Slab-on-Ground Foundation Performance Evaluation

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ABSTRACT

Performance evaluations of foundations, especially those supported on expansive soils, are a complex and divisive subject due to their subjective nature, differing expectations between the owner and the contractor/design engineers, and built-in concrete finishing imperfections. The International Residential Code (IRC) and International Building Code (IBC) require foundations to be designed to "prevent structural damage to the supported structure" and to limit deflection and racking of the supported structure "to that which will not interfere with the usability and serviceability of the structure." The aforementioned building codes do not require foundations to be designed to prevent all cosmetic distress, yet significant cosmetic distress can negatively affect usability and serviceability. While recently published documents by the Post-Tensioning Institute (PTI) and the Texas Section of the American Society of Civil Engineers (TEXASCE) provide guidance to reduce the subjective nature of foundation performance evaluations, they have not eliminated it. When properly implemented, these guidelines provide methodologies that result in a quantifiable, reasonable, and unbiased compromise between the differing expectations of owners and contractors. Unfortunately, in the authors' experience, there are many instances where these guidelines are not followed properly, whether intentionally or unintentionally. This paper will discuss the basis of these guidelines, differences (specifically end point deflection analysis and commonly referred to as cantilever analysis) between the guidelines, and proper implementation of the methodologies (including distress correlation and localized slope versus deflection) which will result in quantifiable, reasonable, and unbiased evaluations.

PURPOSE OF SLAB-ON-GROUND FOUNDATIONS

Foundations that derive their support from near surface soils are commonly referred to as shallow foundations. A common type of shallow foundation is the slab-on-ground (or a slab-on-grade) foundation. The purpose of a slab-on-ground foundation is to:

1. Provide a floor surface for the building; and
2. Transmit loads from the structure to the soil.

By being supported on near surface soils, any volume change of these supporting soils can result in movement of slab-on-ground foundations. As with all shallow foundations, slab-on-ground foundations are not designed to control soil movement. Since they are not infinitely stiff and are movable, they respond to soil movement by either deflecting out-of-plane or tilting as a rigid body. Slab-on-ground foundations have the potential to move throughout their entire life.

The IBC (and by reference the IRC) governs the design of slab-on-ground foundations. Section 1808.6.1 of the 2024 IBC (and previous versions) indicates that slab-on-ground foundations supported on expansive soils *"… shall be designed to resist differential volume changes and to prevent structural damage to the supported structure. Deflection and racking of the supported structure shall be limited to that which will not interfere with the usability and serviceability of the structure."* Slab-on-ground foundations are not required to be designed or constructed to prevent cosmetic distress. Cosmetic distress includes sheetrock cracks, masonry veneer cracks, and floor tile cracks. Unfortunately, foundation movement is not the sole cause of these types of cosmetic distress.

Properly designed and constructed slab-on-ground foundations on expansive soils have the potential for cosmetic distress. It would be cost prohibitive and likely technically impossible to design and construct a slab-on-ground foundation on expansive soils that will not experience some movement and cosmetic distress. Therefore, any evaluation method for the performance of slab-on-ground foundations must allow for some movement and finishing material distress to occur.

Foundation performance evaluations must also consider that no slab-on-ground foundation is ever constructed perfectly planar and level. Some built-in dis-elevation of the slab surface is to be expected. The amount of a built-in dis-elevation is not known for most slab-on-ground foundations, unless an initial elevation survey is performed shortly after finishing the foundation. The Specification for Tolerances for Concrete Construction and Materials published by the American Concrete Institute (ACI 117-10) specifies a slab elevation tolerance at the time of construction of plus or minus ¾ of an inch for a total dis-elevation across the slab of 1.5 inches. Built-in dis-elevation complicates foundation performance evaluations and must be considered. These built-in dis-elevations prevent a well-reasoned foundation performance evaluation method from being based solely upon a current elevation survey.

The fact that all slab-on-ground foundations may move resulting in cosmetic distress puts owners and builders in conflict. The owners want less expensive homes with little to no potential for foundation movement and distress. On the other hand, builders typically want to reduce foundation costs which could increase the potential for foundation movement and distress. In the authors' experience, this conflict can introduce bias, whether intentional or unintentional, into the evaluation process. As referenced above, the IBC states that foundations should resist differential foundation movement. Implied in this statement is that eliminating differential foundation movement is not a Building Code requirement. Therefore, proper, unbiased evaluations should balance the fact that some differential movement and cosmetic distress is expected, with recognizing measured differential movement and related distress that exceed reasonable tolerances. Foundation evaluations must consider both the magnitude of cosmetic distress and the amount of foundation movement based on current elevations and factors indicative of original construction dis-elevation. By doing so, this will strike a balance between the typical expectations of both the owners and builders noted above.

HISTORY OF FOUNDATION PERFORMANCE GUIDELINES

Several sets of guidelines have been published over the years which provide methodologies to evaluate the performance of foundations. These documents are discussed in more detail below.

None of these publications have ‘lines’ that once crossed indicate that the foundation has ‘failed’. They all require judgment of the engineers and a consideration of both the magnitude of movement and distress. Unfortunately, this need for judgment allows an opportunity for biased engineering opinions to control the outcome of foundation performance evaluations.

Circa 1990, the Texas Board of Professional Engineers (“TBPE”, now the Texas Board of Professional Engineers and Land Surveyors, or “TBPELS”) issued a Policy Advisory that addressed residential foundation engineering due to receiving numerous complaints against licensed engineers practicing in this area. Many Texas engineers believed that technical guidelines such as those included in the TBPE’s Policy Advisory should more rightly be created by a technical society such as the American Society of Civil Engineers (“ASCE”). In response to the TBPE’s Policy Advisory, the ASCE Texas Section tasked the Residential Foundations Committee to develop the “Guidelines for the Evaluation and Repair of Residential Foundations” (“TEXASCE Guidelines”) in 1999. After the ASCE Texas Section began work on the TEXASCE Guidelines, the TBPE rescinded the Policy Advisory pending the results of the ASCE Texas Section effort.

The TEXASCE Guidelines were developed and revised by a subcommittee of the Residential Foundations Committee. The development process included review and feedback from a Foundation Oversight Committee, soliciting feedback from other groups of stakeholders and updating and communicating with the TBPE.

The subcommittee volunteers included ASCE Texas Section members from across the state with diverse experience in residential foundations, including geotechnical, design and forensic engineers. While subcommittee members often held strong, but opposing opinions, the subcommittee ultimately voted unanimously to submit the draft of the original version of the TEXASCE Guidelines to the Oversight Committee for review. This review resulted in providing feedback to the subcommittee, eventually leading to recommending adoption to the ASCE Texas Section Board of Direction. This process has continued throughout the consideration of submitted proposed changes and the adoption of subsequent versions of the TEXASCE Guidelines.

The ASCE Texas Section first adopted the TEXASCE Guidelines on October 3, 2002, with an effective date of January 1, 2003. The initial TEXASCE Guidelines included a procedure for adopting changes to them. This process led to the adoption of Version 2 on May 1, 2009 and Version 3 on April 1, 2022. The TEXASCE Guidelines are intended to provide guidance for PEs who evaluate existing residential foundations. Subsequent to publication, many third-party warranty companies throughout the United States incorporated portions of the TEXASCE Guidelines into their respective performance standards.

The Foundation Performance Association (“FPA”), originally formed as the Foundation Performance Committee in 1991, developed FPA-SC-13-0 “Guidelines for the Evaluation of Foundation Movement for Residential and Other Low-Rise Buildings”, which was issued for website publication in 2007. This document was updated to FPA-SC-13-1, which was issued for website publication in 2015. Many of the provisions of FPA-SC-13-1 are similar to those of the TEXASCE Guidelines. The FPA membership consists of individuals involved in the design, construction, inspection, and repair of residential and other light construction foundations, including engineers, designers, builders, repair contractors, inspectors and attorneys, primarily in the Houston, Texas area.

After the publication of the TEXASCE Guidelines and FPA-SC-13, the Post-Tensioning Institute (“PTI”) Slab-on-Ground Committee (DC10) received numerous requests from across the country to establish a nationwide guideline for the evaluation of slab-on-ground foundations. Unlike the Texas Section of ASCE and the FPA, the PTI is composed of members from across the United States and beyond. In 2018, after years of efforts by members of DC10, and review and approval by the PTI Technical Advisory Board, the PTI published DC10.8-18, "Guide for Performance Evaluation of Slab-on-Ground Foundations" ("PTI Guidelines"). The purpose of the PTI Guidelines is to provide guidance to aid in the evaluation of the performance of residential and other similarly constructed low-rise buildings with slab-on-ground foundations. The PTI Guidelines apply to post-tensioned and non-post-tensioned slab-on-ground foundations, as well as to all soil conditions.

The PTI Guidelines methodology is based on visual observations of cosmetic, functional, and structural distress, as well as quantitative analysis of slab deformation in both curvature and tilt modes. Many of the provisions of the PTI Guidelines are similar to those of the TEXASCE Guidelines and FPA-SC-13. The PTI Guidelines also include graphical examples of both proper and improper slab deformation analysis.

Despite the above referenced published guidelines by the ASCE Texas Section, FPA, and PTI, the authors still regularly encounter improper performance evaluation of slab-on-ground foundations by engineers. The authors believe that the improper performance evaluations primarily occur due to 1) a lack of understanding of the collective guidelines by engineers or 2) improper application of the guidelines by some evaluators based upon intentional or unintentional biases.

BASIS OF METHODOLOGIES

There are two primary modes of movement for a slab-on-ground foundation, deflection (also referred to as curvature) and tilt. Deflection is defined as nonlinear movement. Therefore, by definition, a minimum of three points are required to establish deflection. Two points are required to define the reference line, with the third point defining the deviation. Deflection may affect a portion of the foundation (also known as localized deflection) or an entire cross-section of the foundation (also known as overall or global deflection).

There are two primary types of deflection in slab-on-ground foundations, which are differentiated by the location of the deflected point relative to the ends of the reference line. Interior point deflection occurs when the deviation is located between the end points of the reference line. End point deflection, commonly referred to as cantilever deflection, occurs when the deviation is located at one of the end points of the reference line.

Tilt is rigid body movement affecting an entire cross-section of the foundation. Therefore, by definition, a minimum of two points are required to establish tilt of a reference line. Unlike deflection, there is no analogous, localized tilt. The authors have encountered references to localized tilt, which is actually localized slope resulting from deflection.

Exemplar references, developed by the authors, of the primary modes of foundation movement are shown below (refer to Figure 1, Figure 2, and Figure 3). While not shown below, interior point or end point deflection and tilt can occur at the same time.

In a classical single span cantilever beam, the support point is fixed, and the original shape of the beam is known, with the deviation occurring at the free end. Given this situation, only one other point is needed to establish the deviation. However, in a slab-on-ground foundation, there is no fixed end, and the original slab shape is not always known. In order to analyze end point deflection in a slab-on-ground foundation, one must first establish a point of fixity, where relatively linear elevation measurements translate to curvature. Fixity in a slab-on-ground foundation occurs in the back-span area of the foundation which has likely not experienced significant deflection. However, the fixity area of a slab-on-ground may have experienced rigid body tilt movement. Relatively linear recorded elevations and minimal distress in an area of the foundation are used to establish a fixity back-span in a slab-on-ground. The fixity back-span length must be, at a minimum, equal to the length from the point of fixity to the deflected end point.

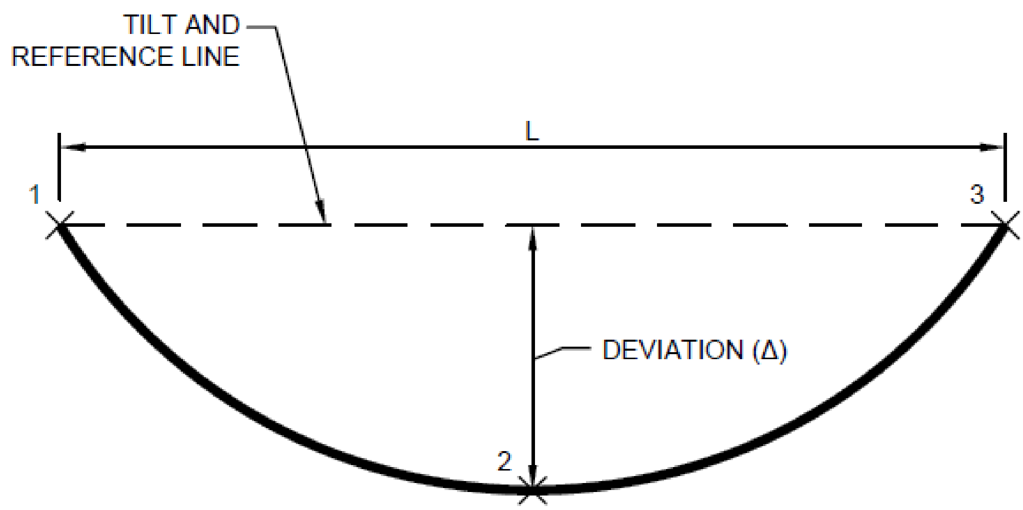

Figure 1. Interior Point Deflection Example

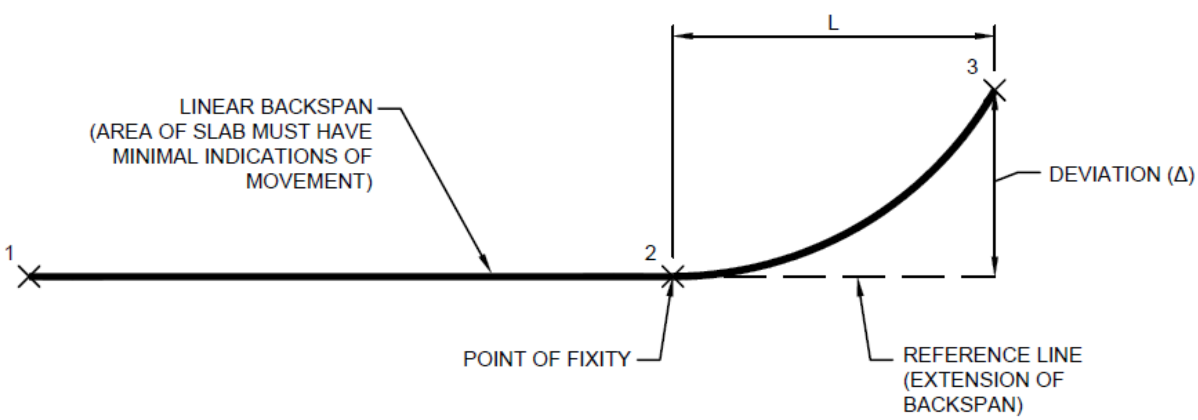

Figure 2. End Point Deflection Example

DEFLECTION RATIOS FOR INTERIOR POINT AND END POINT DEFLECTION ANALYSIS

Historically, model building codes have prescribed maximum allowable deflection ratios for structural members to limit cosmetic distress and to provide for adequate serviceability. Additionally, the commentary to ASCE 7-22 has the following basis for allowable deflections:

***CC.2.1 Vertical Deflections** Excessive vertical deflections and misalignment arise primarily from three sources: (1) gravity loads, such as dead, live, and snow loads; (2) effects of temperature, creep, and differential settlement; and (3) construction tolerances and errors. Such deformations may be visually objectionable; may cause separation, cracking, or leakage of exterior cladding, doors, windows, and seals; and may cause damage to interior components and finishes. Appropriate limiting values of deformation depend on the type of structure, detailing, and intended use (Galambos and Ellingwood 1986). Historically, common deflection limits for horizontal members have been l/360 of the span for floors subjected to full nominal live load and l/240 of the span for roof members. Deflections of about l/300 of the span (for cantilevers, l/150 of the length) are visible and may lead to general architectural damage or cladding leakage. Deflections greater than l/200 of the span may impair operation of movable components such as doors, windows, and sliding partitions.*

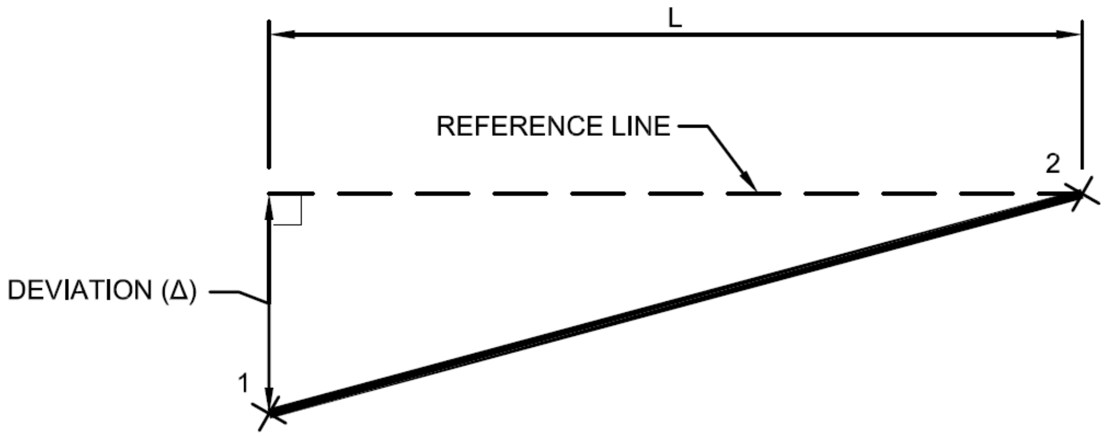

Figure 3. Tilt Example

However, the model building codes do not provide allowable deflection ratios for slab-on-ground foundations. Whether the supporting member is elevated or a slab-on-ground foundation, the goal is the same, to limit cosmetic distress and to provide for adequate serviceability. To this end, Section 5.5 of the TEXASCE Guidelines provide the following deflection limit guidance:

Building codes specify that structural members shall be designed to have adequate stiffness to limit deflections. The International Code Council International Residential Code ™ for One- and Two-Family Dwellings (IRC) specify a maximum allowable live load deflection of any structural floor member of L/360, where L is the unsupported length of the member. This requirement typically is sufficient, in that in-service deflection will not result in excessive damage to cosmetic finishes, racking of door frames, or vibration. This deflection criterion may be appropriate for the analogous in-service deflection of a residential foundation, where for simplicity the entire foundation is considered as though it were a single structural member and differential soil movement is considered analogous to live load.

The FPA and PTI recommend the same allowable deflection or curvature ratio of L/360. It is the authors' belief and understanding that this allowable deflection or curvature ratio of L/360 is applicable to interior point deflection analysis. Interior point deflection ratio, by definition, is a deviation divided by the span between two selected points on the slab surface. An end point deflection, however, is a deviation divided by half of the deflected length. The use of a 2L denominator in deflection ratio calculations for end point deflection analysis is consistent with the deflection limits history discussion in the commentary to ASCE 7-22 (refer to quote CC.2.1 on previous page), the 2024 International Residential Code (IRC 2024) (refer to Figure 4), the 2024 International Building Code (IBC 2024) (refer to Figure 5) and the TEXASCE Guidelines (refer to Figure 6).

STRUCTURAL MEMBER	ALLOWABLE DEFLECTION
Rafters having slopes greater than 3:12 with finished ceiling not attached to rafters	L/180
Interior walls and partitions	H/180
Floors	L/360
Ceilings with brittle finishes (including plaster and stucco)	L/360
Ceilings with flexible finishes (including gypsum board)	L/240
All other structural members excluding guards and handrails	L/240
Exterior walls—wind loads[a] with plaster or stucco finish	H/360
Exterior walls—wind loads[a] with other brittle finishes	H/240
Exterior walls—wind loads[a] with flexible finishes	H/120[d]
Lintels supporting masonry veneer walls[e]	L/600

Note: *L* = span length, *H* = span height.

a. For the purpose of the determining deflection limits herein, the wind load shall be permitted to be taken as 0.7 times the component and cladding (ASD) loads obtained from Table R301.2.1(1).
b. For cantilever members, *L* shall be taken as twice the length of the cantilever.
c. For aluminum structural members or panels used in roofs or walls of sunroom *additions* or patio covers, not supporting edge of glass or sandwich panels, the total load deflection shall not exceed *L*/60. For continuous aluminum structural members supporting edge of glass, the total load deflection shall not exceed *L*/175 for each glass lite or *L*/60 for the entire length of the member, whichever is more stringent. For sandwich panels used in roofs or walls of sunroom *additions* or patio covers, the total load deflection shall not exceed *L*/120.
d. Deflection for exterior walls with interior gypsum board finish shall be limited to an allowable deflection of *H*/180.
e. Refer to Section R703.8.2. The *dead load* of supported materials shall be included when calculating the deflection of these members.

Figure 4. Allowable Deflection of Structural Members, Table R301.7 from the IRC 2024

Therefore, and as referenced above, the accepted practice for calculating the limits of a cantilever deflection, or end point deflection, is to double the distance between the end point and the point of fixity. Allowable deflection ratios for interior point deflection conditions are sometimes mistakenly conflated with those of end point, or cantilever, deflection conditions. As established and referenced above, doing so will result in improperly decreasing the allowable deflection ratios by as much as a factor of 1/2, which is inaccurate and erroneous.

It should be noted that the provisions of various versions of ASCE-7, the IRC and the IBC referenced above have not changed significantly over many years. While the age, condition and use of the structure should be considered when designing remedial measures, evaluation methodologies need not consider these issues for slabs-on-ground foundations.

Do the TEXASCE Guidelines conflict with PTI Guidelines?

Some engineers have opined that Version 3 of the TEXASCE Guidelines conflicts with the PTI Guidelines on the topic of end point deflection, or cantilevered deflection, analysis. Version 3 of the TEXASCE Guidelines (refer to Figure 6) provides the following direction with regard to end point deflection analysis.

The PTI Guidelines provide the following guidance (refer to Figure 7) with regard to improper deflection analysis.

CONSTRUCTION	*L* or L_r	*S* [j] or *W* [f]	*D* + *L* [d, g]
Roof members:[e]			
Supporting plaster or stucco ceiling	*l*/360	*l*/360	*l*/240
Supporting nonplaster ceiling	*l*/240	*l*/240	*l*/180
Not supporting ceiling	*l*/180	*l*/180	*l*/120
Floor members	*l*/360	—	*l*/240
Exterior walls:			
With plaster or stucco finishes	—	*l*/360	—
With other brittle finishes	—	*l*/240	—
With flexible finishes	—	*l*/120	—
Interior partitions:[b]			
With plaster or stucco finishes	*l*/360	—	—
With other brittle finishes	*l*/240	—	—
With flexible finishes	*l*/120	—	—
Farm buildings	—	—	*l*/180
Greenhouses	—	—	*l*/120

For SI: 1 foot = 304.8 mm.

a. For structural roofing and siding made of formed metal sheets, the total load deflection shall not exceed *l*/60. For secondary roof structural members supporting formed metal roofing, the live load deflection shall not exceed *l*/150. For secondary wall members supporting formed metal siding, the design wind load deflection shall not exceed *l*/90. For roofs, this exception only applies when the metal sheets have no roof covering.

b. Flexible, folding and portable partitions are not governed by the provisions of this section. The deflection criterion for interior partitions is based on the horizontal load defined in Section 1607.16.

c. See Section 2403 for glass supports.

d. The deflection limit for the *D* + (*L* or L_r) load combination only applies to the deflection due to the creep component of long-term dead load deflection plus the short-term live load deflection. For lumber, structural glued laminated timber, prefabricated wood I-joists and structural composite lumber members that are dry at time of installation and used under dry conditions in accordance with the ANSI/AWC NDS, the creep component of the long-term deflection shall be permitted to be estimated as the immediate dead load deflection resulting from 0.5*D*. For lumber and glued laminated timber members installed or used at all other moisture conditions or cross laminated timber and wood structural panels that are dry at time of installation and used under dry conditions in accordance with the ANSI/AWC NDS, the creep component of the long-term deflection is permitted to be estimated as the immediate dead load deflection resulting from *D*. The value of 0.5*D* shall not be used in combination with ANSI/AWC NDS provisions for long-term loading.

e. The preceding deflections do not ensure against ponding. Roofs that do not have sufficient slope or camber to ensure adequate drainage shall be investigated for ponding. See Chapter 8 of ASCE 7.

f. The wind load shall be permitted to be taken as 0.42 times the "component and cladding" loads or directly calculated using the 10-year mean return interval basic wind speed, *V*, for the purpose of determining deflection limits in Table 1604.3. Where framing members support glass, the deflection limit therein shall not exceed that specified in Section 1604.3.7

g. For steel structural members, the deflection due to creep component of long-term dead load shall be permitted to be taken as zero.

h. For aluminum structural members or aluminum panels used in skylights and sloped glazing framing, roofs or walls of sunroom *additions* or patio covers not supporting edge of glass or aluminum sandwich panels, the total load deflection shall not exceed *l*/60. For continuous aluminum structural members supporting edge of glass, the total load deflection shall not exceed *l*/175 for each glass lite or *l*/60 for the entire length of the member, whichever is more stringent. For aluminum sandwich panels used in roofs or walls of sunroom *additions* or patio covers, the total load deflection shall not exceed *l*/120.

i. *l* = Length of the member between supports. For cantilever members, *l* shall be taken as twice the length of the cantilever.

j. The snow load shall be permitted to be taken as 0.7 times the design snow load determined in accordance with Section 1608.1 for the purpose of determining deflection limits in Table 1604.3.

Figure 5. Deflection Limits, Table 1604.3 from the IBC 2024

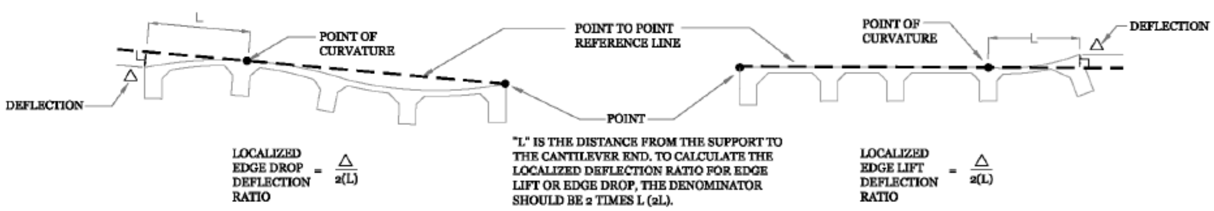

Figure 6. Deflection Ratio Example, Fig. 2 from the TEXASCE Guidelines

In the figures above, both the TEXASCE Guidelines' example and the PTI Guidelines' example have what may be considered end point deflection. However, as discussed above, to establish the condition in which end point deflection analysis is appropriate, a fixity back-span must be established. As discussed previously, relatively linear recorded elevations and minimal distress in an area of the foundation are used to establish a fixity back-span in a slab-on-ground foundation. As can be seen in the figures above, the TEXASCE Guidelines' example has clear fixity back-span areas with relatively linear elevations, while the PTI Guidelines' example does not have a clear fixity back-span. Therefore, the TEXASCE Guidelines' example meets the geometric requirements of end point deflection analysis, while the PTI Guidelines' does not. This is the exact reason the PTI Guidelines includes this as a 'wrong' example, because in this example, a fixity back-span is not present. Therefore, it is clear that not only do the TEXASCE Guidelines and PTI Guidelines not conflict, but they also are in agreement with the fixity back-span requirement discussed herein.

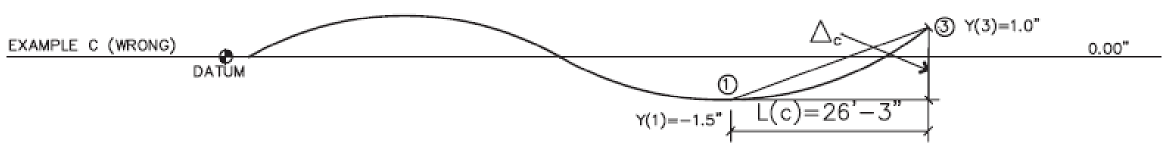

Figure 7. Calculation Example, Fig. 6.3.2-1 from the PTI Guidelines

CONCLUSIONS

Based on the above well established and widely accepted publications, it is clear that:

1. Built-in dis-elevation should be considered in foundation evaluation methodology.
2. Interior deflection analysis must include three points, one at each end of the area being analyzed, and one at the point on the slab that deviates from the line connecting the two end points.
3. End point deflection analysis requires the establishment of a point of fixity.
4. Relatively linear recorded elevations and minimal distress in an area of the foundation are used to establish a fixity back-span in a slab-on-ground foundation.
5. End point deflection analysis requires using double the distance from the point of fixity to the deviated end in the denominator of the deflection ratio.

In the authors' opinions, the foundation performance methodologies included in the TEXASCE Guidelines, FPA-SC-13-1 and the PTI Guidelines discussed in this paper, when implemented correctly and without bias, will result in conclusions that balance the needs of homeowners and builders. Hopefully this paper will assist engineers to better understand and correctly implement the guidelines without allowing their biases, intentional or unintentional, to affect their analysis.

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