COMMENTS ON THE USE OF THE PTI METHOD

AND

SUGGESTIONS FOR FURTHER RESEARCH

by

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of

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PREFACE

This document has been developed by a group of Foundation and Structural design engineers in Texas with the goal of informing engineers and others involved in the design of residential and light commercial foundations of several issues and possible inconsistencies in the industry specifically related to the design of foundations using the Post-Tensioning Institute's "Design and Construction of Post-Tensioned Slabs-on-Ground," 2nd Edition (1996), otherwise known as the PTI method.

The need for this document was prompted by a number of perceived and actual residential and light commercial foundation problems in Texas with an emphasis on experience in Southeast Texas. As a result, this document has been prepared and made freely available to the public through the Foundation Performance Association at www.foundationperformance.org so that owners, tenants, realtors, builders, inspectors, engineers, architects, repair contractors, attorneys, and others involved with residential and light commercial foundations may benefit from the information that it contains.

Over the past 20 to 30 years, concrete slab-on-grade foundations have become a significant portion of the foundations used and constructed to support residential homes. With their increased use have come problems associated not only with the residential construction process, but also with determining how the foundation is actually designed to perform.

Experience has shown that the PTI design procedures used are very successful. One Dallas engineering firm estimated that in their experience, less than 1/2 % of the houses built by volume builders experience some distress, and only a small fraction of those develop serious distress for one reason or another. Considering that most housing developments are built in volume, this is a remarkable record. We do not have the data to interpolate the number of instances of either marginal design, nor design errors in either application of the PTI Method, or in the reference Geotechnical Report. However, there are instances where even a properly designed slab-on-grade foundation will have performance problems over time.

This paper is not intended to red-flag the PTI procedure. The PTI procedure is the best currently available design procedure for certain types of structures. This paper was written with the intention to encourage further fine-tuning by indicating areas where possible additional research may result in even better structural designs.

As building codes and the construction process generally have continued to strive to improve, residential foundations have developed into engineered products. These engineered products have been designed over the last 30 years using a number of proposed and established design procedures. The design procedures have been based on a combination of the noted successes or failures of residential foundations in various areas of the country, numerous studies performed at universities dealing with soil movement and stability, and HUD-funded full-scale tests of residential foundations constructed on various soil conditions over a number of years.

Additionally, the input of the various suppliers, contractors, code officials and governmental agencies and engineers has contributed to the designs we have today.

The idea behind the PTI method was to develop a design procedure that would ultimately provide a product that will work with a high degree of success. Most people involved in the construction of residential homes and single-story commercial buildings would like every foundation to be trouble-free. However this may be an impossibility to achieve. In the design arena, the latest attempt at developing a design procedure that will provide the design basis of an aesthetically pleasing and reliable foundation is the Second Edition of "Design and Construction of Post-Tensioned Slabs-On-Ground" which is published by the Post-Tensioning Institute. This procedure is now 20 years old and has established itself as a "standard" design procedure for slab-on-grade design for small commercial and residential structures. The PTI method is now incorporated into most current building codes.

While it is well established, we must remind ourselves that the PTI method is still a "work in progress" as is every other design method and building code used by the engineering profession. With this in mind, we should be aware that there are areas in any design method or prescriptive procedure, which are based on imperfect data, and analysis methods, which can lead to pitfalls and problems.

Foundation design engineers are asked to design foundations using a prescribed code or procedure, and are generally supplied with a set of architectural drawings and the geotechnical report for the building in question. Once the drawings and the geotechnical report are reviewed, a determination is made (generally by the owner or client) as to the type of foundation system that is going to be placed under the residence or low-rise commercial building. Slab-on-grade foundation designs are often requested, and used for residential and low-rise commercial construction in many major metroplex-areas in Texas.

Current practice for developing a specific area is that the developer hires a geotechnical consultant to provide design soil parameters for the proposed structures. Then the developer contacts engineering firms to ask for design bids. After the design bid is awarded, it is very unusual that the developer will spend additional money on geotechnical work to obtain additional geotechnical data to fine-tune the design. This may result in specific foundation designs to be based on engineering judgments that could lead to under-design of foundation systems. Developers should be prepared to accept that subsequent geotechnical investigations and recommendations might be necessary to arrive at a more appropriate foundation design based upon better defined structural parameters, more precise building plan, and additional geotechnical data.

Since the procedure for slab-on-grade designs is well documented, and relatively simple to use, a design error in itself is seldom the cause of a foundation problem. However, the use of averaging geotechnical data to provide "design parameters" may not provide the most appropriate "slab" for the site and for its intended use. This has led to a review of the information supplied to the design engineer to determine what areas, items, and procedures, etc., seem to have or could have major effects (sometimes detrimental) on the foundation's performance.

This document was written specifically for use in the general southeast area of Texas. Therefore, it should be used with caution if utilized elsewhere, or if adapted for foundations other than those supporting residential or light commercial structures. The Foundation Performance Association and its members make no warranty regarding the information contained herein and will not be liable for any damages, including consequential damages, resulting from the use of this document.

DEFINITIONS

e_m – Edge moisture variation distance (feet).

y_m – Maximum differential soil movement or swell (inches.).

Q_u – Unconfined compressive strength of the soil (psf).

Q_{allow} – Allowable soil heaving pressure (psf).

P – Uniform load on perimeter grade beam (lb/ft).

P.I. – Plasticity index of the soils.

Center lift – The condition of a slab-on-grade foundation where the center area of the foundation appears to have been lifted or crowned (domed up in the center).

Edge lift – The condition of a slab-on-grade foundation where the perimeter of the foundation appears to have been lifted above the central area of the slab.

Transverse Direction – The shorter dimension of a rectangular foundation slab.

Longitudinal Direction – The longer dimension of a rectangular foundation slab.

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1.0 GEOTECHNICAL INFORMATION

Since the bearing soils that support a foundation have a much greater effect on the slab-on grade foundation system than the loads induced by the upper structure, the information in the geotechnical report is extremely important. If properly prepared, it should give a reasonably good assessment of the soil's true performance.

The primary items in the geotechnical report needed by the foundation design engineer are:

- the plasticity index of the soil (PI),
- the soil's bearing capacity (Q_{allow}),
- the prescribed movement parameters:
- the maximum differential soil movement (y_m), and
- the distances for edge moisture variation (e_m).

These last two parameters are given for both an edge heaving condition, and a center heaving condition for the bearing soils. In order to accurately compute these two parameters, it is required to make several laboratory tests such as soil suction, free swell and hydrometer testing (to determine the percent of fine clay). In the past, many geotechnical engineers in the area are believed to have found their own shortcuts in estimating these parameters, which may have contributed greatly to the problems discussed in this paper. However, if the geotechnical report is supplied in accordance with the Foundation Performance Association's Document No. FPA-SC-04, publicly available at www.foundationperformance.org, these inaccuracies should be reduced.

In the Houston area, geotechnical reports typically give y_m values for center lift that range from 0.088" to 3.5", with the majority of values ranging between 0.7" to 1.4". Typical edge lift y_m values range from 0.086" to 2.5", with the majority of values ranging between 0.65" and 1.2". The recommended e_m edge distance numbers for center lift range from 3.5' to 6.0', with typical values running between 4.0' to 5.5'. The e_m edge lift values range from 4.0' to 8.0', with typical values ranging between 5.0' and 6.0'. While the typical values, do not appear to numerically vary over a large range, the changes can have a significant effect on the moments, shears and deflections used by the foundation engineer to design the foundation.

In the past there have been several cases where the foundation engineer received geotechnical reports for a subdivision in Houston from two or even three different geotechnical companies where the PTI parameters were considerably different. Generally the soil description in the borings logs of all reports were in good agreement, with reasonably close soil strata, percent clays, plasticity indices, etc. The design plasticity index given by the foundation design engineer was reported to be within +/- 5 percentage points. For a case in which the design plasticity index in all 3 reports was approximately 40%, the PTI design values given ranged as shown in the table below:

Parameter	Low	High	Parameter Description
y_mCL	0.85”	1.4”	Center lift differential movement
y_mEL	0.7”	1.2”	Edge lift differential movement
e_mCL	3.5’	4.5’	Center lift edge distance variation
e_mEL	5.0’	6.0’	Edge lift edge distance variation

For the above variations, the impact to the foundation design is exemplified in the next table:

Examples of Ranges in PTI Output due to Input Parameter Variations

Ex. #	Input Parameter Variation	Lift Type/ Direction	Output Type	Approx. Output Change
1	y_mCL increased from 0.85” to 1.4”	Center Lift/ Transverse	Moment	+10%
			Shear	+ 2%
			Deflect.	+11%
		Center Lift / Longitudinal	Moment	+10%
			Shear	+ 8%
			Deflect.	+11%
2	e_mCL increased from 3.5’ to 4.5’	Center Lift/ Transverse	Moment	+38%
			Shear	+28%
			Deflect.	+38%
		Center Lift / Longitudinal	Moment	+36%
			Shear	+26%
			Deflect.	+38%
3	y_mCL = 0.85” e_mCL = 4.0’ increased to y_mCL = 1.4” e_mCL = 5.0’	Center Lift/ Transverse	Moment	+47%
			Shear	+27%
			Deflect.	+47%
		Center Lift / Longitudinal	Moment	+45%
			Shear	+33%
			Deflect.	+47%
4	y_mEL = 0.70” increased to y_mEL = 1.2”	Edge Lift/ Transverse	Moment	+43%
			Shear	+43%
			Deflect.	+51%
		Edge Lift / Longitudinal	Moment	+43%
			Shear	+43%
			Deflect.	+51%
5	e_mEL increased from 5.0’ to 6.0’ ’	Edge Lift/ Transverse	Moment	+16%
			Shear	+ 3%
			Deflect.	+14%
		Edge Lift / Longitudinal	Moment	+15%
			Shear	+3%
			Deflect.	+14%

Ex. #	Input Parameter Variation	Lift Type/ Direction	Output Type	Approx. Output Change
6	y_mEL = 0.70” e_mEL = 5.0’ increased to y_mEL = 1.2” e_mEL = 6.0’	Edge Lift/ Transverse	Moment	+66%
			Shear	+47%
			Deflect.	+72%
		Edge Lift / Longitudinal	Moment	+65%
			Shear	+47%
			Deflect.	+72%

As can be seen in the above table, small changes in PTI input parameters can have dramatic results on the foundation design requirements. (Other examples show that something as small as a change in e_m from 5’-0” to 5'-6" with an increase in y_m of approximately 1/4” can increase the flexural moments and deflections by 20% to 25%). The geotechnical engineer should specify these values as accurately as possible because their values have a significant impact on the design and the economy of the foundation.

2.0 LIMITATIONS OF THE PTI PROCEDURE AND DESIGN FORMULAS

The PTI design procedure is relatively straightforward. Once all the input parameters are determined, it is a procedure based on empirical data, computer generated curve fits and the geotechnical engineer’s computation of y_m and e_m values. Therefore, the geotechnical engineer and the foundation design engineer should be aware of the simplifications and pitfalls associated with the use of this procedure or any other design procedure. Design procedures are generally based on the interpretation of large amounts of complex data incorporated into design equations that are useful to the general engineering community. As with any design procedure some considerations requiring judgment will always remain. For example, most design engineers ignore the deflection due to shear stresses when calculating the deflection of the majority of their beams and columns.

2.1 Areas Where Additional Research May Be Useful

We have listed some areas where fine-tuning of the PTI design procedures would be useful to the foundation engineer. The result of this work would further limit engineering judgment required for designs:

a) Load Range

The PTI design formulas were generated using linear loads (P) at the slab perimeter, which range from 600#/ft to 1500#/ft. While the lower limit is consistent with residential design, it has been our experience that perimeter loads can have an upper value from 2000#/ft to 3000#/ft on some larger homes, town homes and apartments. Therefore, the upper bound appears low and the formulas give results that may or may not be conservative for higher loads.

In the case of large edge loads, we can envisage that the edge lift would be mitigated by the much higher vertical soil stresses. In the extreme, a large edge load could cause edge settlement and center lift. Therefore it appears that there is a need for more research with higher perimeter loadings to verify the validity of the existing equations.

b) Torsional Moments in Slabs

In our forensic work we frequently see a typical slab failure in the popular L-shaped residential buildings. It is depicted in Figure 1 below:

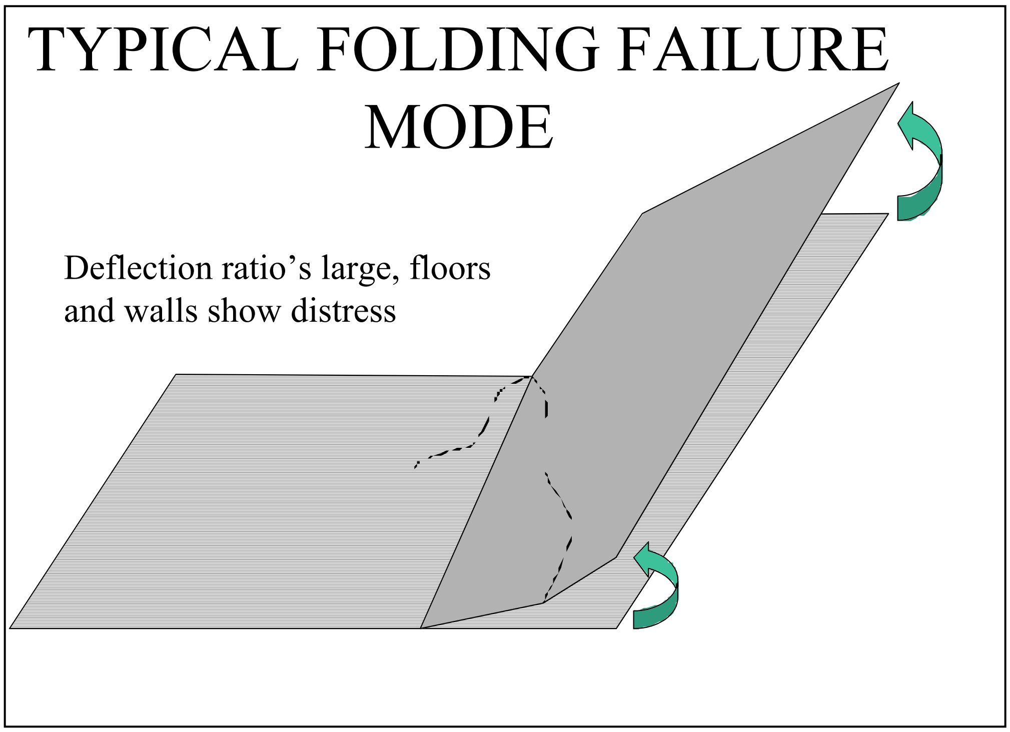

Figure 1: Typical slab failure.

The crack often starts at the inside corner of the L-shaped slab. With homogeneous slab soil support conditions this can logically be explained by a torsional moment which develops at the inside slab corner even for homogeneous soil support conditions. This consideration is ignored by the PTI design method because it is based on a combination of rectangles as follows:

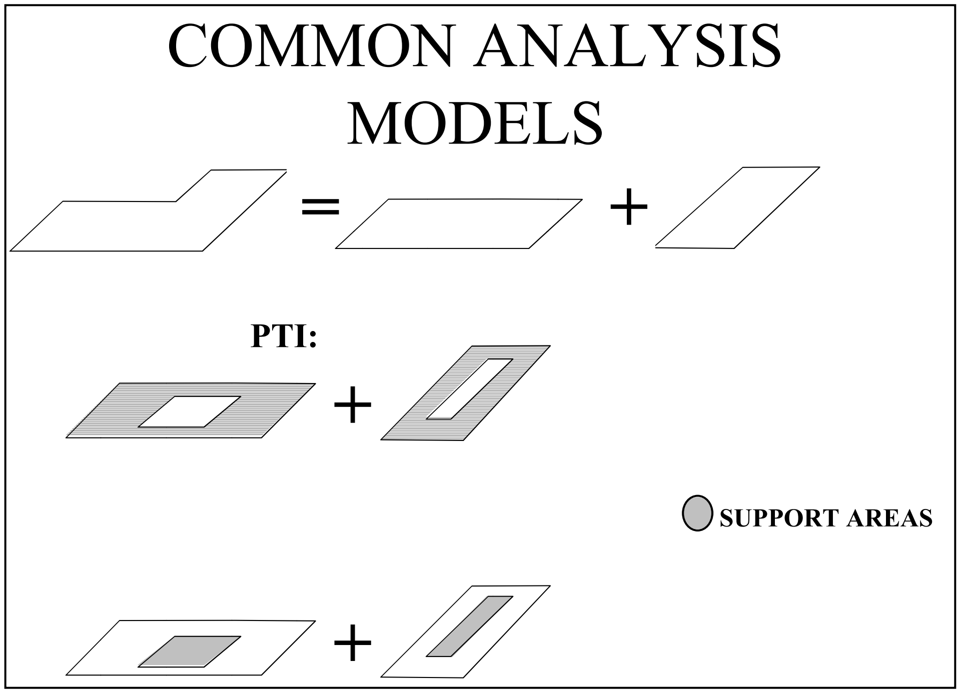

Figure 2: Common analytical models as per PTI

There is no consideration what so ever for the popular L-shape of the foundation slab. It is assumed that the proper design is obtained when the design of the two rectangles satisfies the design condition for the L-shaped foundation. In the WRI design procedure the same assumption is made, BRAB design requirements include a diagonal loading condition as well. The same argument holds for a U-shaped slab and other irregularly shaped slabs. Research is suggested to help the foundation design engineer properly evaluate this torsional effect.

c) y_m and e_m Values

i.e. what should be the design life of a residence?

The design of a slab-on-grade depends on the proper choice of e_m and y_m values. Apart from soil parameters, these values depend on the proper choice of the Thorthwaite index. Values for this index can be read from a map for any particular location. Because of the natural variability in the local annual climate it makes a difference over what period this index is computed.

Suppose we design a house for a 50-year lifetime. *Do we use a 50, 75, or a 100-year Thornthwaite Index for our calculations? Are our historical data good enough for such a determination? Or should we blindly take a value suggested by a map for a particular area and then consider a range of +/- 20, as is occasionally done by some Dallas foundation design engineers?*

This raises important questions here that are interrelated and inseparable:

1) ***What is the design life of a house? Is it the longest period for which one can get a mortgage? Or what is it?*** The applicable design codes fail to provide an answer we need to choose an appropriate Thornthwaite index. This is a complex question of which the answer has large economic consequences.

2) ***Over what time period is the Thornthwaite Index computed: on the average of 20 years? the extreme of 20-year historical data? 50 years? What is the design basis for the Thorthwaite index?*** In other words, the technology to design for a 20, 30, 50 or a 100-year life of a concrete slab needs to be addressed.

3) ***How does homeowner foundation maintenance affect the design life expectancy of a foundation? e.g., extent and frequency of grounds irrigation, proper drainage maintenance, vegetation maintenance, etc.?*** For further information, see Document No. FPA-SC-07, "Foundation Maintenance and Inspection Guide for Residential and Low-Rise Buildings," freely available at www.foundationperformance.org

Recently the PTI adopted an updated "Appendix A" which is expected to modify their current (1996) manual when published. The FPA Structural Committee used both the 1996 PTI procedures and the modified (2002) PTI procedures to derive the center lift and edge lift parameters for soil conditions representative for the Flower Mound, Texas area.

The program VOFLO 1.0 was used to perform the necessary calculations to obtain the PTI foundation design parameters. The 1996 PTI procedures have a banded value for e_m as a function of the Thornthwaite Index. The VOFLO program allows the derivation of the e_m values based on the center, top and lower band relationship. In addition, the foundation edge beam can be introduced as a vertical moisture barrier for moisture moving from one side of the beam to the other. The foundation design parameters that were obtained are tabulated below.

Method	Thornthwaite Index Used	Vertical Barrier Depth (Edge Beam - feet)	Center Lift		Edge Lift	
			y_m (inches)	e_m (feet)	y_m (inches)	e_m (feet)
1996 PTI	0, Center Band	2	1.45	4.3	1.90	3.7
1996 PTI	0, Center Band	None	3.04	4.3	4.43	3.7
1996 PTI	0, Top Band	2	1.45	5.1	1.90	4.1
1996 PTI	0, Bottom Band	2	1.45	3.5	1.90	3.3
2002 PTI	0, Modified PTI	2	1.45	9.0	1.90	4.7

The range of values for y_m is consistent for all cases as one would expect a higher y_m value for the case no vertical barriers are considered. The modified (2002) PTI procedure does not have a provision for moisture barrier.

However, the e_m values increase drastically when the modified PTI procedure is used for the calculation. For center lift the increase is almost a factor of two and for edge lift it is on the order of 20%. Application of this procedure to other typical soil profiles give similar results i.e., when the modified PTI procedure is used larger e_m values are obtained. It means that the slab must be designed for a much larger cantilever in center lift. The past performance of slab-on-grade foundations does not clearly indicate a need for such an increase in e_m. Similarly, the y_m values for edge lift are also found larger when the modified procedure is used.

The FPA Structural Committee feels that additional economic and environmental parametric research would be appropriate.

d) Validity of the Parametric PTI Equations

The PTI procedures are based on parametric studies of design parameters. The computed results were then related to design variables through regression analysis procedures. No practical design information is available on what the variance is of the solutions. Questions in this area may not be unreasonable. This is demonstrated by the difference in design for two rectangular slabs with slightly different dimensions. In the PTI rules there are two different sets of design formulas used for length/width ratios above and below 1.1. There may be no physical reason for that to be the case, however it may be necessary due to mathematical modeling.

We chose the PTI example Appendix A.6 and modified that example for purpose of illustration. The length and the width of the slab were modified to 25*27.49 ft and 25*27.51 ft respectively. The number of beams in both directions was changed to 4. No other changes were made. The solutions for these practically identical conditions should approximately be the same. However, we found the results summarized in the following table:

Slab Dimensions (feet)	M_{MAX} Center Lift K* (feet/foot)	M_{MAX} Center Lift K* (feet/foot)	M_{MAX} Edge Lift K* (feet/foot)	M_{MAX} Edge Lift K* (feet/foot)
	Short Direction	*Long Direction*	*Short Direction*	*Long Direction*
25*27.49	11.59	11.59	2.68	2.68
25*27.51	12.27	11.59	3.03	2.68

The differences shown in the above table for equivalent values are larger than expected for the short direction. Such and similar potential differences are not addressed in the PTI manual. *Are the tests and design data used to produce these equations (some with four significant digits) really that precise when dealing with soil?*

Additional research and validation seem justified to update the parametric equations.

e) Uncertainty in the Soil Support Parameters

PTI-designed slabs are often supported by layered soil systems with varying bearing capacities and soil expansion characteristics. *How does the geotechnical/foundation engineer treat a layered system and to what depth?*

f) Pre-Construction Weather and Local Climatic Conditions (Natural and Man-made)

The y_m and e_m values which are used for local foundation designs are based on long-term regional climatic and soil conditions (Thornthwaite Index) and therefore do not consider local short-term conditions such as the effect of heavy rains, flood plains, side hill drainage, lot vegetation, tree removal, the season during construction (a dry summer, for instance) and the soil moisture conditions at the time of construction. Guidelines should be provided in order that geotechnical engineers may adequately account for these short-term conditions.

In areas where the soils are naturally dry (such as Dallas and San Antonio) consideration should be given to short-term accelerated moisture changes that are owner-induced. In areas that are generally considered relatively dry, once an owner or tenant moves in and establishes a yard, the soils will most likely receive moisture (in the form of irrigation around the foundation) that often exceeds the normal rainfall. Where expansive soils exist, this can cause non-uniform swelling of the soil around the foundation, thereby creating edge lift that could be in excess of the design criteria. Further research should delineate the design consequences of these effects.

The y_m and e_m values must be optimized for pre-construction moisture conditions and ensuing moisture variations. Both short- and long-term climatic conditions should be considered in the PTI parameters provided for the design of the foundation.

Should the initial moisture content at the time of construction and the equilibrium moisture content at a later time be addressed by the PTI method or by the geotechnical engineer using the PTI method? In either case, the PTI method should include suitable guidelines for this to happen.

g) Edge Lift and Center Lift Soil Support Areas

Simplifying assumptions were made for the soil support conditions when the original calculations were made for the PTI procedures in the seventies. These support conditions consisted of a band with a certain width for both center lift and edge lift (see Figure 3):

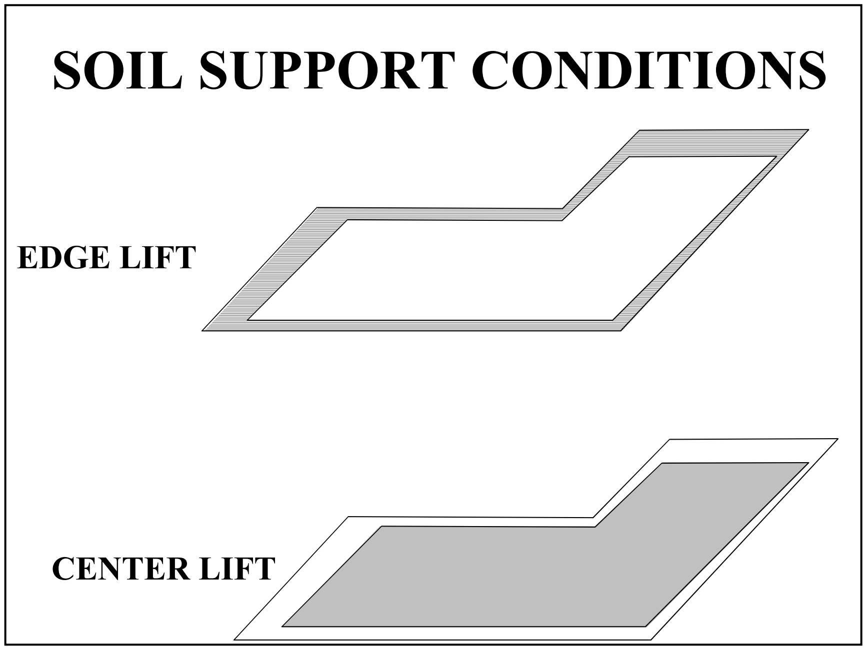

Figure 3: Soil Support Conditions as used for the original PTI calculations

These soil support bands are of equal width and do not consider the influence of the shape of the slab, especially interior slab corners. It is not reasonable that edge lift conditions at the edge outside corners would be the same as for the inside corners of the L-shape. A parallel question is valid for the center lift condition.

A more likely support condition for center lift and edge lift conditions is depicted in Figure 4:

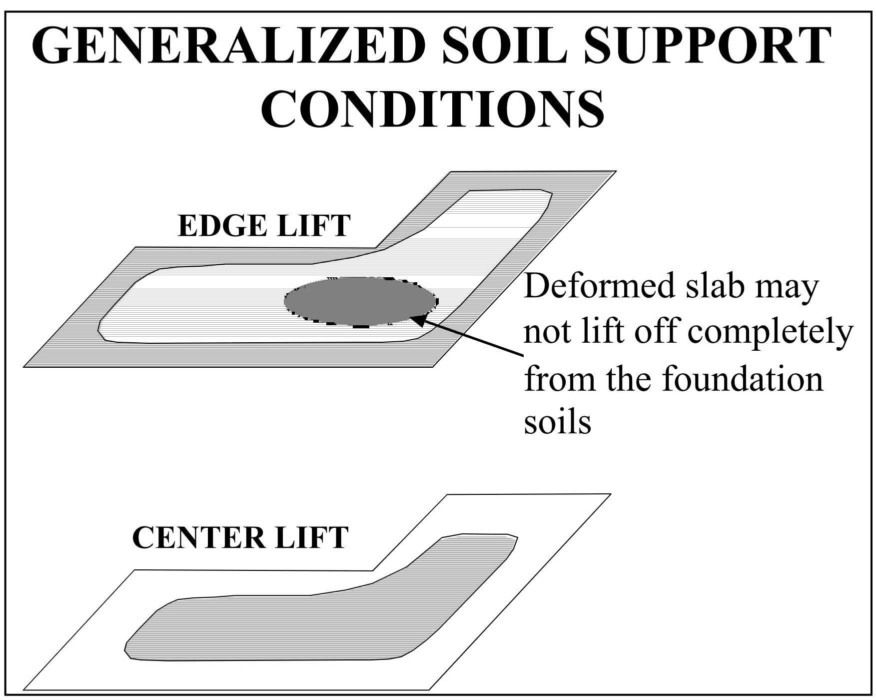

Figure 4: Generalized Soil Support Conditions.

Not only does the shape of the soil support band, or area, vary with the size and shape of the foundation, but the support pressures also vary from location to location. When the slab deforms as a function of edge lift, the center area of the slab may deflect so that it still touches the supporting soil underneath, decreasing the slab deflections.

More data relative to these observations would make the calculation of design moments and shears more realistic.

h) Variable Soil Conditions

No design calculation procedures are recommended if variable soil conditions are present at the slab location. In this context, variable soil conditions consist of significantly varying in-situ moisture contents, or either horizontal or vertical soil changes beneath a slab. This soil condition is not uncommon for areas where cut and fill is used during construction.

It is frequently observed, as part of forensic data gathering, that the soil types and soil moisture conditions differ vastly from one side of the house slab to another. Even for the simplest two-dimensional variation in expansive soil conditions such as depicted in Figure 5, no suitable design guidelines exist:

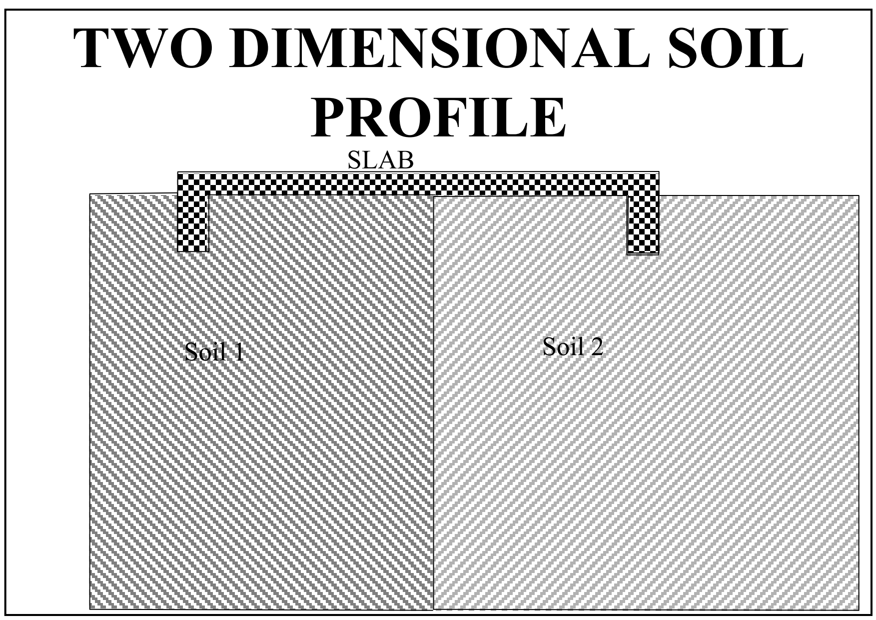

Figure 5: Simple hypothetical two-dimensional non-homogeneous soil profile

There is a need for design research that would indicate, what soil conditions, and slab design support conditions need to be refined (i.e., parameter sensitivity and average effective design parameters).

Soil support pressures and deformations in one area beneath the slab influence the support pressures and deformations in another. Some progress has been made to define these support pressures as well as support areas. Researchers at Texas A&M University used the Boussinesque Theory to derive approximate support conditions using a Finite Element Procedure. However, there are no commercial calculation or simulation guidelines available to the designer.

2.2 Updates to Original Geotechnical Report used for the Foundation Design

The process of subdivision development has been known to create conditions that were not anticipated by the geotechnical engineer who prepared the report for design of the foundations. An example of this would be a subdivision with several elevation changes, requiring that the lots be developed in a stair-stepped configuration. In the civil engineer's design, drainage patterns may adversely impact bearing soil capacities due to water table changes. For this reason, the final drainage designs should be returned to the geotechnical engineer of record for comments.

3.0 CONCLUSIONS

- The actual formulas used to determine the design values for slab-on-grade foundations may be further confirmed by additional research and validation.

- The major factors influencing the design are the y_m and e_m values provided by the geotechnical engineer.

- The modified (2002) PTI procedure to derive the center lift and edge lift parameters for soil conditions (the Appendix A) is more conservative than the original procedure. We are not certain this added conservatism is economically justifiable in view of the performance of foundations designed with the existing PTI procedure.

- Based on the range of values presented in this document for the same locations, it would appear that if a slab-on-grade foundation does have a problem due to the design itself, the problem could very well be due to incorrect geotechnical design values.

- Given the same site to be developed and the same PTI design method, geotechnical engineers should provide similar PTI design parameters for the foundation design engineer.

- There are PTI design areas where further research aimed at validation could lead to more economic designs over the life of the foundation and the structure that rests upon it.

4.0 RECOMMENDATIONS

- More research is needed by PTI (or their designates) to simplify the PTI design procedure It should be confirmed that the modified (2002) PTI procedure to derive the center lift and edge parameters for soil conditions (the Appendix A) is economically justifiable in view of the performance of foundations designed with the existing PTI procedure.

- The PTI method must be improved to provide guidelines for heterogeneous soil conditions in terms of soil properties or moisture content.

- We recommend that geotechnical engineers follow the guidelines recommended in document # FPA-SC-04, "Recommended Practice for Geotechnical Explorations and Reports" publicly available at www.foundationperformance.org. This will lead to a more uniform specification of design parameters for the same site by different geotechnical companies.