The Impact of Market Demands on Residential Post-Tensioned Foundation Design: An Ethical Dilemma

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Abstract

In 2005, a lawsuit in excess of 6 million dollars was brought to trial pertaining to 31 single-family residences in Arlington, Texas. The basis for the lawsuit was distress related to foundation movement. An extensive forensic investigation was performed on each of the structures, and the results of the investigation indicated improper construction and inadequate design of the post-tensioned slab-on-grade foundation systems. Testimony given during the legal proceedings indicated that the foundation design methodologies used deviated from the governing Post-Tensioning Institute (PTI) Design Manual. This paper summarizes the construction and design defects observed during the forensic investigation and the reasons why industry standards were not followed in the design and construction of the foundation systems. The market pressure for the least expensive residential foundations is driving design engineers to compromise their ethics and ignore industry standards.

Introduction

This paper will review a significant number of foundations from a subdivision in North Texas with a focus on the correlation between the financial restraints imposed upon engineers and the quality of engineering produced. The pressure from the residential building industry to provide lower cost products has impacted post-tensioned foundations due to poor design and lack of quality control.

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This market pressure for the least expensive foundations is driving the design engineers to compromise their ethics and ignore industry standards resulting in inadequate foundation designs, poor quality control of construction, and flexible foundations that perform below acceptable limits.

Background

Between March and September 2002, forensic investigations of 31 single-family residential structures were performed. The structures were located in a subdivision of 218 homes in Arlington, Texas and ranged in size from approximately 2200 to 2900 square feet including living and non-living areas. Prior to construction, the subdivision was divided into three sections for geotechnical exploration. Geotechnical data for the site indicated that the soil consisted of expansive clays with Potential Vertical Rise (PVR) of the soils ranging from 2.0" to 4.75". The post-tensioning foundation design parameters provided by the geotechnical engineer of record for soils in the subject section of the subdivision are indicated in Table 1:

Table 1: Post-tensioning Foundation Design Parameters

	e_m (feet)	y_m (inches)
Center Lift	5.0	3.8
Edge Lift	4.5	2.4

A forensic investigation strategy was developed to test the quality of construction, the adequacy of foundation designs, and other influences that could affect the foundation performance. The investigation strategy was extensive including distress mapping, relative elevation surveys of the foundation systems, tendon mapping, testing of post-tensioning strand tension, reviewing as-built dimensions of slabs and grade beams, testing compressive strength of slab cores, reviewing foundation designs, and plumbing testing. The forensic investigations were conducted following the methodologies presented in the Texas Board of Professional Engineers Residential Foundation Committee Policy Advisory 09-98-A, and the Texas Section of the American Society of Civil Engineers (ASCE), "Guidelines for the Evaluation and Repair of Residential Foundations - Version 1".

Distress

Observed distress was mapped on floor plans for each of the structures reviewed. The distress mapping was analyzed to determine patterns of distress in the structures and to determine correlation with the foundation movement topography. The majority of the distress indicated edge lift conditions typical of expansive soil movement. Other distress patterns indicated edge drop and center lift conditions.

Observed distress included cracking and separations at the interior and exterior architectural finishes, inoperable doors/windows, fractures and/or separations in the attic framing, and fractures in the concrete slabs. Several of the fractures at the exterior were observed to open at the bottom of the wall and taper towards the top, which is evident of edge lift. Fractures at some locations were also observed to open at the top and taper to the bottom, which is indicative of edge drop or center lift conditions. Relative elevation surveys of the foundations further indicated generally excessive movement in the structures.

Construction

Nonconformance to foundation plans and specifications was observed at each of the structures reviewed. The nonconformance included weaker concrete material than specified, excessive variations in slab thickness and grade beam depths, and poor placement of slab tendons. In addition, the structures were reviewed for other construction items that could affect the performance of the foundation systems, i.e., roof guttering systems, lot grading, and stressing of post-tensioning tendons.

The specifications for the foundation systems conformed to typical industry standards including construction of a 4" thick slab with 10" wide grade beams of varying depth (24" to 30"). The specified 28-day compressive concrete strength was 3000 psi, and tendons were specified to be ½" diameter, 270 ksi, 7-wire strands.

Concrete Strength

Concrete cores were taken from the slab at each structure and tested in accordance with ASTM C 42. The results from the testing indicated at least one core below 75% of the specified 28-day compressive strength at five of the structures. Two of the structures had compressive strength averages below 85% of the 28-day compressive strength.

Slab and Grade Beam Depths

The concrete cores were measured to determine as-built slab thicknesses. The thicknesses varied from 3 1/4" to 9 3/4" (81 to 225% of the specified thickness). In addition, grade beams were exposed at four areas of each structure in order to measure the depths of the grade beams. The percent variation of the as-built to the design depths of the grade beams ranged from -21% (20 1/2" as-built, 26" design) to +13% (31 1/2" as-built, 28" design).

Tendon Placement

The foundation plans specified that slab tendons should be placed at the center of the 4" slab. The 1996 PTI Design Manual allows for a construction tolerance of ± 1/2" for placement of tendons. With construction tolerances, the concrete cover should range from 1 1/2" to 2 1/2". The observed cover at the subject structures ranged from 0.157" to 6.1". The 6.1" value was the greatest value that the equipment could read. It is possible that the multiple 6.1" readings (7 readings) were actually greater than 6.1".

Additional Construction Items

The finished site grading at eleven (11) of the structures produced negative drainage (slopes toward the structure). A review of the foundation topographies indicated a correlation between the negative drainage and the foundation movement at five (5) of the structures. In addition to the poor drainage, absence of rain guttering was observed at some of the structures. However, it was difficult to determine which structures had been impacted from the lack of rain guttering systems since rain guttering had been installed at various times as a remedial action. Piers had also been installed as a remedial action at a portion of the structures. The foundation systems that had been piered still indicated significant foundation distortion (L/349 to L/124).

Testing of Post-Tensioning Tendons

To determine if the strands were stressed properly during the original construction of the foundations, "Lift-off" tests were performed at each structure, typically involving four tendons. The live ends of the strands were pulled by means of a hydraulic jack until the anchor was unseated. A pressure gauge was monitored during the testing process and values were recorded at the time of the anchor unseating. Under-stressing of some tendons was observed when compared to expected after stress loss values from the PTI manual.

Design

Available foundation designs of the observed structures were analyzed for conformance with PTI design criteria. The analysis was performed using PTI software, PTISlab, and was based on the foundation plans and the geotechnical design parameters contained in the original geotechnical report for the development of the site. As required by the 1996 PTI Design Manual, one (1) to three (3) design rectangles were analyzed as necessary to properly design for the configuration of the foundation. Deflection analysis was based on criteria specified in the 1996 PTI Design Manual.

Due to the irregular geometric layout of some of the foundations, simplifying, conservative assumptions were made for analytical purposes. For example, discontinuous grade beams on the interior were conservatively treated as continuous in determining the quantity of long and short beams. In some cases, these assumptions may have contributed additional strength to the foundations that was not actually present in the design, which gave benefit to the design engineer.

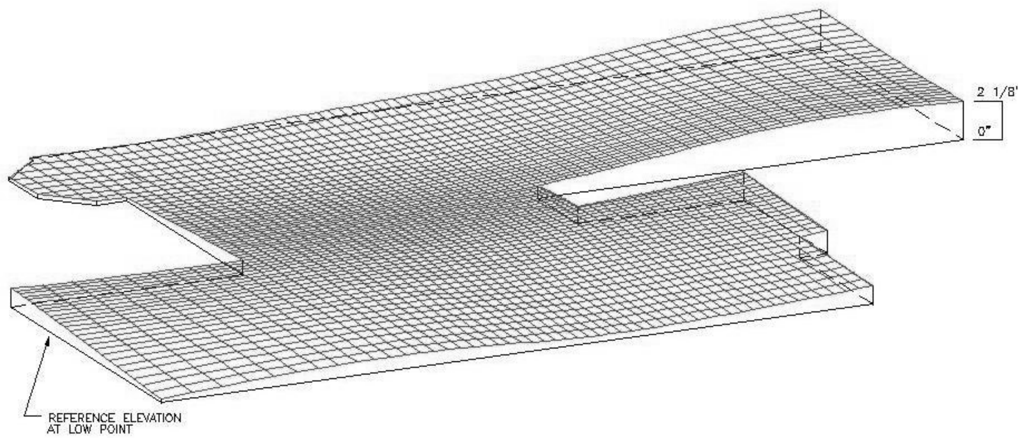
Information was available to analyze foundation designs for 24 of the 31 structures. Analysis of all of the foundation designs reviewed indicated overstress in the edge lift condition that did not meet design criteria put forth in 1996 PTI Design Manual. Overstress ranged up to 105.3% in bending, 59.9% in shear, and 100.2% in deflection.

Foundation designs reviewed were prepared by three different Professional Engineers licensed in the State of Texas. For the purposes of this paper, the engineers that were involved will be referred to as Engineer Alpha, Engineer Beta, and Engineer Gamma. In addition, there were seven different architectural floor plans with minor variations in any given floor plan. There were some similarities in the foundation designs provided by the engineers (slab thickness, beam widths, etc.); however, the designs of similar floor plans varied between the engineers in beam spacing, beam depth, and number of tendons used in the slabs and beams.

Engineer Alpha

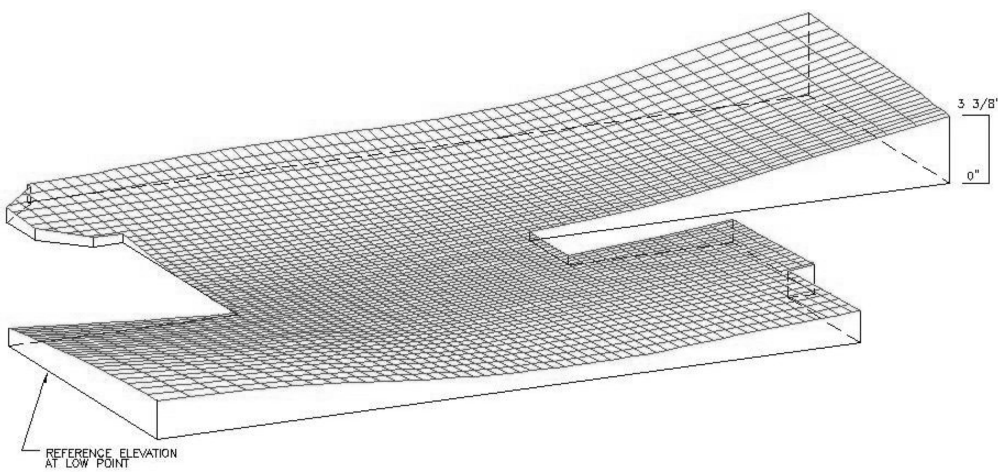
Engineer Alpha provided the majority of the foundation designs for the reviewed structures. Analysis of the foundation designs prepared by Engineer Alpha indicated significant overstress; however, the overstress was generally lower than the other engineers (up to 39.1% in bending, 41.7% in shear, and 60.7% in deflection). There were significant variations observed in Engineer Alpha's foundation designs for structures with the same floor plan, even though the geotechnical design parameters were unchanged. For one particular design (Floor Plan A), the tendons used to reinforce the beams were reduced by 5 tendons in a time span of less than four months. Further, the same design was again reduced by 3 more beam tendons eight days later.

The relative elevation survey of the foundation systems for these Floor Plan A plans indicated more out-of-levelness in the foundations as the number of beam tendons decreased. The out-of-levelness for the foundations with 28 total beam tendons, 23 total beam tendons, and 20 total beam tendons was measured to be 2 1/8", 3 3/8", and 4 3/8", respectively. Representations of the change in out-of-levelness in Floor Plan A are provided in the following Figures 1, 2, and 3:



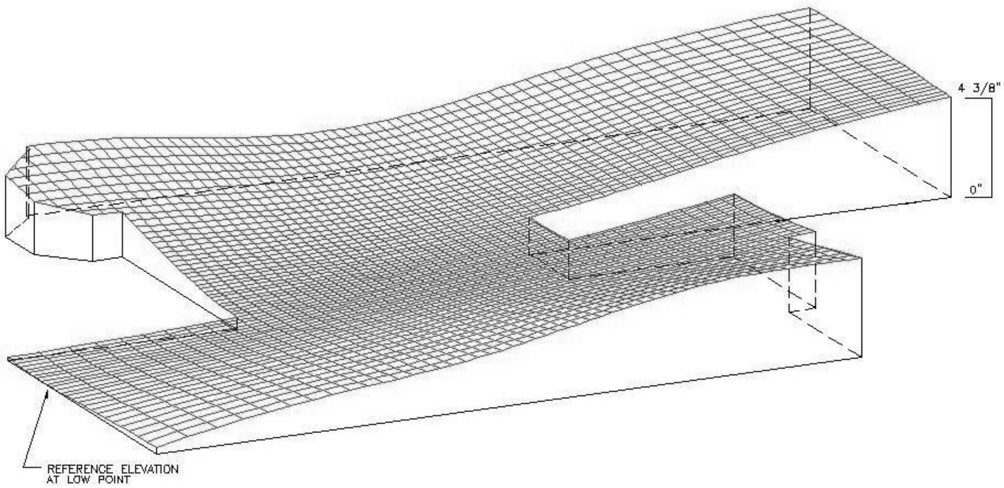
Date of Design	**02/24/98**
Total Number of Beam Tendons	**28 Tendons**
Total Out-of-Levelness	**2 1/8"**

Figure 1. Three Dimensional Representation of Total Out-of-Levelness Floor Plan A (28 Total Beam Tendons)



Date of Design	**06/12/98**
Total Number of Beam Tendons	**23 Tendons**
Total Out-of-Levelness	**3 3/8"**

Figure 2. Three Dimensional Representation of Total Out-of-Levelness Floor Plan A (23 Total Beam Tendons)



Date of Design	**06/20/98**
Total Number of Beam Tendons	**20 Tendons**
Total Out-of-Levelness	**4 3/8"**

Figure 3. Three Dimensional Representation of Total Out-of-Levelness Floor Plan A (20 Total Beam Tendons)

The output from the software used by Engineer Alpha was available for review. The output indicated that only one design rectangle was used for "H" and "Z" shaped foundations, which is in direct conflict with the 1996 PTI Design Manual. Further, Engineer Alpha's design output indicated beam depths greater than those specified in the foundation plans. The variation between the beam depth shown on the foundation plans and the deeper depth suggested by the calculations was significant, ranging from 2.63" to 5.99".

<u>Engineer Beta</u>

Engineer Beta prepared foundation designs for 11 of the foundations reviewed. Comparison of the foundation designs prepared by Engineer Beta to those prepared by Engineer Alpha revealed deeper grade beams by an increment of 2" on average. However, the designs prepared by Engineer Beta consisted of greater beam spacing and did not include double tendons in any of the grade beams. When comparing the foundation designs for similar floor plans between Engineer Beta and Engineer Alpha, there was a 50% reduction of post-tensioning force in the grade beams due to the reduction in the number of beam strands. An analysis of the designs by Engineer Beta using PTISlab indicated higher overstress than those foundation designs by Engineer Alpha (up to 80.2% in bending, 31.8% in shear, and 94.7% in deflection).

A graphic presentation has been prepared to demonstrate the differences in beam layout between Engineers Alpha and Beta. The grade beam locations were highlighted in a floor plan used by both engineers (Floor Plan B), and the highlighted grade beam locations from the plan designed by Engineer Beta was overlain on top of the highlighted beam locations from the design by Engineer Alpha. The graphic presentation is provided in Figure 4; the darker beams are representative of the design by Engineer Beta. Note that there are fewer short direction grade beams in the design by Engineer Beta.

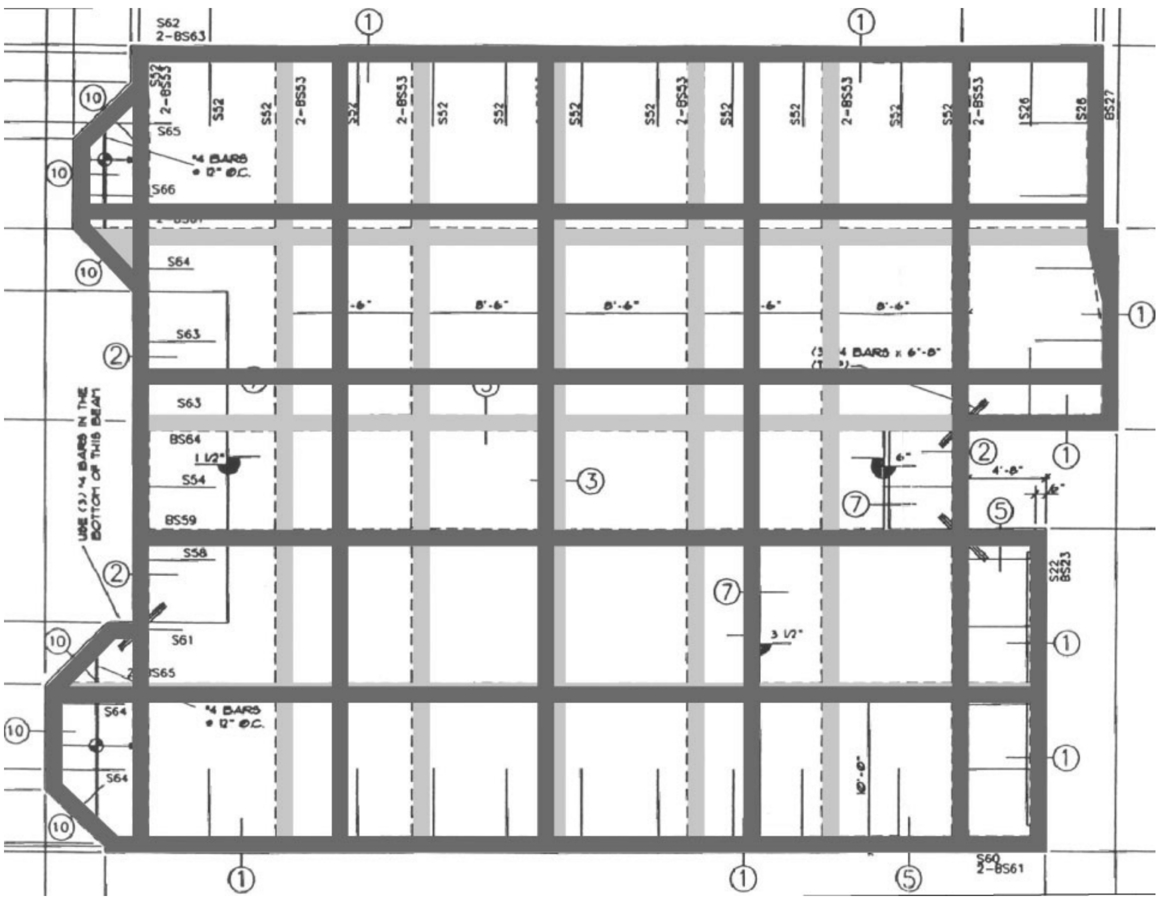


Figure 4. Beam Layouts from Foundation Designs for Floor Plan B

It is interesting to note that Engineer Beta had the deepest grade beams of the three engineers, and, for this sole reason, was not brought in as a party to the litigation. However, due to the use of fewer beams and less reinforcing tendons, the designs performed by Engineer Beta actually failed with much higher design overstress than Engineer Alpha.

Engineer Gamma

One foundation reviewed by our office was designed by Engineer Gamma. The design included single strand beams that were approximately 4" shallower in depth than the designs by Engineer Alpha. As expected, the analysis of the design indicated more overstress than the foundation designs prepared by Engineer Alpha. In fact, it exhibited the highest overstress of the foundations analyzed (105.3% in bending, 59.9% in shear, and 100.2% in deflection).

Engineering Conduct

The review of the foundation designs provided in the subdivision raises questions as to the design processes that have been used in the residential foundation industry. With clear methods indicated in both the Uniform/International Building Code and the PTI Design Method, how can engineers with the same geotechnical data produce such varied results and results that consistently fall so far below the documented industry standards?

Testimony regarding the design methodology used in designing the foundations in this case provided insight into what degree the engineers were involved with or excluded from the construction process and how that impacted the foundation design and construction from start to finish.

Design Process

The design process included a "pre-engineering" of foundations for prototype floor plans based on information provided by the builder. Then information was sent by the builders to the engineers indicating the address, lot and block numbers, and type floor plan. The engineer would then apply site-specific information to the "pre-engineered" foundation plan and issue a sealed letter stating that the foundation had been designed based on the appropriate code and geotechnical report. It was indicated by Engineer Alpha that the total design and production time related to foundation design was approximately three and a half hours and time related to review of drawings and calculations was approximately one half hour.

Testimony by Engineer Alpha indicated that in residential foundation design it is common for the builder to provide a typical floor plan so that the engineer can produce a typical foundation plan for pricing and comparison to designs provided by other engineers. The implication is that the lowest cost design determines which engineer gets the project.

Engineer Alpha did not use the PTI Design Manual method preferring to use proprietary software developed in-house, which had not been peer reviewed. However, the output of the software did not provide the same results as industry accepted software or hand calculations of the procedure put forth in the PTI Design Manual. It should be noted that requests to obtain software were denied; so the exact calculation method performed by Engineer Alpha is not known. However, the results of the calculations by Engineer Alpha do not agree with the calculations performed in accordance with typical industry software.

Pre-Pour Inspections

Pre-pour inspections were not performed by the design engineers since the builder did not request the inspections. It was indicated that pre-pour inspections had been discussed with the builder by Engineer Alpha and that it was presented as a line item under additional services along with an associated fee. Engineer Alpha estimated that a pre-pour inspection would probably take an hour including travel time and further stated that the fee associated with the pre-pour inspection was $75.

As can be seen from the results of this investigation, variations commonly occur between actual construction and the design documents often to the detriment of the performance of the foundations. The purpose of the pre-pour inspections is to ensure that the construction in the field conforms to the original intent of the design documents and that a higher quality product is constructed. Engineers typically review slab and beam depths and tendon placement, the very construction parameters that were documented to be outside of construction tolerance in this case.

Design Costs

According to Engineer Alpha, the fee associated with the design of the foundations in a subdivision would include a fee of $150 for each floor plan and another $50 fee for each house using the same floor plan. The profit from these fees was indicated to be approximately $30 per plan. The design fees were indicated by Engineer Gamma to be $100 per house.

Engineer Alpha added that the total cost for production of foundation designs and a pre-pour site inspection have increased to about $250 since the time of the charges indicated, which was around 1997 and 1998.

Design Divergence

During the time of investigation, Engineer Alpha prepared a spreadsheet of foundations in the subdivision that were designed by their firm. One column in the spreadsheet indicated whether the calculations originally performed by their firm met the allowable design values (overstress, deflection, etc.) as specified by the Post-Tensioning Institute (PTI). By his own review of the foundation design calculations, Engineer Alpha indicated that some of his calculations did not meet the specifications in the PTI Design Manual.

When Engineer Alpha was asked why he did not use multiple rectangles as specified in the PTI Design Manual, he indicated that he chooses not to follow the methodology in the PTI Design Manual, presumably to produce a less expensive foundation and to reduce design time. In fact, the rectangle used by Engineer Alpha typically was not the controlling rectangle, and the design by Engineer Alpha produced beam depths that were shallower and had fewer tendons than an adequate design. The design process by Engineer Alpha resulted in less expensive, less stiff foundation systems that performed poorly.

Testimony by Engineer Gamma indicated that at the time of foundation design the builder had indicated that the geotechnical engineer was still working with the numbers and that they would be about the same as another phase in the subdivision. Engineer Gamma indicated that the builder provided a geotechnical report without PTI design parameters, e_m and y_m values. Since no supplemental information was provided, Engineer Gamma produced his own parameters for the design of the foundation systems.

During the forensic investigation of the homes in the subdivision, Engineer Gamma reviewed his calculations with the PTI design parameters provided by the geotechnical engineer and indicated that his design did not meet the criteria specified in the PTI Design Manual. Engineer Gamma provided some insight into what was driving the design process to diverge from industry standards when he said, "all they [builders] want to do is save money" and "all they care about is money." He further indicated the builder's disregard for engineering codes and standards, stating "they don't care how you got there."

Conclusion

This paper has reviewed a significant number of foundations from a subdivision (31 out of 218) in North Texas with a focus on the correlation between the financial restraints imposed upon engineers and the quality of engineering produced. The pressure from the residential building industry to provide lower cost products has impacted post-tensioned foundations due to poor design and lack of quality control.

Testimony from the Engineers of Record for the foundation designs revealed that engineers have ignored building codes and industry standards in order to provide foundations that use less design time, less material, and less labor, which in effect cost less. The engineers indicated that they did not follow steps specified in the PTI Design Manual, choosing not to use the formulas provided and not to use multiple rectangles for "Z" and "H" shaped foundations. In addition to deviating from industry standards for design, site visits that are typically performed to ensure quality control during the construction phase were not part of the base pricing but were priced on an "a la carte" basis giving builders the opportunity to choose not to include these site visits as part of the design package. Testimony from the engineers indicated that most of these site visits were not performed by the engineers of record or by representatives acting on their behalf.

The residential market pressure for the least expensive foundations is driving the design engineers to compromise their ethics and ignore industry standards. The results are inadequate foundations, poor quality control of construction, and flexible foundations that perform below acceptable limits. The total loss due to the foundation movement in the 31 sites reviewed was claimed in excess of 6 million dollars, and a jury held the builder, the originator of the litigation, responsible for 80% of the liability and held Engineer Alpha responsible for 20% of the liability.

It is clear to the authors that the builder and the engineers involved in this litigation were responsible for the loss; however, the engineering ethics and professional responsibility that governs the professional engineers holds them to a higher standard. To knowingly give into the economic pressures applied by the residential building industry is inexcusable.

References

International Code Council (2000), “International Residential Building Code”, 2000 Edition.

International Conference of Building Officials (1997), “Uniform Building Code”, 1997 Edition.

Post-Tensioning Institute (PTI), "Design and Construction of Post-Tensioned Slabs-on-Ground," 1996 Edition.

Texas Board of Professional Engineers Residential Foundation Committee, "Policy Advisory 09-98-A, Regarding Design, Evaluation and Repair of Residential Foundations", September 11, 1998.

The Texas Section of the American Society of Civil Engineers (ASCE), "Guidelines for the Evaluation and Repair of Residential Foundations - Version 1", 2003.