Designation: E1486M − 14

Standard Test Method for Determining Floor Tolerances Using Waviness, Wheel Path and Levelness Criteria (Metric)[1]

This standard is issued under the fixed designation E1486M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers data collection and analysis procedures to determine surface flatness and levelness by calculating waviness indices for survey lines and surfaces, elevation differences of defined wheel paths, and levelness indices using SI units.

NOTE 1—This test method is the companion to inch-pound Test Method E1486.

NOTE 2—This test method was not developed for, and does not apply to clay or concrete paver units.

1.1.1 The purpose of this test method is to provide the user with floor tolerance estimates as follows:

1.1.1.1 Local survey line waviness and overall surface waviness indices for floors based on deviations from the midpoints of imaginary chords as they are moved along a floor elevation profile survey line. End points of the chords are always in contact with the surface. The imaginary chords cut through any points in the concrete surface higher than the chords.

1.1.1.2 Defined wheel path criteria based on transverse and longitudinal elevation differences, change in elevation difference, and root mean square (RMS) elevation difference.

1.1.1.3 Levelness criteria for surfaces characterized by either of the following methods: the conformance of elevation data to the test section elevation data mean; or by the conformance of the RMS slope of each survey line to a specified slope for each survey line.

1.1.2 The averages used throughout these calculations are the root mean squares, RMS (that is, the quadratic means). This test method gives equal importance to humps and dips, measured up (+) and down (−), respectively, from the imaginary chords.

1.1.3 Appendix X1 is a commentary on this test method. Appendix X2 provides a computer program for waviness index calculations based on this test method.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Document

2.1 *ASTM Standards:*[2]

E1486 Test Method for Determining Floor Tolerances Using Waviness, Wheel Path and Levelness Criteria

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *defined wheel path traffic*—traffic on surfaces, or specifically identifiable portions thereof, intended for defined linear traffic by vehicles with two primary axles and four primary load wheel contact points on the floor and with corresponding front and rear primary wheels in approximately the same wheel paths.

3.1.2 *levelness*—described in two ways: the conformance of surface elevation data to the mean elevation of a test section, elevation conformance; and as the conformance of survey line slope to a specified slope, RMS levelness.

3.1.2.1 *elevation conformance*—the percentage of surface elevation data, h_i, that lie within the tolerance specified from the mean elevation of a test section from the mean elevation of all data within a test section. The absolute value of the distance of all points, h_i, from the test section data mean is tested against the specification, *dmax*. Passing values are counted, and that total is divided by the aggregate quantity of elevation data points for the test section, and percent passing is reported.

3.1.2.2 *RMS levelness*—directionally dependent calculation of the RMS of the slopes of the least squares fit line through successive 4.5-m long sections of a survey line, *L*. The RMS

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[1] This test method is under the jurisdiction of ASTM Committee E06 on Performance of Buildings and is the direct responsibility of Subcommittee E06.21 on Serviceability.

Current edition approved April 1, 2014. Published May 2014. Originally approved in 1994. Last previous edition approved in 2010 as E1486M – 98 (2010). DOI: 10.1520/E1486M-14.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

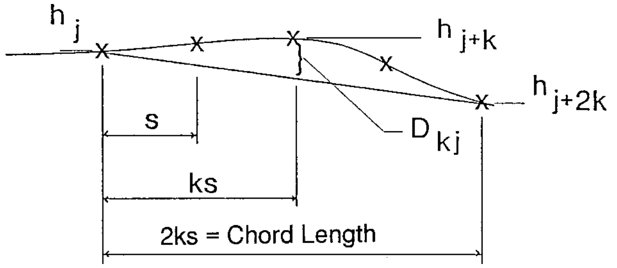

FIG. 1 Explanation of Symbols

LV_L is compared to the specified surface slope and specified maximum deviation to determine compliance.

3.1.3 *Waviness Index Terms:*

3.1.3.1 *chord length*—the length of an imaginary straightedge (chord) joining the two end points at j and $j + 2k$. This length is equal to $2ks$ (see Fig. 1) where the survey spacing, s, is equal to 0.3 m, and where k is equal to 1, 2, 3, 4, and 5 to define chord lengths of 0.6, 1.2, 1.8, 2.4, and 3.0 m, respectively, unless values for s and for k are otherwise stated.

3.1.3.2 *deviation (D_{kj})*—the vertical distance between the surface and the midpoint, $j + ks$, of a chord of length $2ks$ whose end points are in contact with the surface.

3.1.3.3 *length adjusted RMS deviation (LAD_k)*—calculated for a reference length L_r of 3 m, unless otherwise stated, in order to obtain deviations that are independent of the various chord lengths, $2ks$.

3.1.3.4 *waviness*—the relative degree to which a survey line deviates from a straight line.

3.2 *Symbols:*

A = area of test section, m^2.

d = point i, of the $(4.5/s + 1)$ point subset of $i = 1$ to $imax$, where d is a point within the $(4.5/s + 1)$ point subset, used to evaluate RMS levelness.

dh_L = number of elevation data points of survey line, L, which lie within the maximum allowable deviation from the test section elevation data mean, $dmax$.

D_{kj} = deviation from chord midpoint, $j + k$, to the survey line, mm.

$dmax$ = specified maximum allowable deviation from the test section elevation data mean.

EC = percentage of elevation data within a test section complying to a specified maximum deviation, $dmax$, from the mean of all elevation data points within a test section.

EC_L = percentage compliance of each survey line to a specified maximum deviation, $dmax$, from the mean of all elevation data points within a test section.

h_i = elevation of the points along the survey line, mm.

ha_i = elevation of the points along the survey line of the left wheel path of defined wheel path traffic, mm.

hb_i = elevation of the points along the survey line of the right wheel path of defined wheel path traffic, mm.

i = designation of the location of survey points along a survey line $(i = 1, 2, 3 \ldots imax_L)$.

$imax_L$ = total number of survey points along a survey line.

$imax_{Lx}$ = total number of survey points along one of the pair of survey lines, Lx, representing the wheel paths of defined wheel path traffic.

j = designation of the location of the survey point which is the initial point for a deviation calculation $(j = 1, 2, 3 \ldots jmax_k)$.

$jmax_k$ = total number of deviation calculations with a chord length $2ks$ along a survey line.

k = number of spaces of length s between the survey points used for deviation calculations.

$kmax_L$ = maximum number (rounded down to an integer) of spaces of length s that can be used for deviation calculations for $imax_L$ survey points ($kmax_L$= 5 unless otherwise specified).

L = designation of survey lines $(L = 1, 2, 3 \ldots Lmax)$.

LAD_k = length-adjusted RMS deviation based on points spaced at ks and a reference length of L_r.

Lg = total number of survey spaces between primary axles of a vehicle used as the basis for longitudinal analysis of each pair of survey lines representing the wheel paths of defined wheel path traffic. Lg equals the integer result of the primary axle spacing, in metres divided by s.

$Lmax$ = number of survey lines on the test surface.

L_r = reference length of 3 m, the length to which the RMS deviations, RMS D_k, from chord lengths other than 3 m are adjusted.

LD_i = longitudinal elevation difference between corresponding pairs of points separated by Lg of defined wheel paths, mm $(i = 1, 2, 3 \ldots (imax_L - Lg))$.

LDC_i = incremental change in longitudinal elevation difference, LD_i along defined wheel path traffic wheel paths, mm/m $(i = 1, 2, 3 \ldots (imax_L - Lg - 1))$.

Lx = designation of the pair of survey lines used for defined wheel path traffic analysis.

mh_d = mean elevation of each 4.5-m section of survey line, L, mm $(d = 1, 2, 3 \ldots (imax_L - 4.5/s))$.

ms_d = mean slope of the least squares fit line of each 4.5-m section of survey line, L, mm/m $(d = 1, 2, 3 \ldots (imax_L - 4.5/s))$.

n_L = total number of calculated deviations for survey line L (equal to the sum of the values of $jmax_k$ for all values of k that are used). $n_{\Rightarrow \alpha L}$ is a weighting factor used in calculating both the waviness and surface waviness indices.

RMS D_k = root mean square of chord midpoint offset deviations, D_{kj}, based on points spaced at ks.

$RMS\ LD_{Lx}$ = root mean square of longitudinal elevation differences, LD_i, on paired wheel path survey lines for defined wheel path traffic, with primary axles separated by L_g, mm.

$RMS\ TD_{Lx}$ = root mean square of transverse elevation differences, TD_i, on paired wheel path survey lines for defined wheel path traffic, mm.

$RMS\ LV_L$ = RMS levelness, calculated as the root mean square slope of each survey line, L, mm/m.

s = spacing between adjacent survey points along a survey line (0.3 m unless a smaller value is stated), m.

SWI = surface waviness index determined by combining the waviness indices of all the survey lines on the test surface, mm.

TD_i = transverse elevation difference between corresponding points of defined wheel path traffic wheel paths, mm (i = 1, 2, 3 . . . $imax_{Lx}$).

TDC_i = incremental change in transverse elevation difference, TD_i along defined wheel path traffic wheel paths, mm/m (i = 1, 2, 3 . . . ($imax_{Lx}$−1)).

WI_L = waviness index for survey line L with chord length range from 0.6 to 3.0 m unless a different range is stated, mm.

3.3 *Sign Convention*—Up is the positive direction; consequently, the higher the survey point, the larger its h_i value.

4. Summary of Test Method

4.1 *Equations*—Equations are provided to determine the following characteristics:

4.1.1 *Waviness Index Equations:*

4.1.1.1 $RMS\ D_k$ = RMS deviation (see Eq 4).

4.1.1.2 LAD_k = length-adjusted deviation (see Eq 5).

4.1.1.3 WI_L = waviness index (see Eq 6 and 7).

4.1.1.4 SWI = surface waviness index (see Eq 8).

4.1.1.5 $|D_{kj}|$ = absolute value of the length adjusted deviation (see Eq 24).

4.1.2 *Defined Wheel Path Traffic Equations:*

4.1.2.1 TD_i = transverse elevation difference between the wheel paths of defined wheel path traffic (see Eq 9).

4.1.2.2 TDC_i = transverse change in elevation difference between wheel paths of defined wheel path traffic (see Eq 10).

4.1.2.3 $RMS\ TD_{Lx}$ = RMS transverse elevation difference between wheel paths of defined wheel path traffic (see Eq 11).

4.1.2.4 LD_i = longitudinal elevation difference between front and rear axles on wheel paths of defined wheel path traffic (see Eq 12).

4.1.2.5 LDC_i = longitudinal change in elevation difference between front and rear axles on wheel paths of defined wheel path traffic (see Eq 13).

4.1.2.6 $RMS\ LD_{Lx}$ = RMS longitudinal elevation difference between axles on wheel paths of defined wheel path traffic (see Eq 14).

4.1.3 *Levelness Equations:*

4.1.3.1 mh_L = mean elevation of survey line, L, calculated only for use in calculating mh_{TS} (see Eq 15).

4.1.3.2 mh_{TS} = mean elevation of a test section, calculated only for use in calculating dh_L (see Eq 16).

4.1.3.3 dh_L = number of elevation data points of survey line, L, passing the specification, $dmax$, used for calculating both EC_L and EC (see Eq 17 and 18).

4.1.3.4 EC_L = percentage of elevation data points on survey line, L, which comply with $dmax$ (see Eq 19).

4.1.3.5 EC = percentage of elevation data points within a test section complying with $dmax$ (see Eq 20).

4.1.3.6 mh_d = mean elevation of each 4.5-m section of survey line, L, calculated only for use in calculating RMS LV_L (see Eq 21).

4.1.3.7 ms_d = mean slope of the least squares fit line of each 4.5-m section of survey line, L, calculated only for use in calculating $RMS\ LV_L$ (see Eq 22).

4.1.3.8 $RMS\ LV_L$ = RMS of least squares fit 4.5-m slopes (see Eq 23).

4.2 *Waviness Index—Chord Length Range:*

4.2.1 Unless a different range is specified, the waviness index, WI_L, shall be calculated for a 0.6, 1.2, 1.8, 2.4, and 3.0-m chord length range.

4.2.2 The chord length, $2ks$, is limited by the total number of survey points along a survey line. To ensure that the elevation of every survey point is included in the deviation calculation that uses the largest value of k, the maximum value of k, called $kmax_L$, is determined by:

$$kmax_L = imax_L/3\ (\text{rounded down to an integer}) \tag{1}$$

4.2.3 Reduce the maximum chord length so that $2(kmax_L)s$ is approximately equal to the maximum length that is of concern to the user.

NOTE 3—For longer survey lines, $kmax_L$, determined using Eq 1, permits the use of chord lengths $2ks$ longer than those of interest or concern to the floor user.

4.2.4 The maximum chord length for suspended floor slabs shall be 1.2 m, unless the slab has been placed without camber and the shoring remains in place.

4.3 *Waviness Index—Maximum Number of Deviation Measurements per Chord Length:*

4.3.1 As the values of k are increased from 1 to $kmax_L$. the number of deviation calculations decreases.

$$jmax_k = imax_L - 2k \tag{2}$$

4.4 *Waviness Index—Deviation:*

4.4.1 As shown in Fig. 1, the deviation, D_{kj}, is

$$D_{kj} = h_{j+k} - \frac{1}{2}\left(h_j + h_{j+2k}\right)\ mm \tag{3}$$

4.5 *Waviness Index—RMS Deviation:*

4.5.1 RMS D_k is calculated for each chord length using all points along the survey line.

$$RMS\,D_k = \sqrt{\frac{\sum_{j=1}^{jmax_k} D_{kj}^2}{jmax_k}}\ mm \tag{4}$$

4.6 *Waviness Index—Length-Adjusted Deviations:* $LAD_k$is calculated for a reference length, L_r, using Eq 5.

$$LAD_k = \sqrt{\frac{\frac{L_r}{2ks}\left[\sum_{j=1}^{jmax_k} D_{kj}^2\right]}{jmax_k}}\ mm \tag{5}$$

4.7 *Waviness Index*—The values of LAD_k obtained for each value of k shall be combined with other LAD values for each line L by weighing the values in proportion to $jmax_k$ to obtain the waviness index, WI_L:

$$WI_L = \sqrt{\frac{\sum_{k=1}^{kmax_L}\left(jmax_k\, LAD_k^2\right)}{n_L}}\ mm \tag{6}$$

where:

$$n_L = \sum_{k=1}^{kmax_L} jmax_k \tag{7}$$

4.8 *Surface Waviness Index*—The individual values of waviness index, WI_L obtained for each survey line shall be combined to give a surface waviness index, SWI, by combining them in proportion to n_L:

$$SWI = \sqrt{\frac{\sum_{L=1}^{L_{max}} n_L WI_L^2}{\sum_{L=1}^{L_{max}} n_L}}\ mm \tag{8}$$

4.9 *Defined Wheel Path Calculations:*

4.9.1 *Transverse Elevation Difference—TD_i* is calculated for a pair of wheel path survey lines, using Eq 9 *(i = 1, 2, 3 . . . $imax_{Lx}$).*

$$TD_i = (hb_i - ha_i)\ \mathrm{mm} \tag{9}$$

where TD_i is positive when the right wheel path is higher than the left, and negative when the right wheel path is lower than the left.

4.9.2 *Transverse Change in Elevation Difference—TDC_i* is calculated for each pair of wheel path survey lines, using Eq 10 *(i = 1, 2, 3 . . . ($imax_{Lx}$ − 1)).*

$$TDC_i = (TD_{i+1} - TD_i)/s\ \ mm/m \tag{10}$$

where TDC_i is positive when the vehicle tilted left from its previous position, and negative when it is tilted right from its previous position *(i = 1, 2, 3 . . . $imax_{Lx}$).*

4.9.3 *Transverse RMS Elevation Difference*—RMS TD_{Lx} is calculated for a pair of wheel path survey lines, using Eq 11.

$$RMS\,TD_{Lx} = \sqrt{\frac{\sum_{i=1}^{imax_{Lx}} TD_i^2}{imax_{Lx}}}\ mm \tag{11}$$

4.9.4 *Longitudinal Elevation Difference—LD_i* is calculated for a pair of wheel path survey lines, using Eq 12 *(i = 1, 2, 3 . . . ($imax_{Lx}$ − Lg)).*

$$LD_i = \left(\left(\frac{ha_{i+Lg} + hb_{i+Lg}}{2}\right) - \left(\frac{ha_i + hb_i}{2}\right)\right)\ mm \tag{12}$$

4.9.5 *Longitudinal Change in Elevation Difference—LDC_i* is calculated for a pair of wheel path survey lines, using Eq 13 *(i = 1, 2, 3 . . . ($imax_{Lx}$ − Lg − 1)).*

$$LDC_i = (LD_{i+1} - LD_i)/s\ mm/m \tag{13}$$

4.9.6 *Longitudinal RMS Elevation Difference—RMS LD_{Lx}* is calculated for a pair of wheel path survey lines, using Eq 14.

$$RMS\,LD_{Lx} = \sqrt{\frac{\sum_{i=1}^{(imax_{Lx}-Lg)} LD_i^2}{\left(imax_{Lx} - Lg\right)}}\ mm \tag{14}$$

4.10 *Calculations for Elevation Conformance:*

4.10.1 *Mean Elevation of Survey Line—mh_L* is calculated for survey line, *L,* using Eq 15.

$$mh_L = \frac{\sum_{i=1}^{imax_L} h_i}{imax_L}\ mm \tag{15}$$

4.10.2 *Mean Elevation of a Test Section—mh_{TS}* is calculated for a test section using Eq 16.

$$mh_{TS} = \frac{\sum_{L=1}^{Lmax_L} mh_L}{Lmax}\ mm \tag{16}$$

4.10.3 *Elevation Points Passing—dh_L* the number of elevation data points that lie within the maximum allowable deviation, *dmax,* from the test section elevation data mean is calculated using Eq 17 and 18.

$$dh_L = \sum_{L=1}^{Lmax}\ \sum_{imax}^{imax_L} \frac{1}{2}\left(1 + \frac{|x|}{x}\right) \tag{17}$$

where:

$$x = dmax - \left|h_i - mh_{TS}\right| \tag{18}$$

and

$$\frac{|x|}{x} = 0\ when\, x = 0$$

4.10.4 *Elevation Conformance of a Survey Line—EC_L* is calculated using Eq 19.

$$EC_L = 100\left[\frac{dh_L}{imax_L}\right]\% \tag{19}$$

4.10.5 *Elevation Conformance of a Test Section*—EC is calculated using Eq 20.

$$EC = 100\left[\frac{\sum_{L=1}^{Lmax} dh_L}{\sum_{L=1}^{Lmax} imax_L}\right]\% \tag{20}$$

4.11 *Calculations for RMS Levelness*—RMS LV_L, the RMs of the successive 4.5-m least squares fit slopes of each survey line, *L,* is calculated using Eq 21 through Eq 23.

4.11.1 *Mean Elevation over 4.5 m—mh_d,* the mean elevation for each 4.5-m section of survey line, *L,* is calculated using Eq 21 *(d = 1, 2, 3 . . . ($imax_L$ − 4.5/s)).*

$$mh_d = \sum_{i=d}^{d+4.5/s} \frac{h_i}{4.5/s + 1}\ mm \tag{21}$$

4.11.2 *Least Squares Fit Slope over 4.5 m—ms_d,* the mean slope of the least squares fit line through each 4.5-m section of survey line, *L,* is calculated using Eq 22 *(d = 1, 2, 3 . . . ($imax_L$ − 4.5/ s)).*

$$ms_d = \frac{6}{15}\left[\frac{2\sum_{i=d}^{d+4.5/s}(i - d + 1)h_i}{(4.5/s + 1)(4.5/s + 2)} - mh_d\right]\ mm/m \tag{22}$$

4.11.3 *RMS Levelness—RMS* LV_L, the RMS of the slopes of all 4.5-m sections of survey line, L, is calculated using Eq 23 (d = 1, 2, 3 . . . ($imax_L$ − 4.5/s)).

$$RMS\,LV_L = \sqrt{\frac{\sum_{d=1}^{(imax_L - 4.5/s)} ms_d^2}{(imax_L - 4.5/s)}}\ mm/m \qquad (23)$$

5. Significance and Use

5.1 This test method provides statistical and graphical information concerning floor surface profiles.

5.2 *Results of this test method are for the purpose of the following:*

5.2.1 Establishing compliance of random or fixed-path trafficked floor surfaces with specified tolerances;

5.2.2 Evaluating the effect of different construction methods on the waviness of the resulting floor surface;

5.2.3 Investigating the curling and deflection of concrete floor surfaces;

5.2.4 Establishing, evaluating, and investigating the profile characteristics of other surfaces; and

5.2.5 Establishing, evaluating, and investigating the levelness characteristics of surfaces.

5.3 *Application:*

5.3.1 *Random Traffic*—When the traffic patterns across a floor are not fixed, two sets of survey lines approximately equally spaced and at right angles to each other shall be used. The survey lines shall be spaced across the test section to produce lines of approximately equal total length, both parallel to and perpendicular to the longest test section boundary. Limits are specified in 7.2.2 and 7.3.2.

5.3.2 *Defined Wheel Path Traffic*—For surfaces primarily intended for defined wheel path traffic, only two wheel paths and the initial transverse elevation difference ("side-to-side") between wheels shall be surveyed.

5.3.3 *Time of Measurement*—For new concrete floor construction, the elevation measurements shall be made within 72 h of final concrete finishing. For existing structures, measurements shall be taken as appropriate.

5.3.4 *Elevation Conformance*—Use is restricted to shored, suspended surfaces.

5.3.5 *RMS Levelness*—Use is unrestricted, except that it is excluded from use with cambered surfaces and unshored, elevated surfaces.

6. Apparatus

6.1 *Point Elevation Measurement Device:*

6.1.1 *Type I Apparatus*—a device capable of measuring the elevations of a series of points spaced at regular intervals along a straight line marked on the floor surface shall be used for this test method. Examples of Type I point elevation measurement devices include, but are not limited to:

6.1.1.1 *Leveled Straightedge,*

6.1.1.2 *Optical or Laser Level,* with vernier or scaled target,

6.1.1.3 *Taut Level Wire,* with gage to measure vertical distance from wire to floor,

6.1.1.4 *Floor Profilometer,* a device that moves along a line on the floor's surface and produces a continuous record of the elevation, and

6.1.1.5 *Laser Imaging Device.*

6.1.2 *Type II Apparatus*—a device capable of measuring the elevation differences between sequential points spaced at regular specified intervals along a straight line across the floor surface shall be used for this test method. Since the results obtained with this test method varies slightly depending on the particular measurement device employed, all project participants shall agree on the measurement device to be used prior to the application of this test method for contract specification enforcement. Examples of Type II point elevation measurement devices include, but are not limited to:

6.1.2.1 *Inclinometer*—a device that measures the angle between the horizontal and the line joining the two points of contact with the floor's surface, and

6.1.2.2 *Longitudinal Differential Floor Profilometer*—a device that moves along a line on the floor's surface and produces a record of the individual elevation differences.

6.2 *Ancillary Equipment:*

6.2.1 *Measurement Tape,* and

6.2.2 *Chalk Line,* (or other means for marking straight lines on the test surface).

6.3 *Data Recorder*—a convenient means for recording the readings and the information described in the Procedure section shall be suitable for this test method. Examples of means for data recording include, but are not limited to:

6.3.1 *Manual Data Sheet,*

6.3.2 *Magnetic Tape Recorder,* (voice or direct input),

6.3.3 *Paper Chart Recorder,* and

6.3.4 *Direct Computer Input.*

7. Procedure

7.1 *Test Sections*—Divide the test surface into test sections. Assign a different identification number to each test section and record the locations of all test section boundaries. No portion of the test surface shall be associated with more than one test section.

7.2 *Survey Lines:*

7.2.1 Establish the number and location of survey lines to be used in each test section. Assign a different identification number to each survey line and mark each survey line on the test surface. Survey lines shall be parallel to the principal axes of each concrete placement.

NOTE 4—Typical spacing of survey lines should be 10 m or less in order to obtain a sufficiently large statistical sample.

7.2.2 No survey line shall be shorter than 15 s.

7.2.3 Survey lines shall not be prohibited from crossing control joints and construction joints, but shall not cross planned changes in surface slope. Record location of joints in data collected.

7.2.4 For defined wheel path traffic, survey lines shall be equal in length, measured in the same direction, and the survey points on each line shall be directly opposite each other, numbered in identical sequence. Each survey line shall be centered upon the midpoint of the wheel width. Label each pair of wheel path survey lines as L_x, where L_x is the pair designator, for example, (L_x = 1*x*, 2 *x*, 3*x* . . .).

7.2.5 For elevation conformance, measure each h_1 for all survey lines, *L*, in millimetres, deviation from a common benchmark, within each test section to be evaluated; and either measure or calculate all successive h_i so that each is relative to the benchmark.

7.2.6 For RMS levelness, orient each survey line, *L*, in line with each specified slope to be tested.

7.3 *Survey Points:*

7.3.1 Subdivide each survey line into spaces of length, *s*. Sequentially number each successive point down the survey line as 1, 2, 3, and so forth.

7.3.2 The minimum total number of survey points in a test section with an area, *A*, in square metres, shall be *A*/1.5 for random traffic floors.

7.3.3 For defined wheel path traffic, points on each pair of wheel path survey lines shall be located directly opposite each other.

7.3.4 For defined wheel path traffic, assign the total number of survey points, $imax_L$, of either survey line of the pair to $imax_{Lx}$.

7.4 *Elevation Measurement:*

7.4.1 For each survey line of the test section, measure and record in sequence:

7.4.1.1 The elevations of all survey points if a Type I apparatus is used; or

7.4.1.2 The differences in elevation between all adjacent survey points if a Type II apparatus is used.

8. Calculation of Results

8.1 *Elevations*—Calculate the elevation of all survey points along each survey line. Designate these elevations as: h_1, h_2, . . . h_i, . . . h_{imax_L} except for defined wheel path traffic which shall be designated as either:

$$ha_1, ha_2, \ldots ha_i, \ldots ha_{imax_{Lx}}$$

or

$$hb_1, hb_2, \ldots hb_i, \ldots hb_{imax_{Lx}}$$

where *ha* is used for left wheel paths and *hb* is used for right wheel paths; and the *a* and *b* designations are ignored except in Eq 9 and Eq 12.

8.2 *Maximum Chord Length for Waviness Index:*

8.2.1 Using Eq 1, determine $kmax_L$. Reduce $kmax_L$ so that $2kmax_Ls$ equals the maximum chord length of interest.

8.2.2 Choose all values of *k* starting with 1 and increasing to $kmax_L$.

8.2.3 For each value of *k*, calculate the total number of deviations with a chord length 2*ks* along a survey line using Eq 2.

8.3 *Deviation*—For each value of *k*, choose all values of *j* starting with 1 and increasing to $jmax_k$. Using Eq 3, calculate the deviation from the elevations of the three survey points.

8.4 *RMS Deviation*—Sum the values of D_{kj}^2 and calculate the *RMS* D_k, using Eq 4.

8.5 *Length-Adjusted Deviation*—Calculate the LAD_k, using Eq 5 for a reference length, L_r.

8.6 *Waviness Index—*WI_L is calculated using Eq 6, by combining all the LAD_k values for that line. Eq 7 is used to determine n_L.

8.7 *Location of the Largest Deviations*—For the different values of *k* determine the locations where the length adjusted deviations are larger in magnitude than twice the waviness index. This occurs when:

$$|D_{kj}| > 2WI_L\sqrt{\frac{2ks}{L_r}}\,\text{mm} \tag{24}$$

where:

$|D_{kj}|$ = the absolute value of D_{kj}

8.8 Repeat 8.1 – 8.7 for all survey lines on the test section.

8.9 *Surface Waviness Index*—Combine all WI_L values to obtain the SWI, using Eq 8.

8.10 *Additional Requirements for Defined Wheel Path Traffic:*

8.10.1 *Transverse Elevation Difference*—Calculate the transverse elevation differences, TD_i, between corresponding points on each wheel path survey line, using Eq 9.

8.10.2 *Transverse Change in Elevation Difference*—Calculate TDC_i, the successive changes in TD_i, for each wheel path survey line pair, *Lx*, using Eq 10.

8.10.3 *Transverse RMS Elevation Difference*—Calculate RMS TD_{Lx}, the RMS of the transverse elevation differences TD_i, for each wheel path survey line pair, *Lx*, using Eq 11.

8.10.4 *Longitudinal Elevation Difference*—Calculate LD_i, the elevation differences between front and rear axles at corresponding points on each wheel path survey line pair, *Lx*, using Eq 12.

8.10.5 *Longitudinal Change in Elevation Difference*—Calculate LDC_i, the successive changes in LS_i, for each wheel path survey line pair, *Lx*, using Eq 13.

8.10.6 *Longitudinal RMS Elevation Difference*—Calculate RMS LD_{Lx}, the RMS of the longitudinal elevation differences LD_i, for each wheel path survey line pair, *Lx*, using Eq 14.

8.11 *Levelness Requirements*—Calculate the levelness requirements, if specified, as follows:

8.11.1 *Elevation Conformance*—Calculate the elevation conformance, EC_L, of each survey line, *L*, and the overall elevation conformance, *EC*, of each test section as follows:

8.11.1.1 Calculate mh_L, the mean elevation of survey line, *L*, using Eq 15.

8.11.1.2 Calculate mh_{TS}, the mean elevation of the test section using Eq 16.

8.11.1.3 Calculate dh_L, the number of elevation points passing for each survey line, *L*, using Eq 17 and 18.

8.11.1.4 Calculate EC_L, the conformance of elevation data to the specification, *dmax*, for each survey line, *L*, using Eq 19.

8.11.1.5 Calculate *EC*, the conformance of the aggregate elevation data within a test section to the specification, *dmax*, using Eq 20.

8.11.2 *RMS Levelness*—Calculate RMS LV_L, the RMS of slopes of the least squares fit lines through each 4.5-m portion of each survey line, *L*, using Eq 21 through Eq 23.

9. Report

9.1 For each test section, prepare a diagram and report the following information:

9.1.1 Indicate the extent of the test section complete with dimensions in millimetres and metres.

9.1.2 Indicate locations of surface penetrations and planned changes in slope, for example, joints, drains, ramps, and so forth.

9.1.3 Indicate each survey line, *L*, on the diagram. Indicate the starting points in terms of distance from two adjacent edges of the test section, and indicate the direction of survey.

9.2 For each survey line on the test section, report the following information:

9.2.1 Record and plot the elevations of the survey points along the survey line.

9.2.2 Record the values of LAD_k for each value of *k* and plot a graph of LAD_k versus the length 2*ks*.

9.2.3 Record the value of WI_L for the line and plot as a horizontal line starting at the minimum value of 2*s* and extending to $2kmax_Ls$. Report the WI_L as *WI*(0.6–3.0) or as $WI_{0.6–3.0}$, where (0.6–3.0) represents the range of chord lengths, 2*ks* to 2*(kmax)s,* in metres, for example, *WI*(0.6–3.0) is the waviness index for a line based upon a chord length range from 0.6 to 3.0 m. Compare all WI_L values with specification and denote failures, if any.

9.2.4 Record the values of 2*ks* and D_{kj} and the locations *j, j* + *k*, and *j* + 2*k* for all adjusted deviations larger in magnitude than twice WI_L.

9.3 Record the SWI, compare it to the specified value, and denote failure, if any.

9.4 *Additional Requirements for Defined Wheel Path Traffic*—In addition to the requirements in 9.1 and 9.2, report the following information for defined wheel path traffic.

9.4.1 Report all locations of TD_i, in excess of the specified limit for each pair of wheel path survey lines, *Lx*.

9.4.2 Report all locations of TDC_i, in excess of the specified limit for each pair of wheel path survey lines, *Lx*.

9.4.3 Report the *RMS* TD_{Lx}, for each pair of wheel path survey lines, *Lx*, and compare with the specified limit.

9.4.4 Report all locations of LD_i, in excess of the specified limit for each pair of wheel path survey lines, *Lx*.

9.4.5 Report all locations of LDC_i, in excess of the specified limit for each pair of wheel path survey lines, *Lx*.

9.4.6 Report the *RMS* LD_{Lx}, for each pair of wheel path survey lines, *Lx*, and compare with the specified limit.

9.5 *Requirements for Levelness Tolerance*—Report the following based upon the levelness criteria specified, if any:

9.5.1 *Elevation Conformance*—For each test section, report the elevation conformance, EC_L, of each survey line, *L*, and report *EC*, for the entire test section, and compare them with the specified values.

9.5.2 *RMS Levelness*—For each survey line, *L*, report the *RMS* LV_L and compare with the specified value and specified maximum deviation.

10. Precision & Bias

10.1 *Precision*—The precision of the procedures in this test method for measuring waviness indices and for measuring defined wheel path traffic and levelness criteria, is being determined.

10.2 *Bias*—The procedures in this test method have no bias because the values are defined only in terms of this test method.

APPENDIXES

(Nonmandatory Information)

X1. COMMENTARY

X1.1 History of Waviness Index

X1.1.1 The waviness index method was developed by Dr. Robert Loov, Professor of Civil Engineering at the University of Calgary, a result of his review of other quality control procedures when he was a member of the floor surface subcommittee of the Canadian Standards Association Technical Committees A23.1 on "Concrete Materials and Methods of Concrete Construction" and A23.2 on "Methods of Test for Concrete." The details of the waviness index procedure were included as Appendix E in the March 1990 edition of these standards which have been approved as National Standards of Canada by the Standards Council of Canada. Additional information was presented in a paper by Robert Loov and Lloyd Rodway.[3]

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[3] Loov, Robert, and Rodway, Lloyd, "Determining the Elevations, Slope and Waviness of Surfaces Using the Procedures of CAN/CSA-A23.1-M90, Appendix E," *The Canadian Journal of Civil Engineering,* Vol 18, August 1991, pp. 675–680.

X1.2 Introduction to Waviness Index

X1.2.1 The waviness index procedure is used for comparing and combining the results of vertical deviations of the midpoints of imaginary chords of various lengths whose ends are in contact with the floor.

X1.2.2 Intuitively, deviations should become larger as the chord length is increased. Normal statistical procedures used for error analysis in surveying show that, when adjacent slopes are uncorrelated, the root mean square of the deviations varies in proportion to the square root of the chord length. The measured deviations can therefore be compared and combined if they are adjusted in relation to a chosen reference length.

X1.2.3 For the waviness index test method, a reference length of 3 m has been chosen. Deviations for different chord lengths are then adjusted, in proportion to the square root of the 3-m reference length divided by the different chord lengths. The waviness index is the root mean square of the individual length-adjusted deviations obtained for the different chord lengths that have been chosen. A range of chord lengths, $2ks$, of 0.6, 1.2, 1.8, 2.4, and 3.0 m is specified by specifying that k be 1, 2, 3, 4, 5 and by specifying that the survey point spacing, s, be equal to 0.3 m.

X1.2.4 The waviness index can be considered to be an unbiased estimate of the surface quality along a survey line. When the line is at least fifteen 0.3-m spaces long (the minimum length required by 7.2.2), it will be the average of at least 50 deviations as shown in Table X1.1 (see X1.9).

X1.2.5 To compute the surface waviness index for a given floor slab, the waviness indices for all measurement lines are averaged together. The waviness indices and the surface waviness index can be compared to the specified values to monitor profile quality on new construction or to evaluate the profile of an existing facility.

X1.3 Survey Line and Point Spacing

X1.3.1 *For Conventional Facilities with Random Traffic Patterns:*

X1.3.1.1 A grid of approximately equally spaced survey lines should be laid out at approximately 10 m on center and at right angles to each other for each day's concrete placement, in accordance with 5.3.1 and 7.2.

X1.3.1.2 Elevation data should be on the predetermined measurement lines at 0.3-m spacings, s, unless shorter spacings are used for greater accuracy, as should be used for defined wheel path traffic. The equations for waviness index include the survey point spacing so the adjustment for shorter survey point spacing, s, is included in the equations. Instead of direct readings of elevations, the elevation difference between adjacent points may be used (see 6.1).

X1.3.1.3 The number of elevation or slope measurements is a function of the shape of the test area, the survey line spacing and the survey point spacing. Based on a survey point spacing of 0.3 m and a survey line spacing of 10 m, the number of elevation measurements for typical areas are shown in Table X1.2. Section 7.3.2 specifies the minimum number of survey points to be $A/1.5$.

X1.3.2 *For Defined Wheel Path Traffic Patterns:*

X1.3.2.1 Survey lines should follow the centerline of left and right wheel paths, should be measured in the same direction, and start with congruous point numbering so that points from each wheel path at right angles to the other have the same point number (see 5.3.2 and 7.2.4).

X1.3.2.2 It is recommended that the measurement length, s, be halved, for measuring defined wheel path surfaces.

X1.4 Data Collection and Storage

X1.4.1 To minimize conflicts, it is critical that the equipment that is to be used to measure the floor be specified prior to data collection. The instrument should be capable of determining elevations or slopes to the desired accuracy.

X1.4.2 While manual collection and computation can be used to determine wave indices, it is highly recommended that computerized data collection and analysis be used to minimize calculation errors and to speed up reporting (see Appendix X2).

X1.4.3 Measurements for the evaluation of concrete placement and finishing are to be taken and reported within the prescribed 72-h limit (see 5.3.3) to provide timely feedback and to minimize the effect of such long-term changes as curling and deflections that occur subsequent to the concrete placement and finishing operations.

X1.5 Chord Length Range for Waviness Index

X1.5.1 The waviness index tolerance system is particularly well suited for the identification of surface waviness in concrete floors that can affect the operation of industrial vehicles, such as forklifts, stacker cranes, and pallet jacks.

X1.5.2 *Slab on Ground Random Traffic Floors*—Since the typical wheel base of material handling equipment is about 1.5 m, the root mean square (RMS) average of deviations for chord lengths of 0.6, 1.2, 1.8, 2.4, and 3.0 m are computed to arrive

TABLE X1.1 Number of Computed Deviations for Survey Line of 15 s, 4.5-m Minimum Length (for $s = 0.3$ m)

Chord Lengths, m	Number of Deviations Measured
0.6	14
1.2	12
1.8	10
2.4	8
3.0	6
Total Deviations	50

TABLE X1.2 Examples of Specified versus Actual Number of Survey Points

Test Section Dimensions			Min. Specified (A/1.5)	Actual Number of Survey Points
Length, m	Width, m	Area, m^2		
75	12	900	600	860 (2 × 250 + 9 × 40)
30	30	900	600	800 (4 × 100 + 4 × 100)
60	12	720	480	680 (2 × 200 + 7 × 40)
27	27	729	486	540 (3 × 90 + 3 × 90)

TABLE X1.3 Recommended Maximum Waviness Indices for Combined Chord Lengths (0.6 to 3.0 m), $WI_{0.6–3.0}$

Quality Classification	Survey Area (Test Area)	Survey Line (Local Test Line)
Conventional (for ceramic tile or carpet)	8.0 mm	8.5 mm
Moderately flat	5.0 mm	5.5 mm
Flat (for flexible tile)	3.0 mm	3.5 mm
Very flat	2.0 mm	2.5 mm
Super flat	1.3 mm	2.0 mm

at the standard $WI_{0.6–3.0}$ waviness index. The 0.6 to 3.0-m chord length range is approximately one half to two times the typical 1.5-m wheel base length and are those which are likely to affect the equipment. Waves that are less than one half the wheel base are typically too small to affect the vehicle. Waves more than twice the wheel base are typically gradual undulations that the vehicle easily rides over.

X1.5.3 *Suspended Random Traffic Floors*—A waviness index based on length adjusted RMS deviations from a chord length range from only 0.6 and 1.2 m, $WI_{0.6–1.2}$ is used (see 4.2.2). Where forms and shores are used, surveys should be made prior to their removal. The actual $WI_{0.6–1.2}$ tolerances used for suspended floors should be based on surveys of satisfactory suspended floors of similar construction or use, or both.

X1.6 Waviness Index Deviation Calculation

X1.6.1 The locations for measuring deviations, *D*, for each chord length is demonstrated in Fig. X1.1. For example, if data were collected at 0.3-m intervals, the deviation for a 0.6-m chord length is calculated, first using data points 1, 2, and 3, then points 2, 3, and 4, then points 3, 4, and 5, and so forth. The deviations for a 1.2-m chord length are calculated, first using points 1.3 and 5, then 2.4 and 6, then 3.5 and 7, and so forth. The same technique is then applied to lengths of 1.8, 2.4, and 3.0 m. The RMS deviation for each length is then computed.

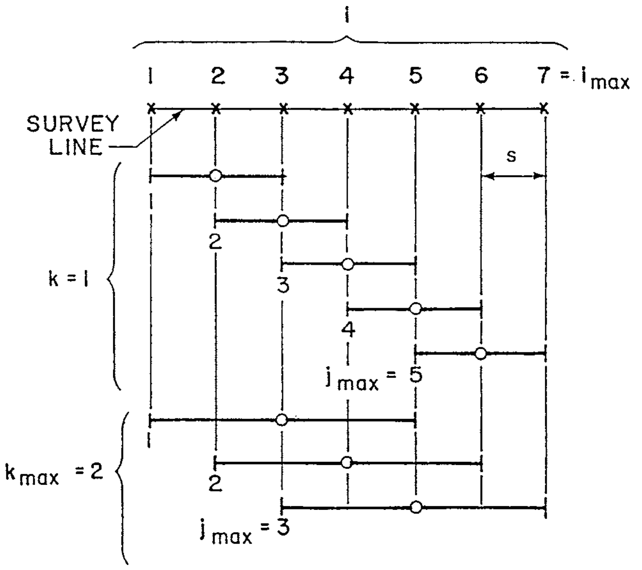

FIG. X1.1 Chord Positions

X1.7 Waviness Index Example

X1.7.1 For a single survey line, examples of RMS D_k, of LAD_k, and $WI_{0.6–3.0}$ are shown in Fig. X1.2. In this example, *k* varies from 1 to 5, and therefore, the chord length varies 0.6 to 3.0 m since *s* = 0.3 m. A parabola is drawn to show the close fit with RMS D_k.

X1.7.2 To get deviations that will be more or less constant, the RMS D_k , values are adjusted for length by multiplying each of them by the square root of $L_r/2ks$. For the chosen reference length of 3.0 m, the length adjusted deviation for a 0.6-m chord can be obtained by multiplying the measured deviations by the square root of 3/0.6 which is 2.24. Points are shifted up when $2ks$ is less than L_r. No adjustment is made when $2ks = L_r$ at 3 m. Points would be shifted down if $2ks$ were greater than L_r.

X1.7.3 If the slope data collected from the floor surface were perfectly random and there were a large number of survey points, this LAD_k line would be a straight horizontal line.

X1.7.4 The average for each survey line is $WI_{0.6–3.0}$. Based on the LAD_k and $WI_{0.6–3.0}$ as shown in Fig. X1.2, it can be seen that, in this example, deviations for chord lengths of 1.2 and 1.8 m are relatively higher than the average, while deviations for lengths of 0.6 and 3.0 m are lower than the average.

X1.8 Waviness Index Recommended Tolerances

X1.8.1 For use as a quality control tool on new construction projects, the following tolerances should be considered. If there is any doubt as to the floor tolerance required, it is recommended that measurements of an existing functional facility be made and the resulting waviness indices used to govern the new construction. To save the owner money, tolerances should not be specified to be more stringent than needed.

X1.9 Waviness Index Confidence Limits

X1.9.1 Independent surveys of the same test area can be expected to produce slightly different waviness indices. The

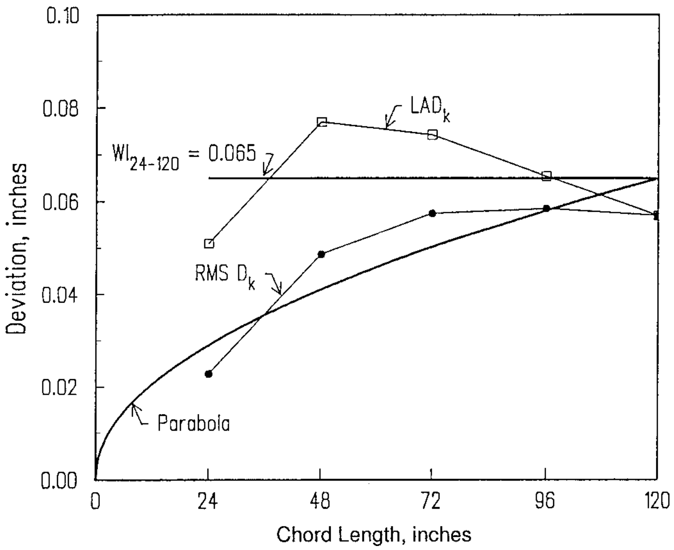

FIG. X1.2 Illustration of Typical RMS Deviations (RMS D_k), Length-Adjusted Deviations (LAD_k), and Waviness Index (*WI*) principal reason for such differences is that each independent survey measures the elevations of a different set of points on the test area. Differences in surveying equipment and operator skill may also influence the elevation data that is gathered. The waviness index computations do not, however, introduce errors or bias.

X1.9.2 Quality control can be improved by using additional survey lines to minimize the possibility of missing local irregularities.

X1.9.3 *Confidence Limits for Waviness Index*—An estimate of the standard deviation for the waviness index is

$$S_{WI} = \frac{WI}{\sqrt{2f_L}} \tag{X1.1}$$

In this equation f_L represents the number of degrees of freedom for a line. For this procedure use $f_L = imax_L - (kmax_L + 1)$. The 90 % confidence limits are based on $\pm 1.7 S_{WI}$. Therefore, there is a 90 % probability that the true value of *WI* is within the range:

$$WI\left[1 - \frac{1.7}{\sqrt{2f_L}}\right] \text{ to } WI\left[1 + \frac{1.7}{\sqrt{2f_L}}\right] \tag{X1.2}$$

Other confidence limits may be used if desired. The factor of 1.7 shall then be replaced by the appropriate value based on statistical tables for the distribution of *t*.

X1.9.4 The estimate of the standard deviation of the waviness index is based on a commonly used equation for the standard deviation of the standard deviation.[4] The symbol f_L is the number of degrees of freedom. Although this becomes rather complicated when repetitive calculations are performed using the same data, a conservative approximation for this standard is to use

$$f_L = imax_L - (kmax_L + 1) \tag{X1.3}$$

X1.9.5 A series of 100 lines each with 100 points has been simulated by computer to verify the applicability of these equations. The standard deviation was computed at each step as the number of survey points in each line was increased from 3 to 100. Fig. X1.3 compares the ratio S_{WI}/WI with the value $\frac{1}{\sqrt{2f_L}}$. The excellent agreement obtained under these conditions is clear from the figure.

X1.9.6 *Confidence Limits for Surface Waviness Index*—An estimate of the standard deviation for the surface waviness index, SWI, is:

$$S_{SWI} = \frac{SWI}{\sqrt{2f_s}} \tag{X1.4}$$

where:

$$f_s = \sum_{i=1}^{Lmax} \left(imax_L - (kmax_L + 1)\right) \tag{X1.5}$$

There is a 90 % probability that the true value of SWI will fall within the range:

$$SWI\left[1 - \frac{1.7}{\sqrt{2f_s}}\right] \text{ to } SWI\left[1 + \frac{1.7}{\sqrt{2\,f_s}}\right] \tag{X1.6}$$

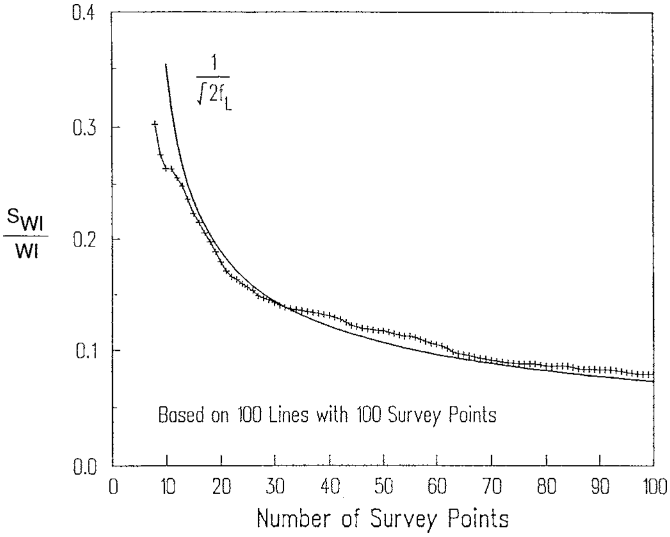

FIG. X1.3 Actual Versus Predicted Standard Deviation

X1.9.7 The prediction of the confidence interval requires a value of *t*. This is a statistical value that varies with the desired confidence level and the number of degrees of freedom. For a 90 % confidence interval and f_L ranging from 10 to 120, *t* varies from 1.812 to 1.658. A reasonable approximation is to use *t* equal to 1.7. Although this is slightly nonconservative when less than 35 survey points are used, this is offset by the approximation to f_L which becomes more conservative with smaller values of $imax_L$.

X1.9.8 To determine whether real floors follow the predicted trend, the waviness index was calculated in a step-by-step fashion for an actual floor profile. The number of survey points was increased step by step from 3 to 108. Fig. X1.4 shows the meandering lines formed by the $WI_{0.6-3.0}$ and the upper and lower 90 % confidence intervals. These results support the predictions. There is only one short length near Survey Point 67 where the 90 % confidence interval falls marginally below a subsequent $WI_{0.6-3.0}$ value. This occurs where the floor is smoother to the left of Survey Point 67 and has a rough patch between 67 and 76.

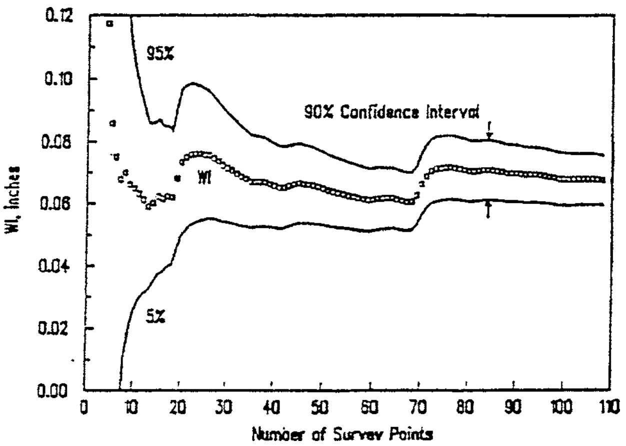

FIG. X1.4 Actual WI Versus 90 % Confidence Interval

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[4] Kennedy, Neville, *Basic Statistical Methods for Engines and Scientists,* 3rd ed., 1986, p. 339.

X1.9.9 The reason for imposing a minimum limit of 16 survey points is shown clearly on these graphs. Useful predictions are not possible with fewer points.

X1.10 Defined Wheel Path Traffic Floor Tolerancing

X1.10.1 Racked warehouse facilities are classic examples, with defined wheel paths between racks. In addition to evaluating the waviness index for each wheel path, this test method provides tolerances for the horizontal roll, in terms of one axle's transverse elevation difference, TD_i, change in transverse elevation difference, TD_i, and RMS transverse elevation difference, RMS TD_{LX}. Front to back pitch is tested in terms of longitudinal elevation difference from front to rear axle, LD_i, change in longitudinal elevation difference, LDC_i, and RMS longitudinal elevation difference, RMS LD_{LX}. The RMS LS_{LX} elevation difference values, RMS TD_{LX} and RMS LD_{LX}, as well as the waviness index for each wheel path, WI_L, are indices, whereas TD_i, TDC_i, LD_i, and LDC_i are point specific criteria.

X1.10.2 Tolerance specifications for the longitudinal and transverse elevation differences are commonly published by vehicle manufacturers, but may also be obtained from *in situ*, acceptable wheel paths. The combination of tested values offer variables that can be used in all kinds of defined traffic conditions from wire-guided towveyors, to forklift trucks, to narrow-aisle/high-stacking turret truck forklifts. The more critical the tolerance, the smaller the measurement length spacing, *s*, so as to obtain enough data to accurately reflect the condition of the surface.

X1.10.3 Gasparinni and Kary[5] and Gasparini, Petrov, and Ozer[6] give much information, some of which is paraphrased as follows:

> "For rigid bodies, pitching is maximum when the wheel base divided by floor wavelength is ½ , $3/2$, $5/2$, . . . for floors it is necessary to measure and control not only the amplitudes of the waves, but also their wavelengths. A floor's wave content can be shifted to longer wavelengths by grinding regions that have small wavelengths."

X1.11 Levelness Tolerances

X1.11.1 Two different levelness tolerances are defined in this test method. One is the RMS of the incremental 4.5-m mean least squares fit slopes of each survey line and the other is the conformance of the elevation data to a plane. The former is to evaluate the slope relative to some externally specified amount, such as for pitches, ramps, etc. The latter is restricted to elevated floor slabs, and tests that all surface elevations occur within reasonable limits of the mean.

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[5] Gasparinni, and Kary, "Response of Vehicles Moving on Rough Concrete Floors," *ACI Structural Journal,* September/October 1989, pp. 546–550.

[6] Gasparinni, Petrov, and Ozer, "Wavelength Content of Concrete Floors and Its Significance for Moving Vehicles."

X2. COMPUTER PROGRAM FOR WAVINESS INDEX CALCULATIONS BASED ON TEST METHOD E1486M[7]

X2.1

```
1. 'Calculation of Waviness Index floor tolerance.
2. 'Using ASTM E1486M based on SI units
3. DIM h(200), m(200), RMSD(5), LAD(5), D2sumK(5), D(5,200)
4. DIM label$(10), nsumL%(10), WI(10), D2sumL(10)
5. 'DIM of 200 and 10 allows for 200 points and 10 lines
6. 'DIM of 5 allows for maximum chord length = 5 * 2 * point spacing
7. INPUT "Input number of lines", Lmax%
8. INPUT "Distance between survey points (metres)", s
9. INPUT "Maximum chord length (metres)", SLmax
10. km% = SLmax/(2! * s)
11. OPEN "inputm.dat" FOR INPUT AS #1
12. OPEN "outputm.res" FOR APPEND AS #2
13. PRINT #2, "Waviness based on ASTM E1486M using units"
14. PRINT #2,
15. PRINT #2, USING "Computations based on ## survey lines with "; Lmax%;
16. PRINT #2, USING "##.## m point spacing"; s
17. Lr = 3!
18. PRINT #2, USING "and a ### m reference length"; Lr;
19. nsumS% = 0
20. D2sums = 0!
21. FOR L% = 1 TO Lmax%
22. INPUT #1, label$(L%)
23. PRINT #2,
24. PRINT #2, "Survey Line Location:"; label$(L%)
25. PRINT #2,
26. nsumL%(L%) = 0
27. D2sumL (L%) = 0!
28. hsum = 0!
29. ihsum = 0!
30. INPUT #1, mmax%, h(1)
31. imax% = mmax% + 1
32. FOR i% = 2 TO max%
33. INPUT #1, m(i%)
34. h(i%) = h(i% − 1) + m(i%)
35. NEXT i%
36. PRINT #2, "     Survey information"
37. PRINT #2, "Point Difference Elevation"
38. FOR i% = 1 TO imax%
39. PRINT #2, USING "#### ########.### #######.###"; i%; m(i%); h(i%)
40. hsum = hsum + h(i%)
41. ihsum = ihsum + i% * h(i%)
42. NEXT i%
43. hA = hsum/imax%
44. mA = (6/(s*(imax% − 1)))*((2/imax%)*(ihsum/(imax% + 1)
45. PRINT #2,
46. PRINT #2, "Average Elevation of"; label$(L%);
```

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[7] Microsoft QuickBasic, Version 4.5.

```
47. PRINT #2, USING "is ###.### m"; hA
48. PRINT #2,
49. PRINT #2, "Average slope of"; label$(L%);
50. PRINT #2, USING "is ##.### mm/m"; mA
51. 'solve for Line Waviness Index (LWI)
52. kmax% = imax %\, 3
53. IF kmax% > km% THEN kmax% = km%
54. FOR k% = 1 TO kmax%
55. a2 = L4/(2 + k% * s)
56. jmax% = imax% − 2 * k%
57. D2sumK(k%) = 0!
58. FOR j% = 1 To jmax%
59. D(k%, j%) = h(j% + k%) − ((h(j%) + h(j% + 2 * k%)) / 2)
60. D2sumK(k%) = D2sumK(k%) + (D(k%, j%)^ 2)
61. NEXT j%
62. nsumL%(L%) = nsumL%(L%) + jmax%
63. D2sumL(L%) = D2sumL(L%) + (a2 * D2sumK(k%))
64. RMSD(k%) = SQR(D2sumK(k%)/jmax%)
65. LAD(k%) = SQR(a2) * RMSD(k%) ,
66. NEXT k%
67. nsumS% = nsumS% + nsumL%(L%)
68. D2sumS = D2sumS + D2sumL(L%)
69. LWI(L%) = SQR(DF2sumL(L%)/nsumL%(L%))
70. PRINT #2,
71. PRINT #2, "      Deviations"
72. PRINT #2, "Straightedge RMS Adjusted"
73. PRINT #2, "      Length Deviation Deviation"
74. FOR k% = 1 TO kmax%
75. PRINT #2, USING "####.## #########.##"; 2 * k% * s; RMSD(k%);
76. PRINT #2, USING "#######.##"; LAD(k%)
77. NEXT k%
78. PRINT #2,
79. PRINT #2, "Waviness Index, WI, of "; label$(L%); "is";
80. PRINT #2, USING "###.# mm"; WI(L%)
81. PRINT #2, USING "based on chord lengths from ##.###"; 2 * s;
82. PRINT #2, USING " m to ##.### m long"; 2 * kmax% * s
83. 'Locate major dips(−) and humps(+)
84. PRINT #2,
85. PRINT #2, "Location of dips(−) and humps(+) with an adjusted deviation"
86. PRINT #2, "      larger than twice the Waviness Index"
87. PRINT #2, "Length Location Adjusted"
88. Print #2, "2kjj + kj + 2k Deviation Deviation"
89. FOR k% = 1 TO kmax%
90. jmax% = imax% − (2 * k%)
91. a = SQR(Lr/(2 * k% * s))
92. Dm = 2 * WI(L%) / a
93. FOR j% = 1 TO jmax%
94. IF (ABS(D(k%, j%)) > Dm) THEN
95. PRINT #2, USING "##.## #### #####"; 2 * k% * s; j%; j% + k%;
96. PRINT #2, USING "######"; j% + 2 * k%;
97. PRINT #2, USING "######.## ######.##"; D(k%, j%); D(k%, j%) * a
98. END IF
99. NEXT j%, k%, L%
100. SWI = SQR(D2sumS / nsumS%)
101. PRINT #2,
102. PRINT #2, "The Surface Waviness Index, SWI, based on";
103. PRINT #2, USING "## survey lines is ##.# mm"; Lmax%; SWI
104. CLOSE #2
105. END
```

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