SLAB-ON-GROUND ALTERNATIVE DESIGN (SOGAD): A BLEND OF ART AND SCIENCE

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The use of post-tensioned residential slab-on-ground foundations has spread from the original confines of Texas throughout the U.S. as the inherent benefits of post-tensioning have become apparent. PTI has been the leader in the development of slab-on-ground design methods, code documents, construction recommendations, and maintenance recommendations since their first publication, "Design and Construction of Post-Tensioned Slabs-on-Ground," was printed in 1980. As the use of post-tensioned foundations has expanded into these new areas, many in the engineering and construction communities have discussed the desire for the development of alternative design methods. This paper documents the significant work of the PTI Slab-on-Ground Alternative Design (SOGAD) Committee, DC-15, and looks at the various options considered, along with new preliminary design concepts dealing with the geotechnical and structural disciplines.

KEYWORDS

Center lift; edge lift; effective swell (ES); expansive soils; post-tensioned slabs-on-ground; soil activity coefficient (SAC); soil saturation coefficient (SSC); swell potential (SP); total swell correction (TSC); total swell potential (TSP); uniform thickness foundations.

INTRODUCTION

As most experienced geotechnical and structural engineers will attest, the design of residential slab-on-ground foundations is truly "a blend of art and science" and is one of the more challenging design assignments one can receive. PTI published the "Design of Post-Tensioned Slabs-on-Ground" (third edition, 2004), along with the companion publications "Construction and Maintenance Manual for Post-Tensioned Slab-on-Ground Foundations" (third edition, 2006), "Standard Requirements for Analysis of Shallow Concrete Foundations on Expansive Soils" (2007), and "Standard Requirements for Design of Shallow Post-Tensioned Concrete Foundations on Expansive Soils" (2007). PTI currently has available the "Design of Post-Tensioned Slabs-on-Ground 3rd Edition with 2008 Supplement" and is continually advancing this technology through its technical committees.

This paper will document the work of the PTI Slab-on-Ground Alternative Design (SOGAD) Committee from its formation in early 2007 through the recent merger and reorganization with PTI's current Slab-on-Ground Committee, DC-10. Included are brief descriptions of the geotechnical swell design concept and the structural beam/plate bending theory design concept. Basic steps are outlined in Table 1 (see page 66).

SLAB-ON-GROUND ALTERNATIVE DESIGN COMMITTEE, DC-15

In the fall of 2006, PTI's Board of Directors issued a mandate to establish a new technical committee, working independently of the long-standing PTI Slab-on-Ground Committee, to explore options for the development of an alternative design method(s) for residential ground-supported foundations.

A committee of 14 members composed of practicing geotechnical and structural engineers from across the U.S. was assembled in early 2007. In addition to the committee members, regional peer group (RPG) members were established in the Dallas/Fort Worth region, Houston/Austin/San Antonio region, Denver region, Phoenix/Tucson/Las Vegas region, and California region. This organizational concept allowed the participation and input of over 75 of the most active structural and geotechnical engineers in the field of slab-on-ground design while keeping the size of the actual committee manageable. An additional organizational goal was accomplished by bringing engineers into the process who had not been involved with the development of the existing PTI design method. This organization and developmental process brought in fresh ideas, experience, and opinions from all

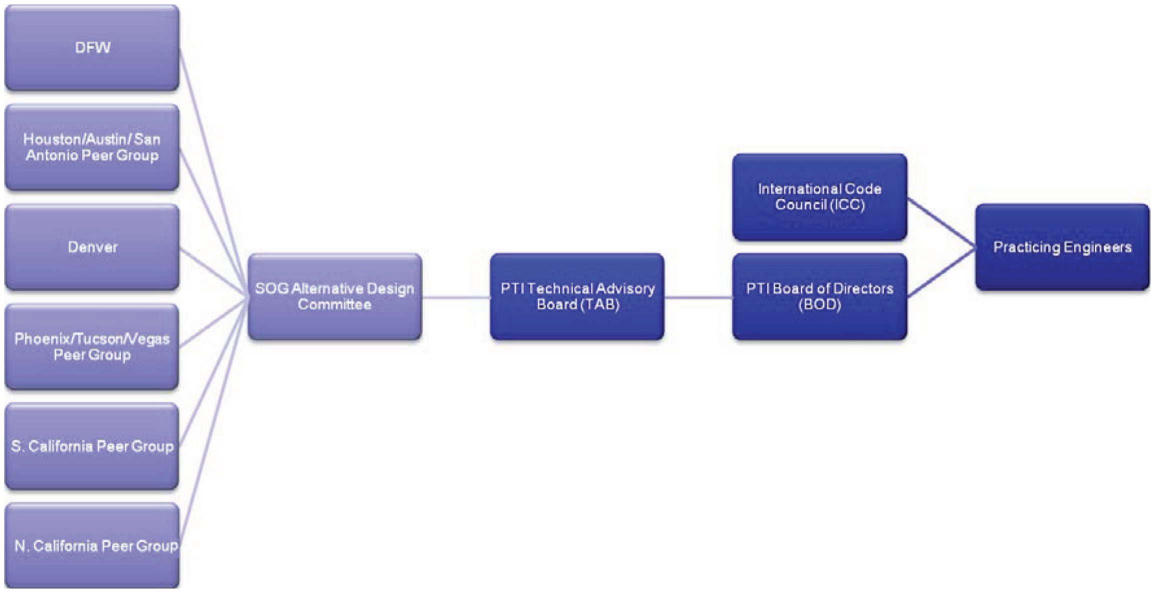


Fig. 1

of the major regional areas using slab-on-ground design (refer to Fig. 1).

Over the next 18 months, 12 meetings in seven cities along with seven conference calls were held to get input and recommendations from this diverse engineering group. There were also communications with other trade associations and several well-respected engineering universities. Everyone involved agreed that an alternative design method would be a helpful tool to have and preferred that it be based on the use of traditional geotechnical testing procedures (swell tests, moisture content, PVR, PI, and consolidation swell) and on basic beam/plate bending theory analysis using moments, shears, and deflections.

REVIEW OF COMMITTEE'S OPTIONS

Many ideas and options were introduced by this enthusiastic group of experienced engineers. The major options to be considered included:

- Developing a new "soil activity" number based on some form of traditional geotechnical testing method calibrated with regional inputs (swell tests, moisture content, and consolidation swell);
- Developing a new structural design method based on the beam/plate bending theory of a slab spanning over a deformed soil profile;
- Developing an empirical design method or including empirical considerations in any new or existing methods;
- Developing equivalent strength design methods for use with BRAB, WRI, and other existing methods;
- Developing conversion methods for uniform thickness slabs to ribbed slabs and ribbed slabs to uniform thickness slabs;
- Developing finite element methods;
- Establishing a perpetual process of evaluating "slab performance" using standard inspection procedures, standard forms, and a national database;
- Developing, publishing, and promoting guidance recommendations on proper design, material specifications, construction, maintenance, and inspection;
- Developing a comprehensive publication(s) illustrating typical design examples for the various design regions;
- Establishing relationships with other trade associations to promote standardized recommendations regarding design methods, material specifications, construction, maintenance, and inspection (trade association partners [TAPs]); and
- Establishing relationships with regional universities to help with the research, creation, and maintenance of slab performance database and educational activities (academic peer groups [APG]).

The committee concentrated its efforts on the development of the new geotechnical and structural methods, as discussed previously. A brief outline of the swell design method for edge lift and edge drop follows.

GEOTECHNICAL DESIGN METHOD

Preface

The PTI SOGAD Committee developed a suite of alternative design procedures to address geotechnical design for expansive soils, shrinking soils, collapsing soils, soil consolidation, and secondary compression. For the purpose of this article, a brief description of the swell design method will be primarily presented. Because the swell and shrink methods are so closely related, there is some discussion of the shrink method contained in this article, but the focus is on a swell design condition.

Introduction

These procedures have been developed as an alternative to the method presented in the "Design of Post-Tensioned Slabs-on-Ground," third edition. Some of the elements that have been incorporated into these design methods include:

- Use of field sampling equipment commonly used;
- Use of laboratory testing methods commonly used; and
- Use of engineering design calculations commonly employed.

The base concept is that in-place soil samples would be obtained during field exploration, relating to the significant soil layers (soils that can shrink, swell, collapse, consolidate, and/or compress) within the design soil profile. These representative samples would then be tested to determine their design properties, as deemed appropriate in the judgment of the design engineer or RPG.

Shrink/swell soils

The structural members of the committee have also devised an alternative method of design based on using beam/plate bending theory. Geotechnical engineers need to provide structural engineers with the following parameters for post-tensioned slab-on-ground design:

- Bearing capacity (psf);
- Coefficient of friction;
- Effective swell (ES+) in swelling condition; and
- Unsupported length (UL) in shrinking condition.

Once the swell percentages are determined from laboratory testing, they may then be used to calculate the swell potential (SP+) that could occur within an individual significant soil layer.

In addition to these commonly used design elements, this method introduces two concepts that are incorporated into calculations of the design procedure. They are:

- Soil activity coefficient (SAC); and
- Soil saturation coefficient (SSC).

Properly used, these coefficients correct the total swell potential (TSP+) to determine an appropriate design value (ES+), which will be used by a professional engineer in the structural design of a post-tensioned slab-on-ground.

General discussion

The SAC relates to the soil's potential to impart differential movement to a foundation system. It is expected that this coefficient will more than likely be applied in a banded fashion to the soil profile (refer to Fig. 2), summed to determine a total swell correction (TSC), which is then subtracted from the TSP calculation. Subtracting the TSC from the TSP yields the (ES+).

It is acknowledged that the swell of the same soil will likely be different under different confining pressure; this is accounted for by performing swell testing under a surcharge and/or correcting for the appropriate loading. The SAC is meant to correct for the difference between the swell-min and swell-max expected to be imparted to a foundation system. For example, a soil with similar properties at different depths will not impart the same differential swell movement to a slab. This value could be banded within the design soil profile—for example, 0 to 5 ft 10%, 6 to 10 ft 50%, and 11 to 15 ft 90% (refer to Fig. 2). In this case, the design soil profile was identified as having a 15 ft (4.6 m) depth. The SAC coefficient can be different for a swelling condition versus a shrinking condition and may well justify specific values being set for specific soil/bedrock types within the local region, where the soil/bedrock types are known to be problematic.

The SSC relates to the soil's potential to become saturated (swell) or dry out (shrink) throughout the design soil profile. For example, rarely do all soils in a soil profile become completely saturated or completely dry out. This coefficient is meant to correct the TSP for soils that are not reasonably expected to be saturated or dry out throughout the entire depth of the design soil profile. Drainage and landscape maintenance are important portions of this coefficient and should be carefully considered. Poor drainage or landscape maintenance would increase this coefficient and good drainage or landscape maintenance (for example, International-Code-Council-compliant drainage and/or proper irrigation) would decrease this coefficient. This coefficient could also be applied in a banded fashion (refer to Fig. 2).

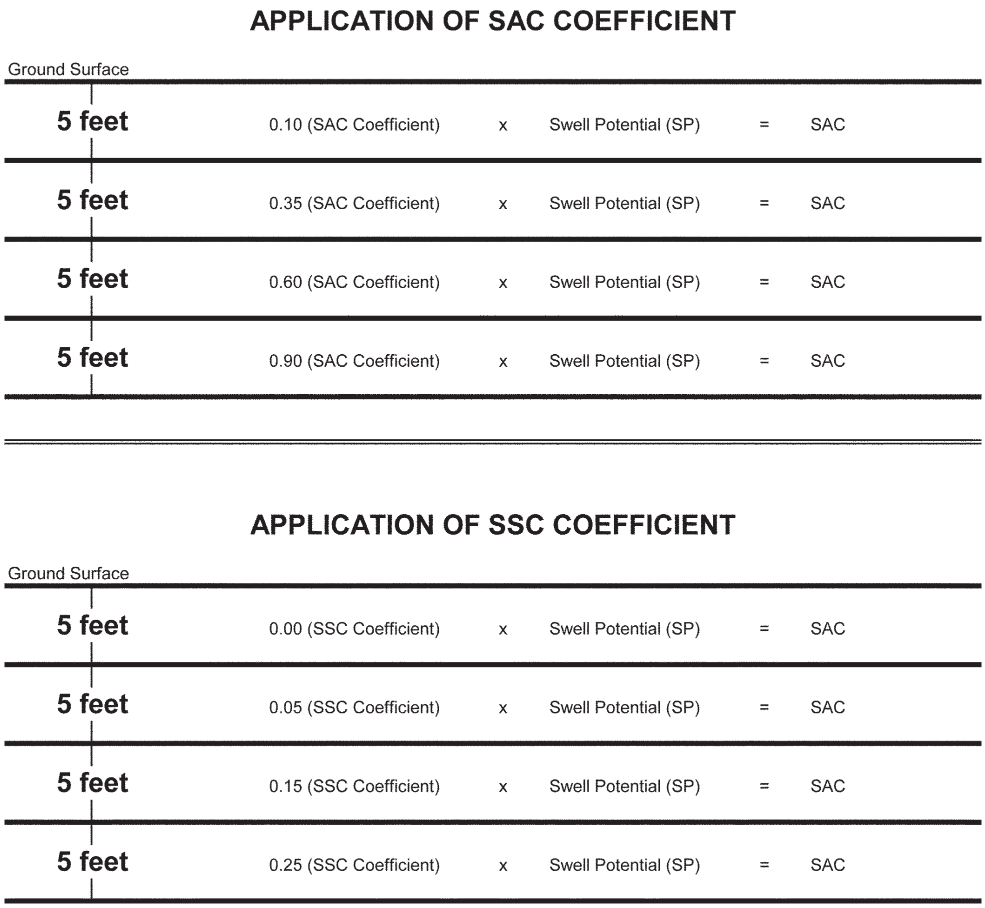


Fig. 2—(Note: 1 ft = 0.3048 m.)

Regional Peer Groups

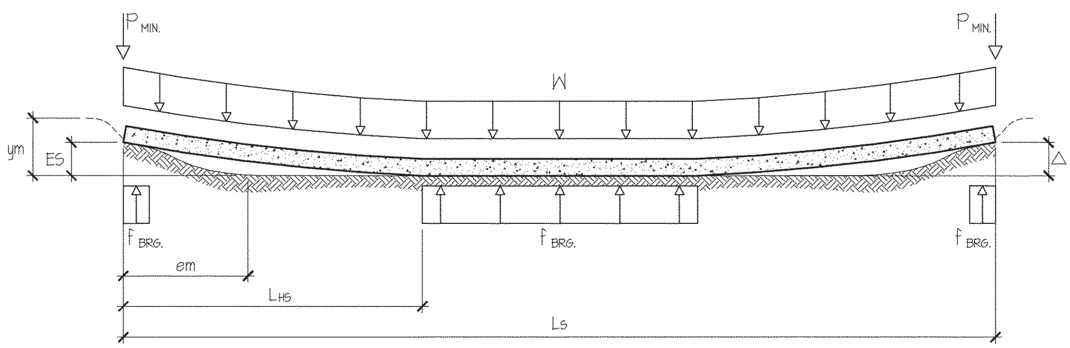
These alternative design procedures are meant to be calibrated by RPGs that will establish proper minimum design values for the SAC and SSC and active and design soil profiles' depths, along with minimum field investigation and laboratory testing standards. This calibration is meant to consist of running trials and comparing those results to known designs that have worked in the regional area.

Landscape irrigation and maintenance of that landscaping can significantly change natural conditions. Each RPG should consider the standards for landscaping and the expected maintenance necessary to preserve landscaping in a reasonable manner. One can often determine the recommended irrigation necessary to properly sustain plant life using a local or regional water district's prescribed watering schedule, subtracting plant use and evaporation and adding perception.

RPGs are also meant to establish the "Standard of Practice" and the minimum "Standard of Care" for their regional area. This procedure will introduce some minimum suggested design parameters, but these criteria are not meant to supersede any "Standard of Care" minimums established by a local peer group. It would be best if the local peer groups also involved the local municipalities that govern the building codes (that is, the International Building Code [IBC] and IRC). It is encouraged that the peer group meet periodically (for example, every code cycle) to compare performance notes and make any necessary adjustments to the "Standard of Practice" or the minimum "Standard of Care" established by the group. It is suggested that these standards be incorporated into the local amendments to the IBC and IRC.

For areas that do not have an RPG established, the "Standards" can be set using the slab-on-ground committee to work with local geotechnical engineers and municipal agents to provide guidance in understanding the overall procedure. The committee will aid in establishing what will be a new area's initial "Standards" for the area.

The selection of the RPG members will be done by the committee with input from local engineers and/or municipal agents.



$$\text{IF } L_{HS} \leq \frac{L_S}{2} \text{ OR } \frac{L_L}{2} \text{ THEN } \Delta = ES = \frac{2L_{HS}}{C_\Delta}$$

Fig. 3—Edge Lift Case 1.

Swell design

For soils that start in a dry state and are reasonably expected to gain moisture, no shrinkage testing is believed necessary unless the RPG determines otherwise. Trees and the location of trees should be considered in design, as they can tend to increase water uptake and cause moisture regime changes to the surrounding soils. This may tend to create a greater differential between swell-min and swell-max, necessitating a change to the design ES beyond what would otherwise be determined.

Determining swell

Based on the results of laboratory testing and the determination of the soil parameters by the RPG, one can now perform the necessary engineering analysis to determine the differential edge lift swell a post-tensioned slab should be designed to resist (ES+ in inches). The procedure is relatively simple and is not meant to be more complicated than outlined in the following steps:

1. First, the designer should determine a representative design soil profile or profiles to be analyzed, as reflected from the boring/excavation logs. This can be done collectively as a composite design soil profile, or the engineer can analyze each log separately. For larger projects and sites with variable subsurface conditions, this is the preferred method. For some sites, different design values (ES+ in inches) for the identified conditions are very appropriate.

2. Next, the engineer should select representative laboratory testing results (a single point or a plot of several results) corresponding to each of the significant soil layers. These significant soil layers would generally be categorized by those that can swell and by their unified soil classification system (for example, CH, SC, CL, and ML). Note that these significant soil layers can/may need to be subdivided.

3. Next, one would use these swell results to determine the SP+ of each significant layer within the soil profile. This is done by taking the thickness of the layer and multiplying it by the percent (%) swell.

4. Once this is done for each of the significant soil layers in the design profile being analyzed, those results are added together to determine the TSP+ for the profile.

5. The next step is to apply the correction coefficients (SAC, SSC) to each significant soil layer in the profile. This is done by multiplying the SP of each significant soil layer by the appropriate correction value. Then, add these swell correction values for each design soil profile being analyzed. This determines the TSC.

6. The final step in the procedure is to subtract the TSC from the TSP for each design soil profile being analyzed to determine the ES. You now have determined your design ES+ value for the soil profile analyzed.

The reader may refer to Fig. 3 for a flowchart for the geotechnical portion of the design method.

STRUCTURAL DESIGN METHOD

Preface

The goal of the new structural method was to create a set of structural equations based on the beam/plate bending theory from engineering mechanics while maintaining the complex soil-structure interaction and three-dimensional (3-D) analysis of the current method. It is important to structural engineers that the design equations are derived from beam/plate theory so that: 1) the design is more intuitive and rational; 2) moment, shear, and deflection are related to one another; and 3) future modifications to the equations can be readily understood, considered, and implemented.

Introduction

The structural behavior of slabs-on-ground on expansive soil can be modeled by the beam theory, with the plate theory for 3-D effects where appropriate. The complex soil-structure interaction is captured by the introduction of two new variables—namely, ES and UL. The maximum expected soil movement (swell or shrinkage) is presumed to occur equally at all edges of the slab. This represents the "worst-case" scenario for design. The design is based on a uniform thickness foundation, but the solution may be converted to a conformant ribbed foundation. Edge lift and edge drop (currently labeled "center lift" in the PTI documents) are considered. New soil modes center lift and center drop are not considered in this paper.

Edge lift

Edge lift is analogous to a uniformly loaded beam with a narrow edge support at each end and a variable length support in the interior (refer to Fig. 3, Edge Lift Case 1). In some cases, the slab must clear the span for the full width and/or length of the slab, as the center support is removed (refer to Fig. 4, Edge Lift Case 2). In this model, a new soil variable is required, namely

ES = Effective Swell from Edge Lift, in.

Another new variable, the length of the half span, must be defined. The length of the half span represents half the length of a simple-span uniformly loaded beam with deflection equal to ES and is derived from beam theory equations.

L_{HS} = Length of half span from edge lift, in.

$$L_{HS} = (4.8E_{cr}I\text{ES}/w)^{0.25}$$

where w is in lb/in.

The length of the half span needs to meet the angular distortion limits of the building materials. This is essentially the stiffness design requirement. The designer increases I to increase L_{HS} to meet the angular distortion limits for a given ES. Once the length of the half span is established, the moment and shear requirements are easily calculated for either Case 1 or Case 2.

If the slab is infinitely long in the long direction, the slab spans in one-way bending across the short direction; as the slab approaches a square, two-way bending effects become significant. The aspect ratio of the design rectangle determines the amount of two-way bending that is present. The r factor listed in the following is used to adjust moment, shear, and stiffness requirements for two-way bending in Edge Lift Case 2.

Design rectangle aspect ratio L_L/L_S	r
5	1.0
4	0.99
3	0.95
2	0.81
1.9	0.79
1.8	0.76
1.7	0.73
1.6	0.69
1.5	0.65
1.4	0.60
1.3	0.56
1.2	0.50
1.1	0.44
1.0	0.38

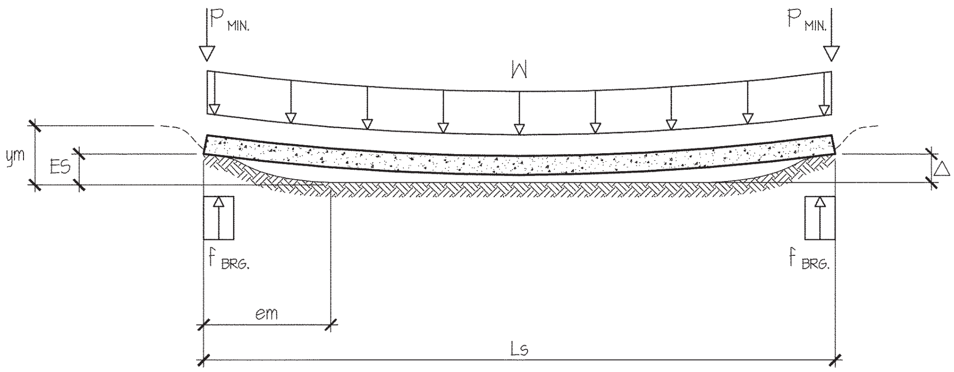
Edge drop

Edge drop is analogous to a beam with cantilevers at both ends with a concentrated point load at each end and a uniform load along the span (refer to Fig. 5, Edge Drop Case 1). The upward deflection of the back span of the cantilevers reduces the slab-soil contact surface area and increases the soil-bearing pressures. In some cases, there is no back span as the width and/or length of the slab is reduced (refer to Fig. 6, Edge Drop Case 2). In this model, a new soil variable is required, namely

UL = Unsupported Length from Edge Lift, ft

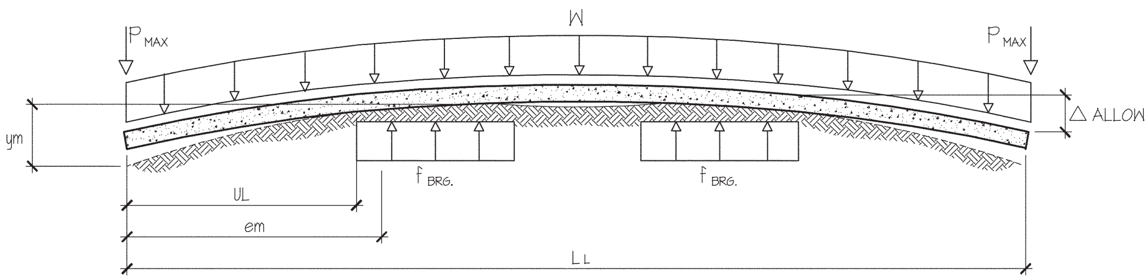
With the unsupported length defined, the moment, shear, and stiffness requirements are easily calculated. Again, angular distortion limits of the building materials are used to determine the stiffness requirement.

The length of the design rectangle determines the length of the cantilever back span. For relatively short slab dimensions, as the length of the back span approaches 0, the deflection at the end of the cantilever is reduced. Also, at the extreme case where UL is greater than $L_s/2$, the UL must be reduced, as the soil-bearing area must be sized to resist the applied loads. For these reasons, the short direction of the design rectangle does not control the edge drop



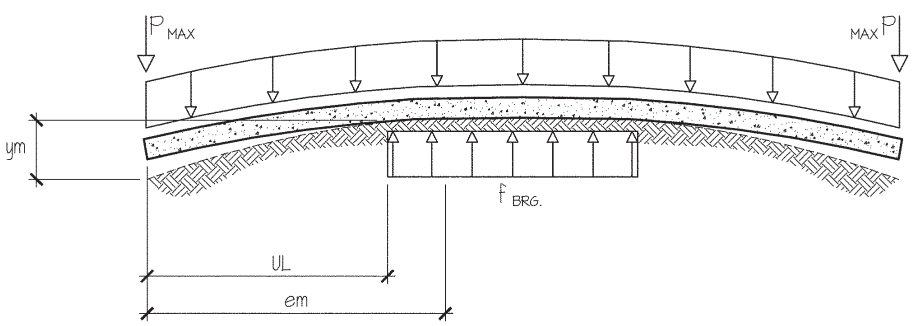
$$\text{IF } L_{HS} > \frac{L_S}{2} \text{ OR } \frac{L_L}{2} \text{ THEN } \Delta = \frac{L_S \text{ OR } L_L}{C_\Delta} < ES$$

Fig. 4—Edge Lift Case 2.



$$\text{WHEN } L_C \leq \frac{L_S}{2} \text{ OR } \frac{L_L}{2}$$

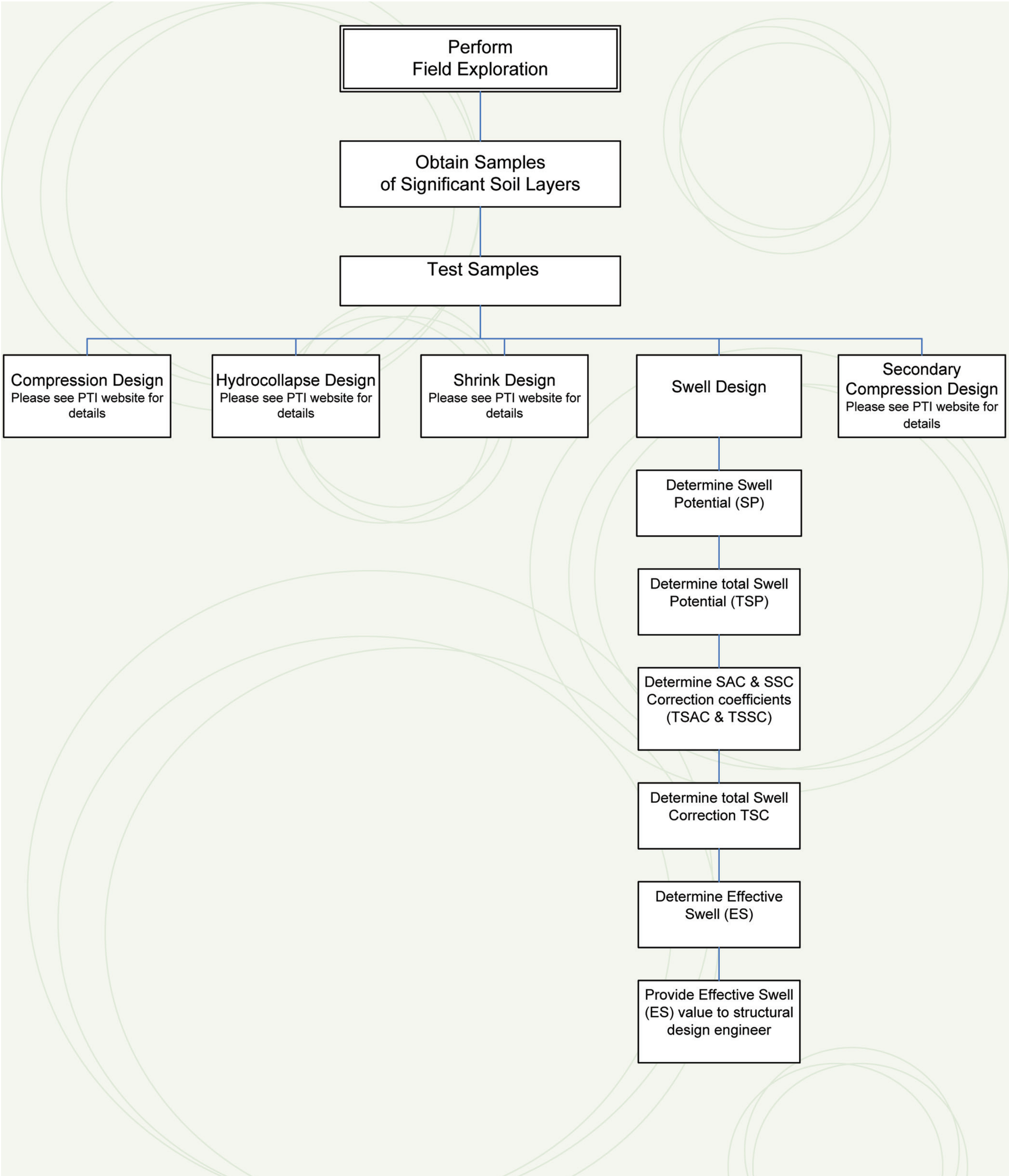
Fig. 5—Edge Drop Case 1.



$$\text{WHEN } L_C > \frac{L_S}{2} \text{ OR } \frac{L_L}{2}$$

Fig. 6—Edge Drop Case 2.

Table 1


Perform
Field Exploration
Obtain Samples
of Significant Soil Layers
Test Samples
Compression Design
Please see PTI website for details
Hydrocollapse Design
Please see PTI website for details
Shrink Design
Please see PTI website for details
Swell Design
Secondary Compression Design
Please see PTI website for details
Determine Swell Potential (SP)
Determine total Swell Potential (TSP)
Determine SAC & SSC Correction coefficients (TSAC & TSSC)
Determine total Swell Correction TSC
Determine Effective Swell (ES)
Provide Effective Swell (ES) value to structural design engineer

slab design. On the other hand, as the back span increases, the deflection at the end of the cantilever is increased. Therefore, the long direction of the design rectangle controls the edge drop slab design.

Conclusions

The alternate structural design method defined in this paper applies for post-tensioned slabs-on-ground on expansive soil. The procedure does not address compressible or collapsible soils. The alternate structural design equations rely on two new soil variables, ES and UL, both of which model the complex soil-structure interaction. The ES represents the effective swell from edge lift. The UL represents the unsupported length from edge drop. The moment, shear, and stiffness equations are derived from the engineering mechanics beam theory. The method includes 3-D effects from the plate-bending theory when appropriate.

SUMMARY AND CONCLUSIONS

This article gives insight into the work that was done by the PTI SOGAD Committee and generates new ideas in this challenging field of residential slab-on-ground design. It is anticipated that the new consolidated PTI Slab-on-Ground Committee, DC-10, will pursue the incorporation of these alternative design concepts into future design manuals and code documents and that the other options and recommendations presented herein will be given serious consideration. Sincere thanks are given to the following SOGAD Committee members: Bryan Allred, PE; Lowell Brumley, PE; Mark Farrow, PE; Pawan Gupta, PE; Ted Neff, PE; Floyd Oliver, PE; Jon Sampson, PE; Tami Spicer, PE, and all RPG members, PTI staff, and others who gave their time and made significant contributions to the advancement of ground-supported residential foundation design.

Jack W. Graves Jr. *has been involved with the post-tensioning industry for over 36 years. He has worked for industry-leading companies VSL Corporation and Dywidag-Systems International, and was Managing Partner of GSI Post-Tension for 13 years. He received his Bachelor of Arts degree from the University of Texas at Arlington, Arlington, TX, and has regularly presented post-tensioning seminars and authored several articles on slab-on-ground post-tensioned foundations. He currently serves as Chair of PTI Committee MKT-150, Marketing. He had served as Co-Chair of PTI Committee DC-10, Slab-on-Ground; Chair of PTI Committee DC-15, Slab-on-Ground Alternative Design, member of PTI Committee DC-80, Repair and Rehabilitation; the PTI Executive Committee; and the PTI Board of Directors. He has also served on the Executive, Board, and Committees for various other business and trade organizations.*

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