Using Slab-on-Ground Elevation Measurements in Residential Foundation Engineering Performance Evaluations

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Abstract: This paper critically examines the use of foundation elevation measurements in the engineering evaluation of slab-on-ground foundation performance. Slab-on-ground foundations that are supported by expansive or active soils can deflect enough to cause the foundation (including the foundation surface) to become perceptibly distorted. Since the levelness of the foundation can be "measured" by taking elevations of the slab surface, it is tempting to use elevation measurements in the evaluation of the performance of a slab-on-ground foundation. The use of slab surface elevation measurements is examined from the perspectives of slab deformation geometry, accepted construction practices, building code requirements and design requirements. Also included are critical examinations of various published protocols for using elevation measurements in foundation performance evaluations, especially for forensic evaluations and evaluations for real estate transactions.

Introduction

The use of foundation surface elevation measurements in evaluating the performance of slab-on-ground foundations has its origin in studies of existing commercial and industrial buildings to develop an empirical, statistical basis for settlement criteria to use in foundation design so that damage to building finishes due to differential foundation settlement could be avoided.[2] Settlement criteria based on the results of these surface elevation studies soon were published in foundation engineering design textbooks and handbooks. At some point, forensic engineers began to use results of published elevation studies in forensic evaluations of existing residential slab-on-ground foundations.[3] In the last few years, the use of foundation surface elevation surveys has bled into the home buyer foundation inspection market. The use of elevation surveys in forensic and home buyer foundation performance evaluations has been addressed in a number of guidelines published in the last several years by the Texas Board of Professional Engineers, the Texas Section of the ASCE and the Houston-based Foundation Performance Association. Also, the Texas Real Estate Commission requires real estate inspectors to address "floor slopes" in the foundation section of home inspection reports; this has encouraged the use of elevation measurements by Licensed Real Estate Inspectors.

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[2] Skempton, A.W. and McDonald, D.H. (1956). "The Allowable Settlement of Buildings", *Proceedings of the Institute of Civil Engineers*, 5(3) 727-768.

[3] Day, R.W. (1990). "Differential Movement of Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 4(4), 236-241.

Regardless of the purpose of a foundation performance evaluation, if an elevation survey is used, it normally is the only quantitative portion of the evaluation.[4] Consequently, it often plays a dominant role in the evaluation of the performance of the foundation.

To some extent, this paper is a report on the current state of practice of the use of elevation surveys in assessing the performance of a slab-on-ground foundation. Since the paper critically examines the use of elevation surveys, there is an emphasis on the limitations of this approach. The paper includes a review of the historical and empirical basis for an elevation survey or levelness approach to foundation performance evaluation. Published criticisms of the use of elevation surveys are also reviewed. Geometry of deformation issues, construction practices and building code requirements relative to foundation surface levelness are discussed. The paper critically reviews several published foundation performance evaluation protocols that rely on elevation survey data. Conclusions are presented concerning the adequacy of published foundation surface elevation survey data, the adequacy of published elevation measurement and analysis methodologies, the extent to which elevation surveys are objective, and the reliability of using elevation surveys in forensic studies and real estate transactions.

Some Historical Perspective

Slab surface geometry is a function of the as-constructed surface geometry and the load-induced post-construction distortion of the slab deflection surface[5] including both the initial settlement of the foundation and distortion due to expansive soil movement. When using slab surface elevation measurements to evaluate the performance of a slab-on-ground foundation, it is important to be able to separate the changes in surface geometry due to foundation movement from other factors that influence foundation surface geometry. As-constructed foundation surface irregularities can easily be accommodated in the framing and finishing of the house. It is only the changes in the surface geometry that result from foundation movement after the construction of the house that causes damage to the house such as door frame distortion, drywall cracking and brick veneer cracking. Thus, the technical literature of interest addresses the as-constructed surface levelness of slab-on-ground foundations and the relationship between measures of foundation surface levelness and damage to the supported structure. Papers that address these issues are discussed below.

Papers Addressing As-Built Slab Levelness

- Koenig (1991)[6] reported data from 54 residential slabs in the San Antonio, Texas area. For each slab, a water manometer was used to take elevations at 9 locations.

[4] It is possible to make an quantitative evaluation of the performance of a slab-on-ground foundation without using foundation surface elevation data. See Gray, R. Michael (2002), “A Structural Analysis Approach to Residential Foundation Performance Evaluation”, Proceedings of the Texas Section ASCE, Waco, Texas

[5] In this paper, I use the term “deflection surface” to mean the middle surface in elastic plate theory; the deflection surface or middle surface plays an analogous role in the theory of elastic plates that the concept of deflection curve or elastic curve plays in the theory of elastic beams.

[6] Koenig, A.S. (1991) “Relative Elevation Data Analysis on Newly Constructed Residential Foundations”, Expansive Clay Research Institute, San Antonio, Texas

The locations used were the center of the slab and eight points around the perimeter. The measurements showed a maximum slab elevation difference that ranged from 1/8 inch to 1 inch with an average maximum elevation difference of .54 inches.

- Marsh and Thoney (1999)[7] published data from a small study that included 6 newly placed slab-on-ground foundations in southern California. The average maximum elevation difference across the slabs was .75 inches. The maximum elevation differences ranged from .6 to 1 inch.

- Bondy (2000)[8] reported on a study involving 4 one-day-old slab-on-ground foundations. The average maximum elevation difference across the slabs was .7 inches; the maximum elevation difference across the slabs ranged from .5 to .9 inches.

- Walsh, Bashford, and Mason (2000)[9] reported an investigation of residential floor levelness for newly placed foundations in the Phoenix, Arizona area. The study included measurements of 89 newly placed slab-on-ground foundations. The average maximum deviation from level at the time of concrete placement was .53 inches with a maximum observed value of 1.18 inches. The average maximum slope was 1/334; the maximum slope reported in the study was 1/101.

Papers Relating Slab Levelness to Damage in the Supported Structure

- Skempton and MacDonald (1956)[10] reported on an extensive study of numerous buildings of different construction over an extended period of time. The purpose of the study was to arrive at an estimate of the settlement a building could experience before damage was likely to occur. The study focused on buildings with true structural foundations such as piers, not non-structural slab-on-ground foundations typically used on home construction. In spite of this, the results of the Skempton and MacDonald study are of interest since it could be argued that interior partitions in a pier-supported building would be subjected to the same distress in walls supported by a slab-on-ground foundation. Also, the results of the Skempton and MacDonald paper are frequently cited in the literature concerning threshold criteria for cosmetic damage in wood frame houses supported on slab-on-ground foundations.

  The most commonly selected damage threshold criterion from the Skempton and MacDonald paper is an "angular distortion" of 1/300; it was argued that angular

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[7] Marsh, E.T., and Thoeny, S.A., (1999). "Damage and Distortion Criteria for Residential Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 13(3), 121-127.
[8] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.
[9] Walsh, K.D, Bashford, H.H., and Mason, B.C.A., (2001) "State of Practice of Residential Floor Slab Flatness", *Journal of Performance of Constructed Facilities*, 15(4), 127-134.
[10] Skempton, A.W. and McDonald, D.H. (1956). "The Allowable Settlement of Buildings", *Proceedings of the Institute of Civil Engineers*, 5(3) 727-768.

distortion in excess of 1/300 would result in visible cracking in wall panels of framed structures. Skempton and MacDonald also reported a maximum differential settlement criterion 1.75 inches for foundations on clay soils.

- Day (1990)[11] published "angular distortion" and maximum elevation difference data from a study of 34 residences all of which were in the San Diego, California area. The measured "angular distortion" and maximum elevation differences were related to observed cosmetic and structural distress. Day concluded that cosmetic damage could result when the maximum elevation difference reached 1.15 inches or the "angular distortion" reached 1/300; structural damage would result when the elevation difference reached 3.5 inches or the "angular distortion" reached 1/100.

- Marsh and Thoney (1999)[12] published data from a review of 401 homes over a 12 year period. Of the 401 homes, 112 were available to assess the levelness of the slab surface. Marsh and Thoney reported measures of slab levelness in terms of maximum elevation difference and maximum "angular distortion". These measurements were related to the observed damage in the houses. The average maximum elevation difference damage threshold was reported to be 1 to 1.10 inches depending on the soil conditions. The maximum "angular distortion" damage threshold ranged from 1/480 to 1/360 depending on the soil conditions.

The table below summarizes the damage threshold criteria reported in the cited literature.

Reported Damage Threshold Criteria		
Source	Maximum Differential Elevation	Maximum "Angular Distortion"
Skempton and McDonald (1956)	cosmetic damage - 1.75 inches	cosmetic damage - 1/300
Day (1990)	cosmetic damage - 1.25 inches structural damage - 3.5 inches	cosmetic damage - 1/300 structural damage - 1/100
Marsh and Thoney (1999)	cosmetic damage - 1 to 1.10 inches, depending on soil conditions	cosmetic damage - 1/480 to 1/360, depending on soil conditions

[11] Day, R.W. (1990). "Differential Movement of Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 4(4), 236-241.
[12] Marsh, E.T., and Thoeny, S.A., (1999). "Damage and Distortion Criteria for Residential Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 13(3), 121-127.

There is one point concerning the concept of "angular distortion" that is not apparent from the table above. It is not clear that the reported "angular distortion" criteria are based on the same definition of "angular distortion". In at least one study, that by Skempton and McDonald, it appears to be used to mean a change in slope over time. In others it is used to mean a calculated slope based one set of elevation measurements.

Published Criticisms of the Elevation Survey Approach

There have been criticisms published in the literature starting with the publication of the Skempton and McDonald paper and continuing today. Various published criticisms of the use of foundation surface elevation measurements for evaluating foundation performance are discussed below.

Karl Terzaghi (1974)[13]

When the Skempton and McDonald paper was published, a number of comments on the paper were also included. One interesting comment came from Karl Terzaghi, then professor of Civil Engineering at Harvard University. He stated that the conclusions regarding the relation between "angular distortion" and maximum settlement were "too sweeping to be accepted in their present form." Terzaghi remarked that the number of settlement records was too small to justify a statistical approach to the relation between "angular distortion" and maximum settlement. He predicted the results of the paper would find its way into engineering texts and handbooks on foundation design. In his judgment, one unintended consequence of the statistical/empirical approach would be a failure to stimulate new ideas and observation in the field of clay foundations.

F. H. Chen (1988)[14]

Chen is very critical of the common use of a single elevation survey as a basis for making judgments concerning the extent and direction of foundation movement. He considers the common use of elevation surveys to be unprofessional, misleading and prone to error. Chen argues that a single elevation survey should never be used as a clue to foundation movement and that any elevation survey is of little use if it cannot be compared to a previous survey of the foundation surface. Even when two surveys are available, Chen argues that any conclusions that may be drawn are doubtful unless the elevation numbers can be compared to a fixed and stable benchmark such as a reinforced concrete bell-bottom pier founded below the active soil zone.

[13] Terzaghi, Karl, "Discussion", Proceedings of the Conference on Settlement of Structures, Cambridge, 1974,

[14] Chen, F.H., 1988, *Foundations on Expansive Soils*, 2nd ed. (New York: Elsevier Science Publishers)

Robert Brown, P.E. (1997)[15]

The late Robert Brown, P.E. published numerous books addressing the evaluation and repair of slab-on-ground foundations. In his publications, Mr. Brown specifically addresses the evaluation of foundation performance for owners and buyers of residential real estate including the case for and against using slab-on-ground foundation surface elevations. Brown's position is that elevation measurements can be both very useful and misleading. Larger than normal differences in elevation between points may be due to post-construction foundation distortion or may be due to original construction. On the other hand, it is possible that a "level" foundation was constructed out-of-level and has distorted to a "level" condition. In both cases the elevation measurements can be misleading and can result in a faulty diagnosis. Brown summarizes his position as follows: "Do not rely too heavily on grade elevations when analyzing foundation problems. If you feel compelled to use this type of approach, at least use a series of elevations taken some time apart. These can be used to estimate movement which occurs over time between the readings."[16]

Ken Bondy (1995)[17]

Bondy states that the most reliable method to quantitatively estimate foundation distortion is to compare two foundation surface surveys, one made soon after the placement of the slab-on-ground foundation and another made at a later time. The use of a single survey does not allow a positive diagnosis of excessive foundation movement unless the as-constructed out-of-levelness is accounted for in a rational manner.

Walsh, Bashford and Mason (2001)[18]

This paper is based on the largest study yet published concerning the levelness of slab-on-ground foundations. The study was specifically intended to test the idea that reliable judgments concerning the extent of foundation movement, measured in terms of "angular distortion" and maximum elevation difference, could be made without accounting for the as-constructed out-of-levelness of the foundation surface. Walsh, Bashford and Mason conclude with the following:

> "These results point out the potential inaccuracies that may arise in forensic engineering studies that rely heavily on the maximum elevation difference or the maximum angular rotation of the residential floor slab. If the forensic engineer uses such measurements to make conclusions about the likelihood of any damage to the structure, they must consider the possibility (indeed the

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[15] Brown, Robert Wade, 1997, *Foundation Behavior and Repair – Residential and Light Constructiong*, 3rd ed. (New York: McGraw Hill)
[16] Brown, Robert Wade, 1997, *Foundation Behavior and Repair – Residential and Light Construction*, 3rd ed. (New York: McGraw Hill)
[17] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.
[18] Walsh, K.D, Bashford, H.H., and Mason, B.C.A., (2001) "State of Practice of Residential Floor Slab Flatness", *Journal of Performance of Constructed Facilities*, 15(4), 127-134.

likelihood) that the floor slab was not level at the time of placement."[19]

R. Michael Gray, P.E. (2002)[20]

Gray has argued that the use of damage and foundation repair criteria such as surface slope and maximum elevation difference are overly simple parameters that fail to take into account the building height and length and type of construction all of which clearly have material impacts on the response of the supported structure to foundation movement. Gray argues that foundation performance should be evaluated in terms of a broader array of damage criteria. Foundation repair threshold criteria should take into account the engineering characteristics of the building materials, the building geometry and the capabilities of foundation repair contractors. It should also be presented in terms that a lay client can understand such as cracks in drywall and brick veneer, sticking doors and rotation of the fireplace chimney away from the house.

Walsh and Miguel (2003)[21]

This paper was not primarily intended to criticize foundation surface elevation surveys, but some of the conclusions presented in this paper constitute a severe critique of elevation surveys as they commonly are used in engineering practice. Walsh and Miguel observe it is widely accepted that the maximum elevation difference and maximum "angular distortion" is sensitive to the points used for taking measurements. For instance, the only way to be sure that the maximum elevation difference is identified is to make a measurement at every point on the slab surface. This is not mathematically possible to do; we have no choice but to estimate the maximum elevation difference using a discrete number of points. Any sample of points selected for measurement and analysis is a sample of the population of possible points that could be selected. It would be expected that the maximum elevation difference in the sample of measured points will be larger as the number of points measured increases. Thus, the conclusions reached are likely to be affected by the number of points selected for measurement and analysis. The Walsh and Miguel paper addresses the effects of sample size, the arrangement of the points selected for measurement and the analysis method used to arrive at an analytical result.

The authors made careful foundation surface elevation measurements using a 1 foot grid for three new slab-on-ground foundations in the Phoenix, Arizona area. The floor elevation data were analyzed to evaluate how many elevation measurements were required to arrive at a reliable and repeatable estimate of the maximum elevation difference and maximum slope. Walsh and Miguel estimate the required sample of

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[19] Walsh, K.D, Bashford, H.H., and Mason, B.C.A., (2001) "State of Practice of Residential Floor Slab Flatness", *Journal of Performance of Constructed Facilities*, 15(4), 127-134.
[20] Gray, R. Michael (2002), "A Structural Analysis Approach to Residential Foundation Performance Evaluation", Proceedings of the Texas Section ASCE, Waco, Texas
[21] Walsh, K.D. and Miguel, George P., (2003) "Method for Forensic Analysis of Residential Floor-Elevation Data", *Journal of Performance of Constructed Facilities*, 17(3), 110-117.

elevations for a typical size residential slab at around 500 points. This is far in excess of normal practice where 15 to 20 points is common. If the analysis provided by Walsh and Miguel is correct, then it must be concluded that residential foundation elevation surveys as they are normally done are not reliable or repeatable.[22]

Walsh and Miguel point out that an important conclusion of their analysis is that when a foundation survey is used as a basis for a foundation performance evaluation, the conclusions are dependent on 1)the assumptions made about the initial as-constructed foundation surface geometry and 2)the number of elevation measurements made and 3)the arrangement of the measured points. Using a small number of measurements, as is almost always done, results in a situation in which different investigators can reach significantly different conclusions merely due to the different points selected for measurement.

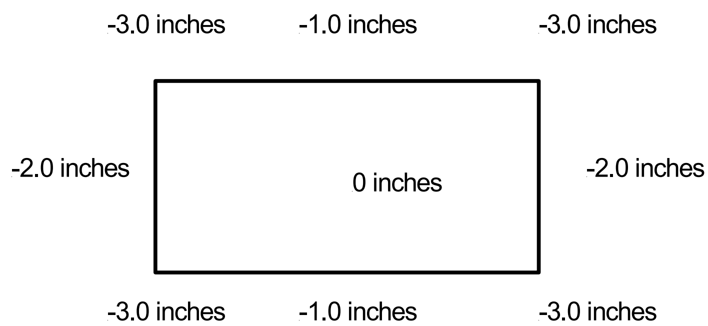
Geometry of Foundation Deformation Issues

It is interesting to evaluate the reasonableness of the two popular levelness approaches (angular distortion and maximum elevation difference) in terms of the geometry of foundation deformation. One reason the use of foundation surface geometry is an attractive concept to some engineers is that, if the as-constructed slab surface is flat and level, then the surface of the distorted foundation is a mirror-image of the deflection surface. While the assumption of an initially level slab surface may not always be realistic or justified, understanding the relation between foundation deformation and the shape of the deflection surface is important.

The most realistic model for a slab-on-ground foundation for purposes of calculating the maximum elevation difference and the maximum angular distortion is an elastic plate.[23] Slab-on-ground foundations can and do exhibit two-way bending. An elastic plate model can accommodate two-way bending; a beam model cannot be used to evaluate the two-way bending common in slab-on-ground foundations.

To illustrate the use of the plate model, assume a 30 foot by 60 foot foundation as shown in the figure below distorted in a center lift mode with the deflection ratio in both directions equal to 1/360. This results in a 2 inch deflection lengthwise and 1 inch deflection across the width. The deflection at the corners of the slab is a superposition of the deflection in each direction, or 3 inches. Thus, the elevation difference between the center of the deflection surface and the corners of the deflection surface is 3 inches.

[22] By "repeatable" Walsh and Miguel appear to mean that the measurement and analysis procedure is capable of being repeated by other investigators who select different points for measurement.
[23] A grid model could also be used.



plan view of a 30-foot by 60-foot slab-on-ground
foundation distorted in both directions 1/360

To calculate the maximum slope of the deflection surface, the plate is assumed to be in pure bending resulting in a plate that is deformed so that the curvature is a segment of a circle in the long and short directions. At each corner, the slope in the long and short direction is .0111. The slope in each direction is a vector and can be added using vector addition to give the maximum slope.[24] The maximum slope is .0157. Thus, the maximum slope of the deflection surface of a plate subjected to two-way bending is over 41% higher than the maximum slope of a one-way beam deflected to the same deflection ratio.

The aspect of slab-on-ground foundation distortion that causes damage to houses is bending or curvature of the foundation. Interestingly, the geometry of deformation of an elastic plate does not reveal a relation between the curvature of the foundation and the maximum elevation difference of the deflection surface. Also, the curvature of the deflection surface is related to the rate of change of the deflection surface slope, but not to the slope itself.

Summary of Geometry of Deformation Issues

Using an elastic plate model to understand the geometry of deformation of a slab-on-ground foundation clearly shows that the maximum slope and maximum elevation difference of the deflection surface are a function of the deflection ratio. The maximum elevation difference is also a function of the geometry of the foundation plan. This fact alone should make us suspicious of any proposed repair criterion based on a maximum elevation difference that is not related to the foundation geometry. The curvature of the deflection surface of an elastic plate is not mathematically related to the maximum elevation difference or to the maximum "angular distortion."

Construction Practices

In this paper, we are considering the slab surface geometry to be a function of distortion due to expansive soil movement and the surface geometry of the original construction.

[24] Timoshenko, S. and Woinowsky-Kreiger, S, 1959, *Theory of Plates and Shells*, 2rd ed. (New York: McGraw Hill), pages 33 - 36.

The geometry of the as-constructed slab-on-ground foundation surface is clearly related to the construction practices used in the placement of the slab. This section looks at accepted slab-on-ground foundation construction practices as they relate to the geometry of the as-constructed slab surface.

Guide for Concrete Floor and Slab Construction *(ACI Committee 302) and* ***Standard Specifications for Tolerances for Concrete Construction and Materials*** *(ACI Committee 117).*

ACI 302 and ACI 117 are the two most authoritative published documents concerning the construction of slab-on-ground foundations. ACI 302 addresses the construction of concrete floor and slab construction including elevated slabs and ground-supported slabs. Section 8.15 specifically addresses flatness and levelness construction tolerances. Construction tolerances for different floors are provided in ACI 117. The following are the most germane points made in these two documents.

ACI 302 recommends that flatness and levelness be described by Face Floor Profile Numbers, usually referred to as the F-number system. This system uses a two-number system in which one number, the "Flatness F-number (F_F), controls the local surface bumpiness by limiting the magnitude of successive 1 foot slope changes when measured along sample measurement lines in accordance with ASTM E 1155." The second number, the Levelness F-number (F_L), "controls local conformance to design grade over distances of 10 feet when measured along sample measurement lines in accordance with ASTM E 1155".

In residential construction, almost all slab-on-ground foundations are conventional wet-screeded and bull-floated finished slab construction. Screeding is normally done with a piece of scrap lumber that appears straight to the eye. Since the screed piece is typically shorter than one or more of the slab plan dimensions, some portions of the slab surface may be screeded by eye only. Plumbing and other slab penetrations obstruct the screeding process and make it more difficult to level the slab surface. The forms are frequently walked on after being leveled, possibly making them unlevel during the placement and finishing process. Bullfloating is done using hand or power equipment. In this type of construction, the minimum acceptable (local worst case) F_L value is 10; the minimum average F_L value is 13.[25]

Face numbers can be used to estimate the as-constructed maximum elevation difference between any two points on the slab surface in the following manner. The specified Face number is calculated using the following equation:

$$FaceNumber = 12.5/(3\sigma + Z)$$

where σ equals the standard deviation of the differences in elevation between adjacent points 10 feet apart and Z equals the average difference in elevation between adjacent points 10 feet apart. First, assume that the average elevation difference between points

[25] ***Standard Tolerances for Concrete Construction and Materials*** (ACI 117-90), American Concrete Institute, 1990, Detroit, Michigan, page 117-8.

spaced 10 feet apart is zero[26] and that the average levelness Face number is 13. This gives 3σ as .962 inches. Using the Empirical Rule to estimate the largest elevation difference, we can say that there is a 99.7 % chance that all points on the elevation surface will lie somewhere between ±3σ or ±.962 inches; this gives a maximum as-constructed elevation difference of 6σ or 1.924 inches. Thus, there is a 99.7% chance that the maximum surface elevation difference will not exceed 1.924 inches.

Another way to use Face numbers to estimate the largest as-constructed elevation difference between any two points on the foundation surface is as follows. First, assume the slab surface has an elevation difference of 1.25 inches between two points 10 feet apart; this complies with the minimum acceptable local levelness (worst case) where F_L = 10. Also, assume the rest of the slab surface has elevations that comply the overall levelness Face number of F_L = 13 and that the average difference in elevation between points 10 feet apart is Z = 0 inches. We can calculate 3σ to be .962 inches. Thus, the maximum as-constructed surface elevation difference for a slab that meets the local (worst case) levelness construction tolerance could be as much as 1.25 inches plus .962 inches or 2.12 inches.

There is an important caution concerning the use of F-numbers. In residential construction there is no control on the levelness of the foundation surface. It should also be noted that F-number levelness tolerances are achievable by competent, knowledgeable concrete crews under "standard" job conditions.[27] After a foundation has been placed and finished, it is impossible for an inspector or engineer to verify the quality of the crew or the conditions that existed during the construction of the foundation. When using F-numbers in the performance evaluation of a slab-on-ground foundation, the engineer should always be mindful that the foundation may have been placed and finished so that it fails to meet the F-number construction tolerances.

Summary of Construction Practices

There are two essential points that should be clear from the foregoing discussion of construction practices.

First, the preferred way to measure the levelness of the surface of a slab-on-ground foundation is to use Face numbers. The Face number approach is more rational than other approaches because it is based on empirical studies that relate foundation levelness to actual construction and concrete finishing techniques. Since virtually all residential slab-on-ground foundations are wet-screeded and bull-floated, levelness criteria provided by the F-number system can be used that are realistic.

Second, the Face number approach is a statistical approach to foundation surface levelness measurement and cannot be used directly to provide a maximum slope or a

[26] This is a reasonable assumption since the assumption that the elevation of the foundation surface is zero means that the foundation surface slopes up as much as it slopes down. The average elevation typically is zero or close to zero.

[27] "Guide for Concrete Floor and Slab Construction", ACI 302.1R-96, American Concrete Institute , Farmington Hills, Michigan

maximum likely elevation difference. For a wet-screeded slab-on-ground foundation, the local (worst case) F_L of 10 implies a maximum as-constructed surface slope of 1.25/120, or .010. The average and worst case Face numbers can be manipulated to make an argument that the surface of a wet-screeded slab-on-ground foundation could have a maximum elevation difference of around 2 inches.

Building Code Requirements

It is my experience that some advocates of the use of foundation levelness models will justify their approach on the basis of a belief that the "code" specifies a maximum allowable deflection; alternatively, it is sometimes argued that a maximum allowable slope can be derived based on a code-allowable maximum deflection. The "code" referred to almost always is ACI 318, specifically the deflection criteria given in Table 9.5(b).

In this section, I state, briefly, what ACI 318 actually says about the allowable deflection of an existing slab-on-ground foundation. I also examine what the **International Residential Code** and the **International Building Code** say about the deflection of existing slab-on-ground foundations.

ACI 318

The question of the applicability of ACI 318 to the performance evaluation of existing slab-on-ground foundations is discussed at length in a PTI Technical Note authored by Ken Bondy.[28] I will not repeat Mr. Bondy's discussion here. But it is important to understand that ACI 318 does not contain any provisions that apply to the allowable or tolerable deflection of existing ground-supported structures such as slab-on-ground foundations. With few exceptions, ACI 318 addresses the calculated, or design, deflection of elevated structures. ACI 318 does not address the measured, or actual deflection of slab-on-ground foundations.[29]

International Residential Code for One and Two Family Dwellings

The Texas State Legislature recently adopted the **International Residential Code for One and Two Family Dwellings** as a state building code. The following is a summary of some key issues from this code:

1. There is no stated requirement that foundation deflection not be allowed to exceed some specified amount such as L/360.

[28] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.
[29] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.

2. The Building Official has the discretion to permit the construction of a slab-on-ground foundation without an engineered design if past experience has shown that the proposed slab-on-ground foundation has performed adequately.[30]

3. For a non-engineered slab-on-ground foundation to be judged to be performing adequately, it must meet three stated criteria.

- *The foundation must be able to resist differential volume changes.* While this would eliminate some minimal foundation designs, almost all foundation designs typically used in the metropolitan areas of Texas could be said to provide some degree of resistance to differential soil volume changes.

- *The foundation must be able to prevent structural damage to the supported structure.* In this context it is clear that structural damage means damage to the supported structure that reduces the ability of the supported structure to carry the imposed loads in a safe manner. Most foundations would be able to pass this test.

- *Deflection and racking of the supported structure shall be limited to that which will not interfere with the usability and serviceability of the structure.* This would imply that the foundation deflection should not result in functional problems such as doors or windows that bind and stick. This is clearly a problem with some homes.

For engineered slab-on-ground foundations on expansive soils, there are two code approved design protocols that may be used, one published by the Post-Tensioning Institute (PTI) and the other published by the Wire Reinforcement Institute (WRI). The 1996 edition of the PTI document **Design and Construction of Post- Tensioned Slabs-On-Ground** includes the following wording: "Application of these recommendations results in slab designs similar to those that have exhibited satisfactory performance." The WRI publication, **Design of Slab-on-Ground Foundations – An Update,** includes similar wording. Neither code approved design protocol promises that the actual deflection of engineered slab-on-ground foundations will be less than some stated amount. They do promise that actual foundation performance in terms of superstructure distress will be "satisfactory" and the distress "minimal." I think it is fair to say that slab-on-ground foundations designed and constructed in accordance with either design protocol will not deflect enough to cause structural (load-bearing) damage to the superstructure. There is likely to be some degree of cosmetic distress and some minor door problems. The levelness of the slab surface is not addressed by either design protocol.

Misconceptions Concerning the Use of Calculated Design Deflection Calculations for Performance Evaluation

The use of calculated design deflections to judge the performance of an existing concrete structure rests on two significant misconceptions:

[30] International Code Council (2000). International Building Code, section 1805.8.2

The first misconception is that the load-deflection behavior of a reinforced concrete slab-on-ground foundation is consistent and predictable. Based on the evidence, this is not likely to be the case. It is well-established that the load-deflection behavior of simply supported reinforced concrete beams exhibit considerable variability when constructed by research engineers in a laboratory setting.[31] Any design procedure that results in a single deflection quantity cannot adequately describe the load-deflection behavior of a member that behaves in a variable manner, especially where the variability of the deflection is significant. In the case of a simply supported reinforced concrete beam, careful studies have shown that the actual deflection is likely to range between 20% less than the calculated deflection to as much as 30% more than the calculated deflection.[32] The ACI recommends that the design engineer understand that an actual reinforced concrete beam constructed under field conditions may deflect up to 40% more than what the design calculations show.[33] While these studies were for simply supported reinforced concrete beams, it is difficult to see any rational reason why these numbers would not apply to the expected deflection performance of slab-on-ground foundations.

There are three important implications of the variability of the load-deflection behavior of slab-on-ground foundations:

1. It is not possible to accurately describe the load-deflection behavior with a single deflection ratio. Such an approach may be adequate for design purposes, but it is not adequate for purposes of describing or evaluating the performance of an existing slab-on-ground foundation.

2. Design deflection calculations should be interpreted as approximations of the actual or expected deflection; while the design deflection is a precise, known quantity, the actual deflection is a random variable best described in statistical terms such as standard deviation.

3. If it can reasonably be expected that a concrete structural member could deflect as much as 40% more than what design calculations would indicate, then there is no reason to consider a foundation to have failed or be performing in an unexpected manner merely because it has deflected more than the calculated design deflection.

The second misconception concerns the purpose of design deflection calculations. The purpose of calculating defections is to compare different designs and allow the engineer to make more rational engineering judgments concerning the foundation design. The deflection calculations predict the future behavior of the foundation only in a very general and approximate sense.

[31] ACI Committee 435 (1972), "Variability of Deflection of Simply Supported Reinforced Concrete Beams", *Journal ACI*, 69(1)
[32] ACI Committee 435 (1972), "Variability of Deflection of Simply Supported Reinforced Concrete Beams", *Journal ACI*, 69(1), p. 29
[33] ACI Committee 435 (1995), "Control of Deflection in Concrete Structures", ACI 435R-95

Foundation Evaluation Protocols Using Foundation Elevation Measurements

In this section, I critically examine several published foundation evaluation protocols that use foundation elevation measurements.

PTI-Bondy (2000): In July 2000, the Post-Tensioning Institute published a technical note authored by Ken Bondy titled *Performance Evaluation of Residential Concrete Foundations*.[34] Ken Bondy is currently on the ACI 318 and 423 committees and is chairman of the PTI Slab-on-Ground Committee. The Bondy article was peer-reviewed by the PTI Slab-on-Ground Committee and was issued only after all objections were removed. This technical note deserves careful study by any engineer practicing in the field of residential foundation performance evaluation.

Mr. Bondy states early in the article that most foundation performance evaluations fall into one of two categories. One category makes use of a level survey of the slab surface; the other category relies not on a level survey but on damage to the supported structure such as drywall cracks, door frame distortion, brick veneer cracks, etc. Bondy sees both approaches as having shortcomings, at least in the way they are used in practice.

Mr. Bondy says level surveys are typically made during the discovery phase of a construction defect lawsuit. According to Mr. Bondy, forensic consultants often allege on the basis of a single level survey that the foundation has experienced excessive movement; this is then used as a basis for recommending repairs to the foundation, usually underpinning. Level surveys often ignore construction effects and attribute all slab surface out-of-levelness to foundation movement. A foundation performance evaluation that rests on the unverified and, in fact, unverifiable, assumption of an initially level slab-on-ground foundation is not, according to Bondy, an acceptable approach.

The purpose of Bondy's article was "to present a rational protocol for the performance evaluation of residential concrete foundations, focusing primarily on the estimation of as-built construction levelness using standardized, published criteria."[35] The PTI-Bondy protocol states that a "reasonably certain" diagnosis of excessive expansive soil and foundation movement requires three conditions to be met. These are listed below:

- The slab surface must be out-of-level to a degree that the levelness is "substantially in excess of published American Concrete Institute standardized levelness tolerances."

- There must be visible damage in the supported structure that is in the vicinity of the excessive soil/foundation movement. The damage must also be "consistent with the orientation of the relative elevation differences in the slab surface profile."

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[34] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.
[35] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.

- The overall shape of the slab surface profile "must be consistent with recognized patterns of deformation known to be caused by expansive soil movement."

If any of these conditions are not met, then a diagnosis of excessive expansive soil and foundation movement cannot be made. If the three conditions are met, the diagnosis of excessive soil and foundation movement is characterized by Mr. Bondy as being a "reasonable diagnosis."

From the perspective of slab surface levelness, the PTI-Bondy protocol calls for comparing the levelness of the slab surface with published ACI levelness construction tolerances, specifically the local (worst case) levelness tolerance found in ACI-117-90. This specification calls for elevations to be made every 10 feet. Elevation differences are then calculated between every adjacent point. The Face number, or F-number, for the local (worst case) levelness is calculated using the following equation:

$$F_L = 12.5 / z_{\max}$$

where z_{max} is the largest difference in elevation between two adjacent points 10 feet apart.

As discussed previously, for a wet-screed strikeoff and bullfloated slab-on-ground foundation, ACI-117-90 reports the minimum local (worst case) Face number to be 10. Using the equation above, a Face number of 10 gives a maximum elevation difference between any two adjacent points 10 feet apart of 1.25 inches.

There are aspects to this protocol that may not be apparent in a first reading. The protocol would not be used unless there was a rational reason to be suspicious of the performance of the foundation. This would typically be the presence of drywall cracks, cracks in brick veneer or stucco and/or sticking or binding doors. In an expansive soil area, the presumption would be that expansive soil and foundation movement could be the cause of the distress, although there is a possibility that other factors such as framing issues might be the cause. The PTI-Bondy protocol requires that any possible foundation distortion be ignored if the surface levelness is potentially explainable by construction tolerances. The practical effect of the PTI-Bondy protocol is to reduce the number of houses exhibiting such symptoms of possible foundation movement from being positively diagnosed as having damage due to foundation movement. Thus, if there was a group of houses showing signs of possible foundation movement in the form of damage to the supported structures, only a percentage would meet all three criteria. The set of houses that fails to meet the criteria could include houses that do in fact show damage due to excessive foundation movement. In fact, Bondy admits that it is possible for a slab to undergo excessive foundation movement and for the surface profile to be within ACI standardized levelness tolerances.[36]

On the other hand, the set of houses that met all three criteria could also include houses that in fact are not suffering damage due to foundation movement since it is always

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[36] Bondy, K.B. (2000). "Performance Evaluation of Residential Concrete Foundations", *Technical Note Number 9*, Post-Tensioning Institute, Phoenix, Arizona.

possible for the visible damage to be due to some other cause. Thus, it is possible for the protocol to give misleading results for specific houses.

The requirement that the slab surface be out-of-level to a degree that the levelness is "substantially in excess of published American Concrete Institute standardized levelness tolerances" is almost meaningless from a quantitative perspective; Bondy does not state what this phrase means quantitatively. It is possible for a slab-on-ground foundation constructed with the local (worst case) F-number of 10 and deflecting to L/360 in both directions to have a surface slope of .024 or 4.3/180. This is a very high slope. It should also be noted that the foundation surface geometry is dynamic; the foundation surface changes as the soil shrinks and swells. While the foundation may become more level with time, at least some damage to the supported structure does not disappear, such as cracks in brittle wall coverings. Thus, it is possible that a house that shows cracking in brittle wall coverings may fail to be properly diagnosed because the foundation surface profile was judged to be "level" at the time of the inspection.

The PTI-Bondy requirement that the overall shape of the slab surface profile be "consistent with recognized patterns of deformation known to be caused by expansive soil movement" is misleading. Bondy implies that the only recognized patterns of distortion are a center lift distortion mode and an edge lift distortion mode. But this is clearly arbitrary. It is true that the center lift and edge lift modes of distortion are the only two distortion modes used in the standard PTI design procedure. But these two distortion modes were selected for design purposes because they maximize the shear, bending moment and deflection of the foundation model,[37] not because they are the only "recognized patterns of distortion." The fact is that the surface distortion can appear to be random with some portions of the slab heaving and other portions settling.[38] There is no rational, logical reason to refuse to make a positive diagnosis merely because the surface profile does not conform with one of two distortion profiles that are used for design purposes.

The PTI-Bondy protocol relies on the assumption that the as-constructed foundation surface was constructed to the ACI levelness tolerances. This assumption is impossible to justify. As stated previously, in residential construction practice the ACI levelness tolerances are not used to control the construction of the slab. The assumption of an as-constructed levelness compliance is an assumption that cannot be verified; it is possible that a foundation was placed out of compliance of the ACI construction tolerances.

Robert W. Day (1990)

Robert W. Day has authored numerous articles addressing various aspects of residential slab-on-ground foundation performance evaluation. The protocol used by Mr. Day is a

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[37] Wray, W. K., "Development of a Design Procedure for Residential and Light Commercial Slabs-on-Ground Constructed Over Expansive Soils," Dissertation Presented to Texas A&M University at College Station, Texas in 1978, Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy.
[38] Wray, W. K., "Development of a Design Procedure for Residential and Light Commercial Slabs-on-Ground Constructed Over Expansive Soils," Dissertation Presented to Texas A&M University at College Station, Texas in 1978, Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy.

derivative of the procedure used by Skempton and McDonald in their paper published in 1956.[39] The essentials of Mr. Day's approach can be stated as follows:

- Mr. Day advocates the use of elevation surveys using the concepts of maximum "angular distortion" and maximum differential settlement. Day does not explicitly define the term "angular distortion" but he appears to use the term as the elevation difference between two points on the slab surface divided by the distance between the two points.

- Mr. Day has written that the points used to calculate "angular distortion" should be a "reasonable" distance apart such as 15 feet. The 15 feet rule is intended to minimize the influence of localized distortion or anomaly in the slab-on-ground foundation surface.[40]

- Based on various empirical studies, Mr. Day reports that the maximum "angular distortion" for residential floor slabs is 1/300 for cosmetic damage and 1/100 for structural damage defined as damage to the wood frame beam and column elements.

Mr. Day believes his approach is superior to a visual damage inspection because a visual inspection can be inaccurate due to hidden or patched repairs.[41]

There is one aspect of Day's approach that is easy to overlook. Day relies on a relationship between maximum foundation surface elevation differences and "angular distortion" versus severity of damage. This relationship is shown in a figure Day has published that shows an empirical linear relationship between the maximum elevation difference or maximum settlement (Δ) and maximum "angular distortion" (δ/L) for various types of foundation movement including expansive heave of slab-on-ground foundations. The figure Mr. Day has produced obscures the variability in the data since the maximum "angular distortion" is a very small number compared to the maximum differential settlement.[42] If the data is shown on logarithmic scales, then it is clear that for any one value of "angular distortion" or maximum differential settlement the other corresponding value varies by a factor of 7.[43] Thus, the Day protocol leaves a lot of room for error.

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[39] Day, R.W. (1990). "Differential Movement of Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 4(4), 236-241.
[40] Day, R.W., (1990). "Differential Movement of Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 4(4), 236-241.
[41] Day, R.W. (1990). "Differential Movement of Slab-on-Grade Structures", *Journal of Performance of Constructed Facilities*, 4(4), 236-241.
[42] Washington, Allyn J. (2000), *Basic Technical Mathematics*, 7th edition, (Reading, Massachusetts: Addison-Wesley)
[43] Boone, Storer J., (2003) "Ground Movement-Related Building Damage: Closure", *Journal of Geotechnical Engineering*, 124(5), 463-465.

Walsh and Miguel (2003)[44]

Walsh and Miguel recommend a three-standard-deviation approach to analyze residential floor surface elevation data. This requires a sample size of at least 80 points for a typically-sized slab-on-ground foundation with the points distributed across the entire extent of the slab surface. This normally requires a grid spacing of around 5 feet. The standard deviation of the elevation data is calculated and then multiplied by 6 to obtain an estimate of the maximum elevation difference across the foundation surface. According to the analysis presented by Walsh and Miguel, this type of approach is conceptually similar to a maximum elevation difference approach; but the sample size ensures that the result will be repeatable by different investigators.

The Walsh and Miguel approach is intended for new slabs. It should be noted that Walsh and Miguel are not confident this protocol is suitable for evaluating the performance of existing slab-on-ground foundations. The location of walls, furniture and stored material in an existing house compromises the selection of random points for measurement. In addition the presence of finish flooring makes it impossible to take foundation surface elevation measurements.

The Knight Engineering Services Corporation (KESCORP) Repair Determination Protocol[45]

The KESCORP protocol is worthy of careful examination for several reasons. KESCORP is owned by Weldon Knight, P.E. and one of his sons. The Knight family is deeply involved in the foundation performance and evaluation business in the Greater Houston Area. Weldon Knight has another son, David Knight, P.E., with whom he owns a company named Engineered Concrete Products, Inc. This company manufactures concrete cylinders that are used by foundation repair contractors in the Greater Houston Area. David Knight, P.E. is the inventor of the Cable-Lock foundation repair method, one of the most popular repair methods currently used in the Greater Houston Area.

KESCORP performs three services that are of interest in the context of this paper: engineering foundation performance evaluations for homeowners and buyers, foundation repair designs and foundation repair services. From an engineering perspective, KESCORP uses a specific analysis methodology of elevation measurements to arrive at a recommendation to underpin or not underpin the foundation.

The KESCORP protocol claims to be based on Table 9(b) in ACI 318. It takes a design deflection limitation of L/360 for an elevated reinforced concrete beam as a basis for a

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[44] Walsh, K.D. and Miguel, George P., (2003) "Method for Forensic Analysis of Residential Floor-Elevation Data", *Journal of Performance of Constructed Facilities*, 17(3), 110-117.

[45] The description of the KESCORP protocol is based on numerous written material in the author's files including a letter, numerous foundation evaluations produced by KESCORP and a copy of an oral deposition of Weldon Knight, P.E., May 15, 2003. In the original version of this paper the KESCORP protocol was called the "foundation repair contractor protocol". That term could be unintentionally misleading; I do not believe any honest foundation repair contractor would use a protocol like the KESCORP protocol.

performance and repair standard for an existing slab-on-ground foundation. The protocol consists of the following elements:

- The allowable design or calculated deflection for an elevated reinforced concrete beam is equal to the length of the beam between the supports divided by 360. Thus, if an elevated reinforced concrete beam spans 30 foot (360 inches), the calculated allowed design deflection is 1 inch.

- If the shape of the deflection curve to taken to be such that the maximum deflection is at the center of the span between horizontal supports[46], then it follows that the average slope between the middle of the span and the beam supports is 1/180 or .00556.

- This average slope (1/180) is taken to be the allowable slope of the surface of the slab-on-ground foundation.

- If a foundation surface elevation survey shows areas with a slope that exceeds the allowable slope of 1/180, the foundation is deemed to be in need of repair.

The KESCORP protocol is susceptible to attack on a number of grounds as discussed below:

- As discussed previously in this paper, it is a well-established fact that reinforced concrete beams do not exhibit a consistent load-deflection behavior. This characteristic of the material behavior of reinforced concrete beams calls into question the idea that the design deflection ratio is a logical candidate for a repair or performance standard. If the load-deflection behavior of a reinforced concrete beam is within the expected range of behavior, it is difficult to see why it should be designated as in "need of repair."

- Weldon Knight claims that "the American Concrete Institute's most commonly used standard for maximum allowable deflection…(L/360)…produces an average slope of 1-inch in 15-feet." This statement is impossible to defend on at least two grounds. First, as pointed out earlier in this paper, the ACI does not publish any "standard for maximum allowable deflection" applicable to existing slab-on-ground foundations. Second, a deflection limitation of L/360 is just that, a limitation on the calculated deflection; it is not a slope limitation. A deflection limitation of L/360 does not produce any specific slope, average or otherwise. The slope of a deflection curve is determined by the shape of the deflection curve, not its deflection ratio.

- This protocol is supposed to allow an engineer to compare slopes calculated from elevation differences to the standard of 1/180 to locate areas of "excessive" slope so they can be identified as in "need of repair." It is interesting to use this

[46] Weldon Knight does not explicitly state he is assuming that the maximum deflection is at the center of the beam, but that assumption is clearly a necessary part of his argument.

protocol to evaluate not a slab-on-ground foundation, but a reinforced concrete beam that is deflecting to L/360 since the protocol (apparently) considers a beam deflecting to L/360 as acceptable. Consider what happens when we apply the protocol to a horizontal beam that is 30 foot (360 inch) long and sags 1 inch in the center of the beam.

- Since the deflection (1 inch) is very small compared to the span (360 inches), the deflection curve could be modeled as a segment of a circular arc.

- The slope at the point of maximum deflection (the center of the beam span) is zero. The slope mid-way between each end and the middle is 1/180. The slope at each end is 2/180, twice what the slope protocol considers acceptable; in fact, the slope at every point between the ends and half way to the middle exceeds the "maximum allowable slope". Fully 50% of the deflection curve has a slope that dictates repair using the KESCORP protocol.

- The KESCORP repair protocol understates the "allowable slope" significantly because it uses a one-way bending model instead of a two-way bending model. As shown in the previous discussion in this paper, using a two-way bending model results in a "maximum allowable slope" that is over 41% greater than a one-way bending model.

- The slope Weldon Knight considers as indicative of a "real need for repair" is significantly less than published ACI slab-on-ground foundation surface construction tolerances.

- As previously discussed, it is the curvature of the foundation deflection surface that causes damage to the house; slope as such causes no damage to the house. Nor is slope mathematically related to curvature; curvature is related to the rate of change in the slope, not to the slope.[47]

A Texas Section ASCE Deflection Ratio/Elevation Profile Protocol[48]

In 2002 the Texas Section of the American Society of Civil Engineers (TSASCE) published a document titled *Guidelines for the Evaluation and Repair of Residential Foundations*. A detailed discussion of the TSASCE document is beyond the scope of this paper, so this discussion will be limited to a few issues. The TSASCE document briefly discusses evaluating the deflection and tilt of a slab-on-ground foundation using elevation measurements. The authors state the following with regard to deflection: "Deflection is characterized by the deflection ratio, which is defined as the maximum deviation from a straight line between two points divided by the distance (L) between the two points."

[47] This can be seen from the standard slope curvature equation in which the curvature is proportional to the rate of change of the slope of the deflection curve.
[48] Texas Section American Society of Civil Engineers, *Recommended Practice for the Design of Residential Foundations, version 1*.

The document points out that an elevation survey only yields the shape of the foundation surface at a given point in time and may not provide enough information to support a reliable conclusion. A single elevation can provide only an approximation of the degree of foundation deflection and should not be the only basis for recommending foundation repair. A reliable evaluation may require repeated finish floor elevation surveys performed over months or even years. When more than one survey is made, the deflection of the foundation is judged based on the change in the foundation surface shape between surveys.

Clearly, the more reliable approach is to use two or more elevation surveys. Whether one uses a single survey or two or more surveys, the finish floor profile is analyzed to determine the deflection ratio of the profile. The deflection ratio is then compared to the deflection ratio that is to be used a repair criteria such as 1/360. Whether the profile provides an adequate basis for recommending repair depends on the apparent deflection ratio and the degree of visible damage to the house judged to be due to foundation movement.

What is interesting about the TSASCE approach, as compared to other elevation survey approaches, is the idea of using the apparent deflection ratio as a basis for evaluation instead of a slope or maximum elevation difference.

Protocol Summary

A review of the published protocols discussed in this paper shows that, in the current state of practice, there appears to be little agreement on how elevation survey data should be used in the performance evaluation of slab-on-ground foundations. There is no agreement concerning the spacing or number of elevations. The different protocols assign very different meanings to the results of elevation survey analysis. Because there is no agreement concerning the spacing or number of elevations, different engineers using the same protocol can approach the performance evaluation of a foundation very differently and may reach different, even conflicting, conclusions.

One interesting fact about these protocols is that they are not related to the capabilities of foundation repair contractors. Repair contractors warranty their work in terms of future settlement, not in terms of levelness, regardless of how it is measured. This leads to an interesting situation in which a foundation could be evaluated as in "need of repair" but in fact is not capable of being repaired, unless the owner was willing to tolerate severe damage to the house and possibly to the foundation.

Also, none of these protocols recognize that a foundation may exhibit "excessive" slope or "angular distortion" and be stable. Another problem with any maximum elevation difference approach is that it is possible for a foundation surface to distort in a way that reduces the as-constructed maximum elevation difference.

The Use of Foundation Elevation Surveys in Forensic Studies

Foundation surface elevation surveys are frequently used in foundation performance evaluations intended for forensic reports in construction defect lawsuits. In the normal situation, an elevation survey is intended to shed some light as to whether visible damage, such as drywall cracks, is due to foundation movement or to some other issue, such as framing.

The literature leads to an expectation that cosmetic distress becomes visible at an "angular distortion" of around 1/300 and a maximum elevation difference of 1.25 inches. However, based on an analysis of Face numbers and the empirical studies of as-constructed foundation surface geometry, it is likely that new slab-on-ground foundations will have areas with slopes in excess of 1/300; in fact, the maximum local (worst case) Face number implies a slope of 3.12/300; the overall Face number implies a common slope of 1.04/300 and a maximum elevation difference of 1.92 inches.

The problem is that foundation surface construction tolerances are large compared to the published damage criteria. In cases where it is possible to interpret the elevation measurements as indicating foundation movement is the cause of the visible damage, it is also likely that the elevation differences can be interpreted as due to the original construction. How an engineer interprets the measurements depends on assumptions he makes regarding the as-constructed slab surface geometry. Absent a survey made very soon after the concrete is placed, the elevation survey approach requires the engineer to assume an as-constructed surface geometry. The assumed surface geometry is necessarily subjective; it cannot be tested.

Another point that is relevant to assessing the reliability of foundation surface surveys is the question of possible errors. If a manometer is misread or if an elevation measurement is not transcribed properly, an error will be introduced into the survey process. The normal methodology used in making an elevation survey is susceptible to this type of error. Also, since the normal methodology does not provide for calculating the error of closure, the cumulative error cannot be calculated.[49] For this reason alone, the reliability of foundation elevation surveys made in a normal way is questionable.

Texas Board of Professional Engineers Rule 22 TAC 131.153(c) states that "engineering opinions which are rendered as expert testimony and contain quantitative values shall be supported by adequate modeling or analysis of the phenomena described." It is difficult to see how any single elevation survey model can be an adequate basis for a quantitative estimate of the distortion a foundation has experienced.

The result is that there is no way for a court to judge how reliable the results of an elevation survey are. Based on the limited analysis presented in the paper by Walsh and Miguel, the reliability and repeatability of a normal elevation survey that uses a small number of measurements is suspect.

The Use of Foundation Elevation Surveys in Real Estate Transaction Evaluations

There are important but subtle differences between foundation evaluations for purposes of a real estate transaction and for a construction defect lawsuit. Performance evaluations for real estate transactions typically must be done very quickly; the buyer usually has an

[49] Chen, F.H., 1988, *Foundations on Expansive Soils*, 2nd ed. (New York: Elsevier Science Publishers)

option period of 10 days or less. The inspection normally must be done within a window of only a few hours with the report due within 24 to 72 hours. In some cases, the engineer is providing a second opinion regarding the need for underpinning and the time frame from appointment to report delivery may be less than 24 hours. The owner may have an interest in hiding visible distress. Also, there may be past distress that the current owner is not aware of. At least initially, the inspecting engineer must go by what he can see in terms of visible distress and any relevant distress history from the owner. There sometimes are also property access restrictions as well.

The most important difference between a foundation performance evaluation for a real estate transaction and a forensic study is that a causation study is always included in a forensic study. Indeed a forensic study may not include anything another than a causation study that addresses whether the visible distress is due to foundation movement or to some other cause. In an evaluation for purposes of a real estate transaction, visible distress that is commonly associated with foundation movement is generally assumed to be caused by foundation movement; the visible damage is evaluated to provide the buyer (typically) two pieces of information:[50]

- *An unbiased subjective opinion of the performance of the foundation:* It is widely accepted that the purpose of a slab-on-ground foundation is to act as a buffer to mitigate the damage that would otherwise result to the supported structure as a result of expansive soil movement. The only rational way to judge how well the foundation is performing as a buffer is to observe the condition of the house, not the levelness of foundation surface.

- *An unbiased subjective opinion as to whether the foundation should be underpinned:* It is not clear why the levelness of a slab-on-ground foundation is intimately related to the foundation repair decision. Foundation repair contractors usually do try to make the foundation surface more level. But they reserve the right to terminate leveling operations if the process is causing damage to the house. Also, no warranty is made regarding the levelness of the foundation surface; foundation repair contractors normally warrant only that the underpinned area of the foundation will not settle more than L/360; the typical repair warranty addresses future foundation settlement; it does not address the surface levelness of the slab.

One point that should always be kept in mind when recommending underpinning is Texas Board of Professional Engineers Rule TAC 22 131.151(a), which states that engineers have an obligation to protect the property interests of the public. The decision to recommend underpinning has to take into consideration the possibility that the repair process may damage the house, perhaps even severely. The underpinned foundation may not perform as well as expected, in which case, the repair costs might be considered a waste. The assessment of the risks involved in underpinning or not underpinning is a

[50] Texas Real Estate Commission, Standards of Practice for Real Estate Inspectors, sections 535.227 and 535.228

matter of subjective judgment; it is not related to the issue of foundation surface levelness.

If it could be demonstrated that an elevation survey would prove that hidden damage exists in a subject house, that could alter the opinion of an inspector/engineer concerning the performance of the foundation and whether underpinning would be recommended. The problem with this approach is that published construction tolerances imply larger slopes and elevation differences than published damage criteria. Once again, it is possible to interpret the data in significantly different ways. Also, as in the previous discussion, absent an as-constructed elevation survey of the slab surface geometry, some assumption concerning the as-constructed slab surface geometry must be made. Whatever assumption is made is necessarily subjective and cannot be verified.

Summary and Conclusions

This paper has addressed a number of issues related to the use of foundation surface elevation surveys in evaluating slab-on-ground foundation performance. The following is a summary of the most important issues addressed in the paper.

- *No Mathematical Relation Between "Angular Distortion" or Maximum Elevation Difference and Deflection Surface Curvature:* The aspect of slab-on-ground foundation distortion that causes damage to the supported structure is the curvature; but there is no mathematical relation between the slope of the deflection surface or the maximum elevation difference and the curvature of the deflection surface. The maximum elevation difference and "angular distortion" or slope of the foundation surface are (rough) measures of levelness; they are not measures of deflection surface curvature.

- *Foundation Levelness is Neither a Design Nor a Construction Control:* The levelness of the foundation is not a design parameter. It is frequently said in residential construction that you get what you inspect and control; foundation levelness criteria are normally not specified in the construction documents nor is levelness inspected or used as a construction control.

- *Inadequate Data for a Statistical Approach:* In 1974 Karl Terzaghi remarked in a published discussion of the Skempton and McDonald paper that the number of settlement records were too small to justify a statistical approach to the relation between "angular distortion" and maximum settlement. The situation is not any better concerning the published records relating "angular distortion" and elevation differences to visible damage. The published records are few in number, restricted to a few geographical areas and were made using mathematically suspect measurement and analysis techniques.

- *No Standard Measurement Protocol or Standard Analysis Methodology:* There is no widely-accepted published protocol that addresses how elevation measurements should be made and how the elevation data should be analyzed. There seems to be no doubt that elevation measurements are sensitive to the number and spacing of the measurement locations. Based on the published work by Walsh, Bashford, and Mason (2000) and Walsh and Miguel (2003) it would appear that any mathematically defensible protocol must be much more rigorous than what is normal in engineering practice. The normal practice of taking 15 to 20 elevations appears to be inadequate; it is neither reliable nor repeatable. The Walsh and Miguel (2003) paper also forces us to be suspicious of the reliability of the published data relating measures of levelness to visible damage.

- *No Logical or Empirical Relation to Realistic Foundation Repair Capabilities:* The foundation surface elevation approach recognizes no limitations on the ability of foundation repair contractors to re-level foundations. In fact, limitations on the abilities of foundation repair contractors play no role in any published elevation survey foundation performance protocol.

- *The Subjective Nature of an Elevation Survey Approach:* Even with a standard measurement and analysis protocol, a single elevation survey approach will necessarily be subjective since the approach requires that the analyst make some assumption regarding the as-constructed surface geometry. Whatever assumption is made is inescapably subjective and not capable of verification. In this respect, an elevation survey is arguably no more objective than a visual evaluation. Even the published levelness data is clearly subjective. This can be illustrated with the use of the term "angular distortion". What is called "angular distortion" is in fact a slope between two points. The use of the term "angular distortion" implies that the slope is the result of a change from the original placement and, without an as-constructed elevation survey that can only be based on a subjective judgment.

- *A Propensity to Mislead:* Finish floor elevation surveys have the capacity to mislead a home owner or home buyer. The KESCORP protocol is highly susceptible to this problem. It is important for any engineer or inspector who chooses to use elevation measurements to make sure their client understands the limitations involved and the tentative nature of any conclusions that are based on such measurements, especially when only a single elevation survey is used.

- *Using Elevation Measurements in Forensic Evaluations:* Published data on foundation levelness thought to be related to visible damage in the supported structure can be found on new slab-on-ground foundations. This is the case whether we use published measurements from new slabs or use F-numbers to calculate possible as-constructed slopes and elevation differences. In view of the fact that we normally have no data concerning the as-constructed surface geometry and the problems with levelness measurement as it is normally done, the use of elevation measurements in forensic evaluations may not be effective.

- *Using Elevation Measurements in Real Estate Transaction Evaluations:* The idea that elevation measurements can identify hidden damage in the supported structure appears to have no rational basis since the published damage slope criteria are smaller than slopes likely to be found on new, undistorted slabs. Elevation survey data do not appear to have any clear value in answering the two main questions that need to be addressed in a foundation performance evaluation for purposes of a real estate transaction.

The entire subject of the effectiveness of elevation surveys in the performance evaluation of slab-on-ground foundations has been the subject of too much belief and too little analysis. The use of elevation surveys is almost never accompanied by any discussion of the limitations of this approach. Much of this paper has focused on understanding the limitations inherent in the use of elevation surveys, especially in forensic studies and real estate transactions. Foundation surface level surveys require the engineer to assume some as-constructed geometry; regardless of what assumption is used, there is no way to determine if the assumption has some reasonable correlation to reality. Nor is there any way to determine if the assumed as-constructed geometry is consistent with the accuracy required by the purpose of the evaluation.

Foundation surface survey data should be used with a due regard for the limitations inherent with this type of approach as well as the limitations specific to the data being used. Foundation surface surveys can provide useful data for purposes of assessing the performance of a slab-on-ground foundation if at least two professionally made surveys are available. Given the current state of practice, the use of a single elevation survey, especially one done in a normal manner with a small number of measurement locations, may be misleading and ineffective.