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Performance Evaluation of Residential Concrete Foundations

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INTRODUCTION

Many contemporary construction defect lawsuits involve light wood-framed residential buildings supported on post-tensioned concrete foundations built on expansive soils. Foundation performance is often an issue in these lawsuits. A primary tool for the evaluation of foundation performance in these cases is a level survey of the slab surface profile, typically made during the discovery phase of the lawsuit. Usually this survey is made using a water level, or "manometer", a simple and inexpensive instrument which can provide reasonable accuracy if the survey is properly executed. Forensic consultants often allege, on the basis of the level survey, that excessive foundation movement has occurred due to the effects of expansive soil volume changes, requiring expensive repairs to the foundation system. In some cases the consultants attribute ***all*** of the current slab surface elevation differentials to soil movement, thus completely ignoring construction effects and effectively assuming that the slab was built perfectly level. Those consultants who do recognize construction effects often use non-standard criteria for their evaluation, which vary wildly from consultant to consultant and are based largely on anecdotal personal opinions, unsupportable by any published, generally accepted study or work.

PURPOSE

The purpose of this Technical Note is 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. The protocol developed is applicable to both post-tensioned and non-prestressed foundations.

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TWO SURVEYS

The most reliable and certainly the easiest way to evaluate foundation performance, including construction effects, is by comparing two competently executed level surveys made on the slab surface, one current and one made immediately after the slab was built. If the current surface profile is very similar to the original profile it may be reasonably concluded that the slab was built in its current position. If the current surface profile is substantially different from the original profile, it may be reasonably concluded that foundation movement has caused the difference. Unfortunately, the earlier survey is rarely available, and diagnoses of foundation performance must generally be made with only one survey, made years after the slab was built.

Lacking an initial survey it is impossible to determine with certainty whether the slab 1) was built with its current surface profile, 2) was built with a completely different surface profile and deformed into its current shape, or 3) attained its current surface profile by some combination of 1) and 2). However with the use of the protocol proposed herein a reasonable diagnosis of the presence or absence of ***significant*** soil and foundation movement is possible.

PROTOCOL FOR SINGLE-SURVEY EVALUATION

In the absence of survey information about the as-built slab surface profile, the subsequent diagnosis of excessive expansive soil movement requires, in the author's opinion, three related and concurrent conditions, all of which must be carefully evaluated, and all of which must be present to establish a reasonably certain diagnosis of excessive soil and foundation movement:

1. The slab surface must be out of level substantially in excess of published American Concrete Institute (ACI) standardized levelness tolerances. *Excessive soil movement cannot be diagnosed on the basis of current levelness alone if the slab surface is level within anticipated construction levelness tolerances. Published ACI standard construction levelness tolerances for residential slabs require a minimum levelness F-Number $F_L = 10$ (see the discussion which follows.) This is the equivalent of a maximum permissible differential elevation of 1.25 inches between any two points ten feet apart on the slab surface. If a competent level survey of the slab surface indicates that the maximum elevation difference between any two points ten feet apart is less than or equal to 1.25 inches, the slab satisfies this ACI construction levelness tolerance criteria. Conformance to ACI standardized levelness tolerances can be determined from a competently executed survey of the slab surface.*

2. There must be related distress in the superstructure. *If excessive soil movement has occurred, it will be accompanied by significant distress in the superstructure (pervasive asymmetrical, unidirectional diagonal cracking in interior gypsum wallboard and exterior plaster walls) in the vicinity of the excess soil movement, and consistent with the orientation of relative elevation differences in the slab surface profile. An engineer trained and experienced in the behavior of residential structures can identify this distress from an interior and exterior visual examination of the superstructure. Lacking this distress, excessive soil and foundation movement cannot be diagnosed.*

3. The overall shape of the slab surface must be consistent with recognized patterns of deformation known to be caused by expansive soil movement. *The profile of the slab surface must reasonably look like either edge lift or center lift (see "Design and Construction of Post-Tensioned Slabs-on-Ground" 2nd Edition, Section 4.2(B), by the Post-Tensioning Institute.) The examination of slab surface profiles can be made by plotting the slab surface profile, from a level survey, on an exaggerated vertical scale at carefully selected sections through the slab. Random, irregular slab profiles that are not reasonably consistent with overall edge lift or center lift shapes are indicative of construction effects, rather than soil movement.*

A positive diagnosis of excessive foundation movement caused by expansive soil volume changes cannot be made if any one of the above stated conditions is not satisfied. It should be noted that the minimum levelness *F-number* criteria for conventional residential slabs ($F_L = 10$) corresponds to a maximum elevation gradient on the slab surface of 1 vertical to 96 horizontal, or about 1 percent. It is known that damage to gypsum board and plaster walls can be incipient at deformed gradients less than 1 percent. Thus it is possible that soil movement could produce wall cracking, and the slab could still be level within ACI construction levelness tolerances. Based upon the author's experience, however, it is unlikely that a slab, which is currently level within ACI construction levelness tolerances, could have experienced enough deformation to produce excessive wall cracking. It would be extremely difficult, under those conditions, to isolate the cracking caused by soil movement from that which can be caused by other factors not related to soil movement. In such a situation soil movement cannot be eliminated as a cause for wall cracking, but neither can it be positively diagnosed.

All three of the listed factors are important in the evaluation of residential foundation performance. The second two factors are admittedly subjective, and while a reasonable protocol exists for studying both of them, it requires the careful consideration of an engineer experienced in the behavior of residential foundations, superstructures, and materials. The estimation of construction effects, however, can be evaluated on a substantially objective basis using standardized criteria developed and published by ACI.

The competent evaluation of residential slab performance requires a firm understanding of these ACI standards for slab construction levelness criteria, and how those criteria can be effectively used to predict the initial degree of construction levelness attainable by various finishing techniques. Following is a discussion of those standards, and a number of significant issues related to the evaluation of construction levelness effects:

ACI STANDARDS FOR FLATNESS AND LEVELNESS

Slab "flatness" describes the local irregularities or "roughness" of the slab surface, and has primary relevance only for slabs upon which there is random vehicular traffic, rather than foot traffic. Slab "levelness" describes the overall shape and curvature of the slab surface. If one were driving on a dirt road, flatness would relate to the high-frequency washboard effect, levelness would describe whether you were driving uphill or downhill, and how steep the hill is. Slab levelness, rather than flatness, is the most relevant parameter in the evaluation of residential slab foundation behavior because it relates to the overall shape of the slab rather than the local roughness.

There is only one published American standard for slab levelness tolerances developed in conformance with the standardization procedure of the American National Standards Institute (ANSI). It is found in "Standard Specifications for Tolerances for Concrete Construction and Materials" (ACI 117-90), Section 4.5.6, published as a standardized document by ACI in 1990.

ACI standardized documents represent the most rigorously developed of all ACI publications. They are developed and approved, on a consensus basis, by a standing ACI Technical Committee, approved by the Technical Activities Committee and the Standards Review Board, and are published in an internationally distributed journal for review and comment by the entire ACI membership, and the interested public at large. The ACI Technical Committee Manual, August 1999, states on page 16:

"[Standardization] ensures the widest input and overall quality assurance for a document. The ACI Standardization process is approved by ANSI..."

F-NUMBERS

ACI standard slab construction levelness tolerances are based upon the "F-Number" system, which was developed, in part, from an extensive study of levelness in hundreds of existing functional slabs with a variety of different occupancies. The F-number system describes the levelness of a concrete slab surface with a single numerical value, called the floor levelness number (F_L). The higher the F_L number, the more level the slab surface. Floor levelness numbers are determined using the protocol described in ASTM Standard E1155-96, "Standard Test Method for Determining F_F Floor Flatness and F_L Floor Levelness Numbers".

AVERAGE LEVELNESS F-NUMBER

To determine F_L for a slab area, elevation measurements are made at a specific number of points on the slab surface, all ten feet distant from each other. The total number of points required for a particular area, and the precise method for locating them, are specified in ASTM E1155-96. The difference in elevation Z_i between each pair of adjacent points is tabulated (in inches). The entire set of elevation differences Z_i for pairs of points ten feet apart throughout the test area is called "Sample j". F_L for the test area, also known as the "average" F_L number, is then calculated in accordance with Section 9.12, Equation 22 of ASTM E 1155-96 as follows;

$$F_L = \frac{12.5}{3S_{z_i} + \left|\bar{Z}_{i_j}\right|} \qquad \text{Equation (1)}$$

Where:

S_{z_i} = the standard deviation of the set of elevation differences in sample j.

$\left|\bar{Z}_{i_j}\right|$ = the absolute value of the mean of the Z_i values in Sample j.

ACI 117-90 specifies a minimum acceptable value for this ***average*** F_L number as a function of 3 categories of floor profile quality, conventional, flat, and very flat. For conventional quality, two sub-categories are included, bullfloated or straightedged (finished with a highway straightedge). For conventional bullfloated construction, applicable to virtually all residential slab-on-ground construction, the minimum average F_L number is 13.

LOCAL (WORST CASE) LEVELNESS F-NUMBER

ACI 117-90 also specifies a minimum local F_L number, which represents the lowest acceptable F_L number measured between any two individual points in the sample set of measurements. Since the standard deviation for a single value is zero, and the mean of a single value is the value itself, the minimum local F_L number can be determined from Equation (1) as follows:

$$F_L = \frac{12.5}{z_{max}} \qquad \text{Equation (2)}$$

Where:

z_{max} = the maximum difference in elevation between any two points ten feet apart in Sample j (the single largest Z_i value in the set of elevation differences)

For a residential slab-on-ground, finished with a wet-screed strikeoff and bullfloated, where the floor profile quality classification is "conventional" in accordance with ACI 117-90 in Section 4.5.6, the minimum required ***local*** F_L number is 10.

A careful examination of a slab surface level survey can determine if the local or the average F-number is the controlling factor in satisfying the ACI 117 tolerance specification. If the maximum surface gradient or curvature (the point where the local F-number is a minimum) occurs at only one or two isolated locations, and the remainder of the slab is substantially more level than at those points of maximum gradient, it is likely that the local F-Number will be more critical than the average F-number. If the maximum surface gradient (the minimum local F-number) appears widely throughout the slab surface (as in a tilted slab), then it is likely that the average F-number will be more critical since it is always larger than the local F-number.

This discussion is important, since it means that conformance to ACI standard slab construction levelness tolerances can generally be determined with reasonable reliability without the necessity of running the entire test protocol and determining the average F_L number. The minimum local F_L number can be determined accurately from any competent survey of the slab surface. This is done by examining the survey and determining the maximum difference in slab surface elevation between any two points ten feet apart. If the minimum local F_L number satisfies ACI 117-90 criteria for levelness tolerance (for example, 10 in the case of conventional quality), and the locations of points of maximum gradient are few and isolated, then it may be reasonably concluded that the average F_L number will also be satisfied and that the slab satisfies ACI 117-90 criteria. If the maximum gradient is pervasive throughout the slab, the F-number associated with the maximum gradient must then be compared with the more restrictive average F-number criteria. If the minimum local F_L number is greater than the average F-number criteria, the ACI 117-90 criteria are obviously satisfied.

Equation (2) can be rearranged as follows:

$$z_{max} = \frac{12.5}{F_L} \qquad \text{Equation (3)}$$

Substituting the ACI 117-90 criteria of 10 for the minimum local F_L number for conventional levelness quality permits the calculation of the largest acceptable value of z_{max} (the maximum difference in elevation between any two points on the slab surface ten feet apart), to satisfy the levelness criteria:

$$z_{max} = \frac{12.5}{10} = 1.25 \text{ inches} \qquad \text{Equation (4)}$$

Thus for "conventional" residential slabs-on-ground, wet-screeded and bullfloated, ACI slab construction levelness tolerances are satisfied if the maximum difference in elevation between any two points on the slab surface ten feet distant from each other is no greater than 1.25 inches.

LEVEL ALIGNMENT

ACI 117-90 also establishes a 3/4 inch tolerance for the specified surface elevation of a slab-on-grade in 4.3.1.1. This means that when an elevation is specified for the top surface of a slab-on-ground, it can vary by ±3/4 inch (the actual slab surface can be 3/4 inch higher or lower than the specified elevation). Thus the as-built surface elevation must be within an envelope of 1-1/2 inches straddling the specified elevation, and the local variations in elevation addressed by 4.5.6 must fit within that 1-1/2 inch envelope. This is stated in ACI 117R-90, "Commentary on Standard Specifications for Tolerances for Concrete Construction and Materials", Sections 4.3, 4.4, and 4.5, p. 117R-6:

> *"The acceptable elevation envelope of the slab surface and soffit is ±3/4 inch. The rate of change of the adjacent surface elevation points within the acceptable elevation envelope is governed by specification Section 4.5.5 [which includes the F-Number levelness criteria]."*

It should be noted that Section 4.3.1.1 only applies when an elevation is specified for the slab surface. If no elevation were specified, Section 4.5.6 would be the sole criteria for slab levelness tolerances.

The level alignment tolerance is an arbitrary value and has not been related to actual slab construction methodology and equipment as has the F-number levelness criteria. It has been the author's experience that, even when a slab surface elevation is specified, the level alignment tolerance is rarely verified with a level survey made immediately after the slab is cast. Like the older tolerances for slab flatness (specified as a maximum clearance under an unleveled straightedge, for example), it is likely that the level alignment tolerance is rarely achieved, even when specified.

LEVELNESS AS A FUNCTION OF SLAB FINISHING METHODS

ACI 117-90 establishes the required degree of slab levelness for various occupancies using the F-number system. ACI Committee 302, in "Guide for Concrete Floor and Slab Construction (ACI 302.1R-96)" uses the F-number system to determine the degree of levelness attainable by various finishing techniques. This is exceptionally useful for the evaluation of the deflection of existing foundations, where the initial as-built levelness of the slab is unknown (no initial survey of the slab surface exists). Knowing the finishing techniques likely to have been used for the slab, the initial levelness of the slab (the starting point) can be reasonably estimated. This is consistent with the recommendations of the Slab-on-Ground Committee of the Post-Tensioning Institute, which states in Design and Construction of Post-Tensioned Slabs-on-Ground, 2nd Edition, p. 28:

"The evaluation of existing slabs for deflection involves considerable engineering judgment because flexural deflection must be separated from construction effects (built-in out-of-levelness, for example.) Ideally, this can be done using an initial level survey made immediately after the slab is cast. Lacking an initial survey, accepted construction tolerances (such as those found in ACI 302) must be used to estimate construction effects."

ACI 302.1R-96 states in Table 8.15.3.a that a slab-on-grade whose perimeter forms are set with optical or laser surveying equipment, finished with a wet-screed, single strikeoff technique, is likely to achieve minimum local F_L numbers between 10 and 15. To consistently achieve local F_L numbers greater than 17, a vibrating screed must be used for the initial strikeoff. To consistently achieve local F_L numbers greater than 20, at minimum a vibrating screed and multiple strikeoffs are necessary. Thus for typical residential slab-on-ground construction finished with a single wet-screed strikeoff, it is likely that the maximum initial as-built difference in elevation between any two points on the slab surface ten feet apart will be between 0.8 and 1-1/4 inches (F_L ranging from 15 to 10).

The author recently had the opportunity, as a forensic consultant in a construction defect litigation case in California[2], to participate in the design, construction, and evaluation of four full-scale slabs-on-ground using typical California design details and construction techniques. The plan dimensions of the slabs were 12 feet by 48 feet, the slab thickness was four inches, and a down-turned grade beam was built at the perimeter and at selected locations at the interior of the slab. Finishing of the concrete was by wet-screed strikeoff (with a 2x4 board) and bullfloating, the finishing method used for decades on the vast majority of California residential slabs-on-ground.

One of the purposes of these "test slabs" was to determine as-built surface levelness. This was done by making a level survey of the slab surface on the day following slab concrete placement. Considering the fact that the placing and finishing crews were highly experienced, the placing and finishing of the concrete was continuously observed and scrutinized by a large group of bystanders, and that the shorter dimension of the rectangular slabs measured only 12 feet, it is felt that the as-built levelness of these test slabs should exceed that found in normal "production" slab work.

The maximum difference in as-built surface elevation measured in these four slabs ranged between 0.5 inches and 0.9 inches, averaging 0.7 inches. The slabs exhibited an average local F_L number of 19, which, considering the unique circumstances cited is very consistent with and supportive of ACI 302 recommendations.

BUILDING CODE DEFLECTION CRITERIA

First, it should be noted that the deflection limits specified in both Uniform Building Codes (UBC) and American Concrete Institute (ACI) codes are for ***elevated*** structural members that span between precisely located and dimensioned isolated supports. These deflection limitations do not apply to slabs-on-ground or foundations that are continuously supported by soil and have no definable "spans".

These criteria are not applicable to slabs-on-ground. In fact, there are no provisions in either the UBC or the ACI Code that address actual measurements of apparent deflection in any existing structure, elevated or ground-supported. Code limitations on deflection are for ***computed*** deflections, not measurements made on existing structures.

The current UBC (1997) presents deflection limitations for concrete structural members in Table 19-C-2, page 2-181. The table is titled *"MAXIMUM PERMISSIBLE **COMPUTED** DEFLECTIONS"* (bold emphasis by the author). All UBC 1997 references to the deflection limitations in Table 19-C-2 clearly indicate that they are for computed deflections only. For example (bold emphasis by the author):

> For one-way non-prestressed construction:
> *"1909.5.2.6 Deflections **computed** in accordance with this section shall not exceed limits stipulated in Table 19-C-2."*
>
> For two-way nonprestressed construction:
> *"1909.5.3.4 ...if shown **by computation** that the deflection will not exceed the limits stipulated in Table 19-C-2."*
>
> For prestressed concrete construction:
> *"1909.5.4.3 Deflections computed in accordance with this section shall not exceed limits stipulated in Table 19-C-2."*

The current ACI Code (ACI 318-99) limits deflections in structural concrete members in Table 9.5(b). The title of this table is

[2] Peters v. Brighton/Brannon, OCSC Case Nos. 76 51 77, 77 24 00, 78 12 58

*"MAXIMUM PERMISSIBLE **COMPUTED** DEFLECTIONS"* (bold emphasis by the author). This table is referenced in sections addressing both non-prestressed and prestressed construction:

For non-prestressed construction:
*"9.5.2.6 Deflection **computed** in accordance with 9.5.2.2 through 9.5.2.5 shall not exceed limits stipulated in Table 9.5(b)."*

For prestressed construction:
"9.5.4.3 Deflection computed in accordance with 9.5.4.1 and 9.5.4.2 shall not exceed limits stipulated in Table 9.5(b)."

Specific references to computed deflection limits appear in previous versions of the UBC since 1967 and in ACI Codes since 1963, making it clear that code deflection limits apply to computed deflections, rather than measured apparent deflections.

ACI Committee 423 is precisely on point in "Recommendations for Concrete Members Prestressed with Unbonded Tendons", ACI 423.3R-96, Section 3.8. While this document generally addresses prestressed concrete construction, this Section is clearly applicable to both prestressed and non-prestressed members (underlining emphasis by the committee):

"It is important that the deflection limits of Section 9.5.4 [which cites Table 9.5(b)] refer to computed deflections only and not to measurements made on the actual structure. Field surveys of apparent deflections can be influenced by many construction factors which are beyond the control of the designer and impossible to isolate from true deflections caused by applied loads."

SUMMARY AND CONCLUSIONS

Lacking a level survey of the slab surface made immediately after construction, the diagnosis of excessive expansive soil movement in residential concrete foundations requires the estimation of initial as-built construction levelness, an engineering examination of the superstructure to determine if excessive distress exists which can be related to differential soil movement, and an evaluation of the slab surface profile to see if it is consistent with known expansive soil swell modes.

The estimation of construction effects can be objectively evaluated using standards for slab construction levelness developed and published by the American Concrete Institute. These ACI standards relate as-built slab levelness to known construction methods, and provide the best available estimate of the degree of levelness which is likely to have existed at the time the foundation slabs were built.

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