.

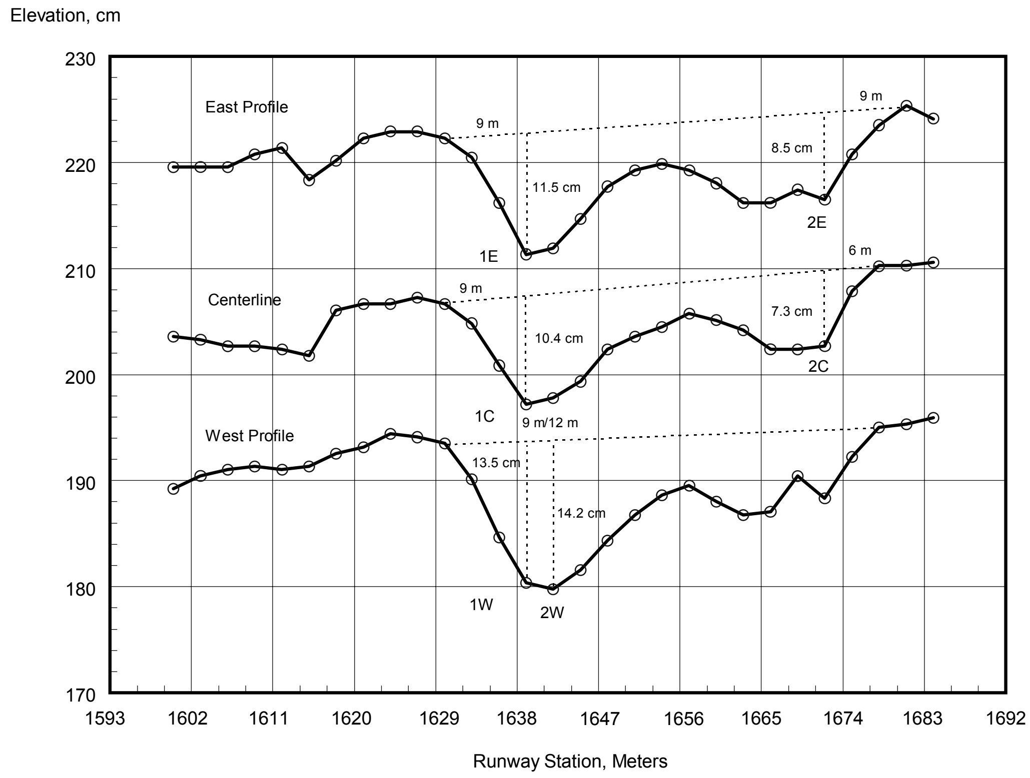

Figure 14. Runway Profile - Example of Frost Heave

The bump length is not the same as the total wavelength. It is, rather, the shortest length over which the bump height is measured, since aircraft can operate in either direction on a runway. For example, bump (depression) 1W has a total wavelength of 48 meters, but a bump length of 9 meters. Measurement of bumps in this manner accounts for aircraft travel in either direction, and it allows for simple assessment of "step" bumps.

Determination of the critical bump height at a given location may require the examination of several points. For example, bump 1W has an elevation shown as 13.5 cm over a

9-meter bump length. However, it can be seen that this is not the maximum depth of the depression. Using the greater depth of 14.2 cm, as shown for bump 2W, increases the bump length to 12 meters. Alternatively, the bump length could be shortened, with a corresponding reduction in bump height.

The Boeing criteria chart of Figure 15 is a reproduction of Figure 10, with the addition of critical bumps as determined from the Figure 14 profile. Note that in this case, bump 1E is more critical than bump 2E, according the criteria, even though they are both part of the same bump. As can be seen, a several bumps are in the "unacceptable" range for this particular runway, including at least one bump for each survey track. Consequently, Boeing would recommend that no further commercial jet transport operations be allowed on this portion of the runway until it is repaired. The repairs could be accomplished by either cold-planing the high points or patching the depressions to a point where the resultant bumps were below the "excessive" range on the Boeing criteria chart.

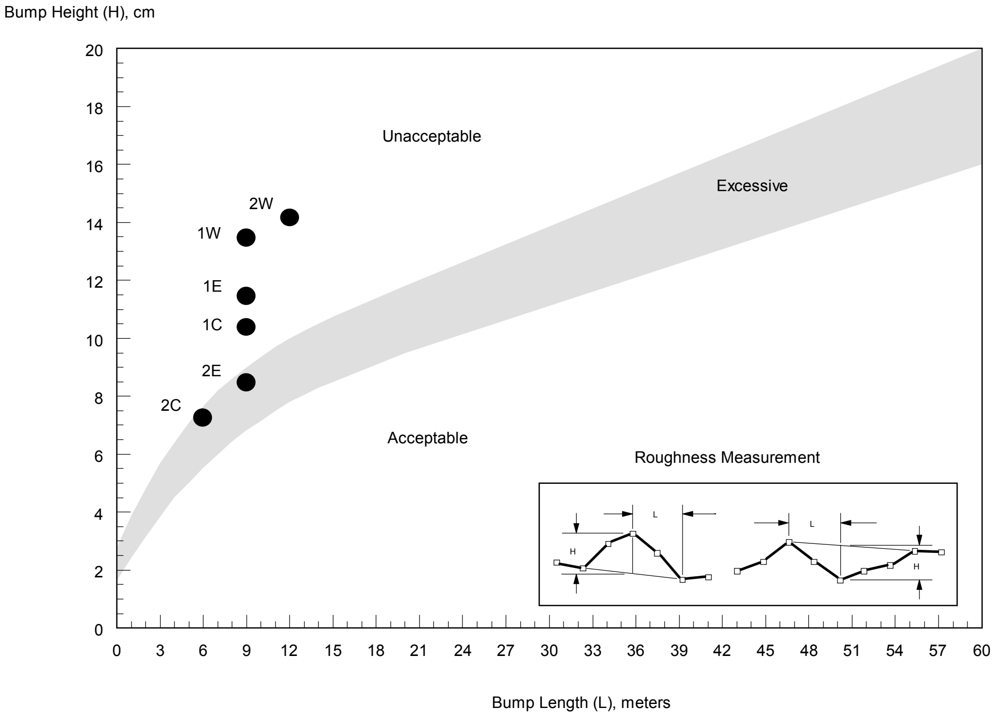

Figure 15. Application of Boeing Criteria to Frost Heave Profile

3.3 Application to a Typical Runway - Long Wave Depression

The profile of Figure 16 is a plot of runway elevation versus runway station for a long-wave depression. The elevations on the vertical axis are exaggerated and offset for ease of evaluation, as previously stated.

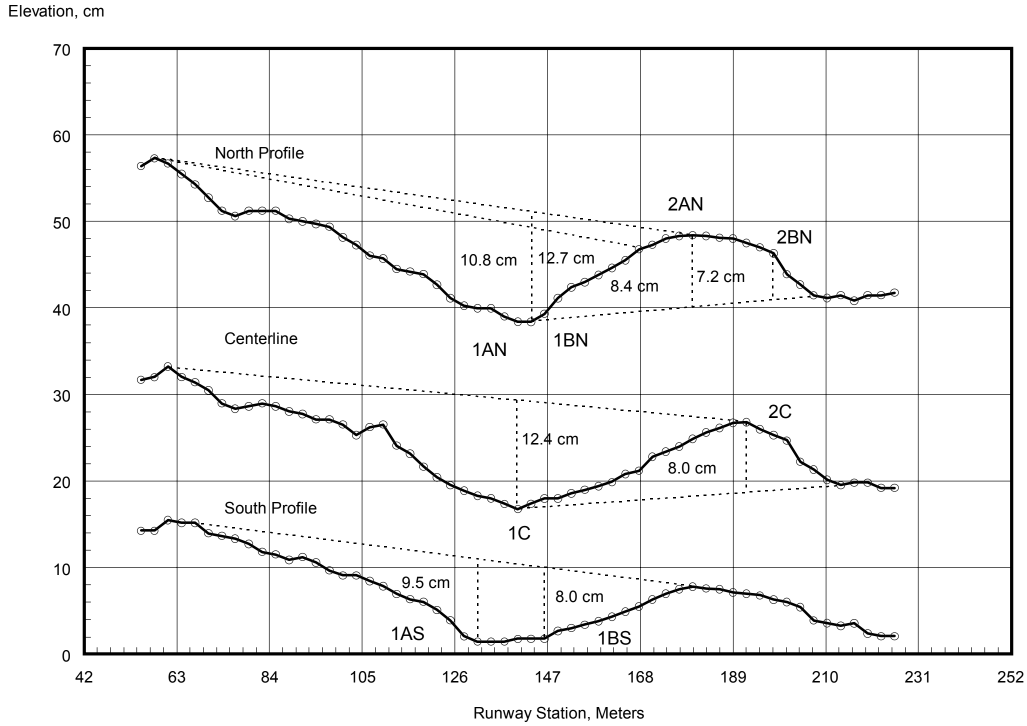

Figure 16. Runway Profile - Example of Long Wave Depression

Bump 1N has a depth of either 10.8 cm over a 24-meter bump length (1AN) or 12.7 cm over a length of 36 meters (1BN). Both bump positions are in the “excessive” range, as seen in Figure 17. This is an example of trying several bump lengths to determine the maximum at a given point. Often, this will determine whether or not a bump is located in a critical range. Another example is bump 2N in which the 2AN location is less critical than the 2BN position, indicating that the extreme of the bump is not always the most crucial.

Several bumps, shown in Figure 17, are in the “excessive” range for this particular location on the runway. Boeing would advise that commercial jet transport operations be allowed to continue on this portion of the runway, although immediate repair would be strongly advised. The repairs could be accomplished by either cold-planing the bumps or patching the depressions to a point where the resultant bumps were below the “excessive” range on the Boeing criteria chart. For example, a 2.5 cm (1 inch) overlay from runway station 110 to station 170 would alleviate all excessive roughness in this area.

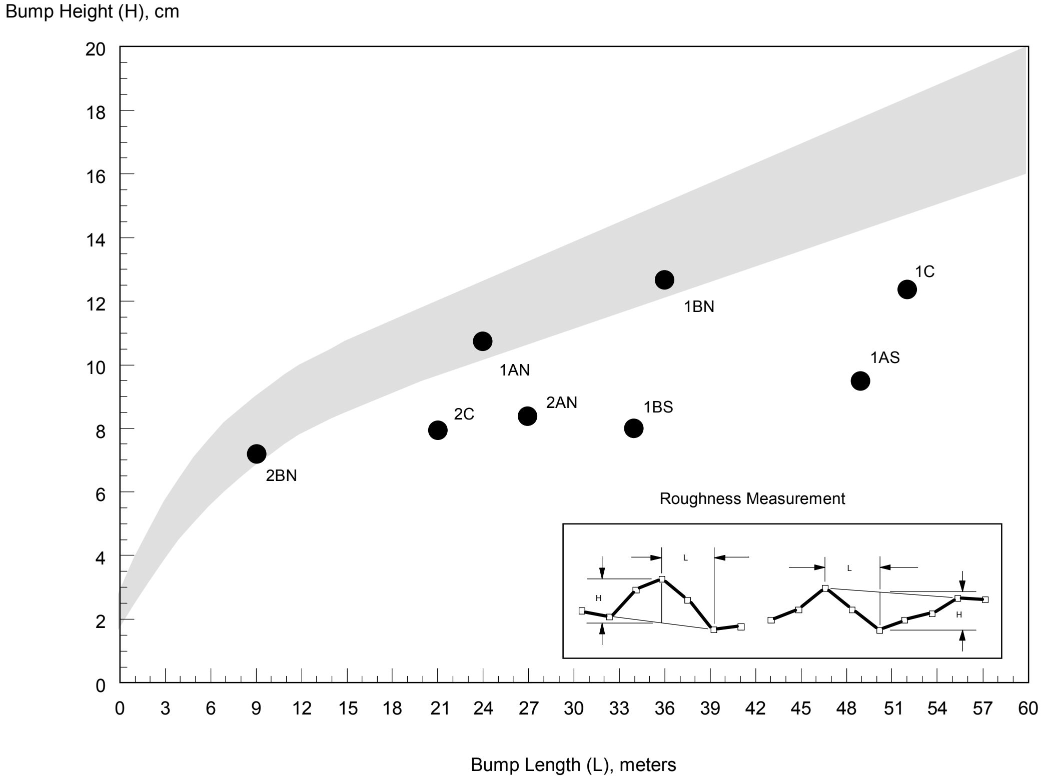

Figure 17. Application of Boeing Criteria to Long Wave Profile

3.4 Application to Temporary Ramping

When surface overlays are constructed on active runways during off-peak hours, temporary ramps that provide transition between the original surface and the new overlay are suggested as a satisfactory solution for short term usage (21). Entire runways can be overlaid during off-peak hours when done with temporary ramps that meet the Boeing criteria. The criteria of Figure 10 allows for short term aircraft operations on temporary ramp bumps that have roughness at or near the bottom of the "excessive" range. Within the United States, the FAA has issued an advisory circular AC 150/5370-13 (20), which deals with details within the entire process of temporary ramping, from cold-planing to construction practices and techniques. International guidance is provided in ICAO Annex 14 (19).

The FAA, in reference (20), states that the construction of this transition is one of the most important tasks in the work period because a ramp that is too steep could cause structural damage to an operating aircraft or a malfunction of the aircraft's instruments. Alternatively, a ramp that is too long, in addition to the waste in materials and labor, may result in the loosening of the temporary pavement materials and potential damage due to engine ingestion of foreign objects.

The techniques to build an acceptable transition from a new pavement overlay to an existing surface in conformance with Boeing criteria are provided as an interpretation of the guidelines of Figure 10. This figure provides design guidance that considers the length of temporary ramping for any given overlay thickness. However, practical construction considerations suggest that standard slope ramps be used. In general, ramp slopes of 1 in 100 (1.0%) for overlays up to 5 cm in thickness and 1 in 200 (0.5%) for overlays greater than 5 cm are proposed as feasible requirements. This is shown in Figure 18, which is a reproduction of Figure 10 with the ramp slope criteria added. Conformance to these slopes will ensure that the "excessive" range of roughness is not encountered and that high g-loading in the aircraft landing gear will not occur on the temporary ramp.

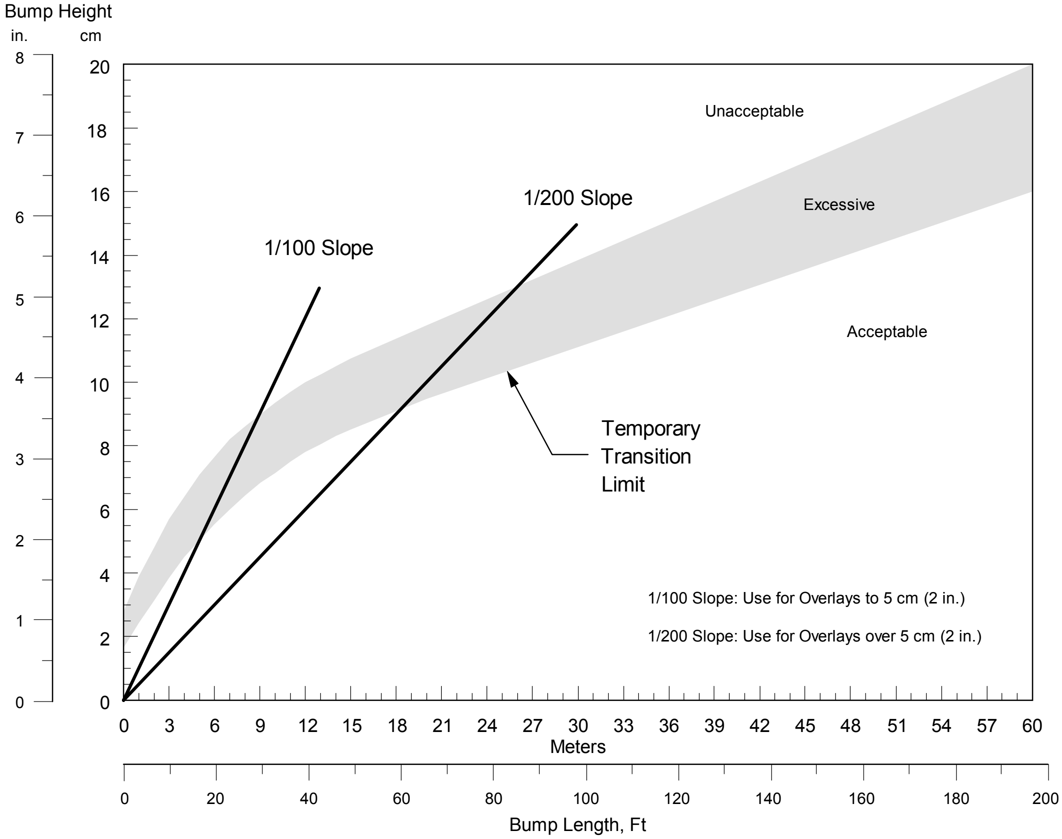

Figure 18. Application of Boeing Criteria to Temporary Ramping

Typical asphalt overlays are placed in layers of 5 cm (2 inch) thickness, which by the Boeing criteria would require a 5 meter (16.4 foot) ramp length. The FAA criteria requires a 4.6 meter (15.0 foot) ramp length for the same thickness and is therefore somewhat less conservative than the limits determined by Boeing. The ICAO guideline calls for a ramp slope of between 0.8% and 1.0%, which results in ramp lengths of 6.25 meters (20.5 feet) to 5 meters (16.4 feet) for a 5 cm overlay. This fits within the Boeing criteria for overlays of 5 cm or less, but results in significantly more allowable roughness for overlays greater than 5 cm.

In more detail, using the Boeing criteria for a overlays of 5 cm or less, a 1% ramp slope would require a 5 meter ramp length. A 2.5 cm thick overlay would necessitate a 2.5 meter ramp length. In order to not encroach into the excessive range, overlay pavements of greater thickness than 5 cm would require a reduced ramp slope. For example, at 9 cm, for a 0.5% slope, an 18 meter ramp length is indicated. In practical matters, however, these requirements are somewhat imprecise, and the reduced slope limitations could be adjusted to the previously mentioned general requirements.

Every effort should be made to pave the full width of the runway or taxiway during each work period. However, in cases where it is necessary to construct a transverse transition ramp, the maximum slope should be 1.5 meters (5 feet) in the transverse direction for each 2.5 cm (1 inch) of new pavement overlay (21).

Transition ramps may be constructed in one of two ways, depending on the type of equipment that is available. The simplest way is to construct a ramp down to the original surface, which should be feathered to no less than the maximum aggregate size and then sealed to prevent blast erosion. The most efficient method is to use a cold-planing machine to heel cut the pavement at the beginning and at the end of each work period area. This method is shown in Figure 19, and it results in a pavement that has good pavement joints suitable for the long-term support of aircraft loads.

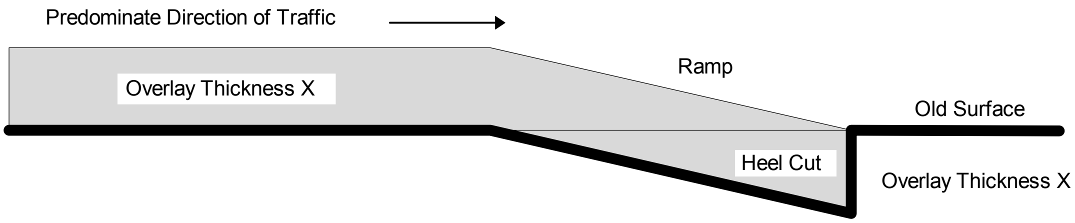

Figure 19. Heel-Cut Ramping Technique

Notes:

1. When the overlay thickness “X” is 5 cm (2 inches) or less, then the ramp slope = 1.0%.
2. When the overlay thickness “X” is more than 5 cm (2 inches), then the ramp slope = 0.5%.

When the paving operation is resumed, a short heel cut into the previous days’ ramp will provide an adequate joint for aircraft support (Figure 20). When paving the final surface course, the transition ramp should be completely cut back and the entire transition removed. In no case should a bond breaking layer be placed under the ramp for the purpose of ease of removal in the next work period. The bond breaking layer is likely to come loose during daytime aircraft operations, resulting in subsequent breakup of the pavement and foreign object damage.

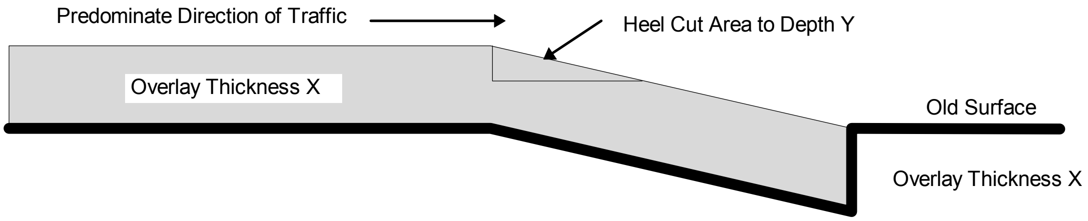

Figure 20. Surface Preparation Prior to Resumption of Paving.

Note: Depth "Y" should be greater than the maximum aggregate size.

Section 4

Conclusions

1. The Boeing developed runway roughness criteria of Figure 10 provides a simple and suitable means of accessing runway surface ride quality acceptability for ongoing use by commercial aircraft.

2. The limits of acceptability in this criteria provide a satisfactory means for airports and airlines to judge whether continued use of marginally rough runways can be sustained or whether surface corrections are necessary. Consideration of the upper regions of acceptability will result in lessening of passenger discomfort from runway roughness effects.

3. Unacceptable limits of roughness can be readily determined which will allow airlines to cease operations and give guidance to airports on how to take immediate corrective action to alleviate the problem found. Avoidance of unacceptable roughness will protect the airplane from excessive landing gear fatigue problems.

4. Adoption of the Boeing runway roughness criteria as an international standard will allow responsible authorities a means to uniformly quantify roughness in a manner that is easily explained and applied, with application to all commercial transport jet operations.