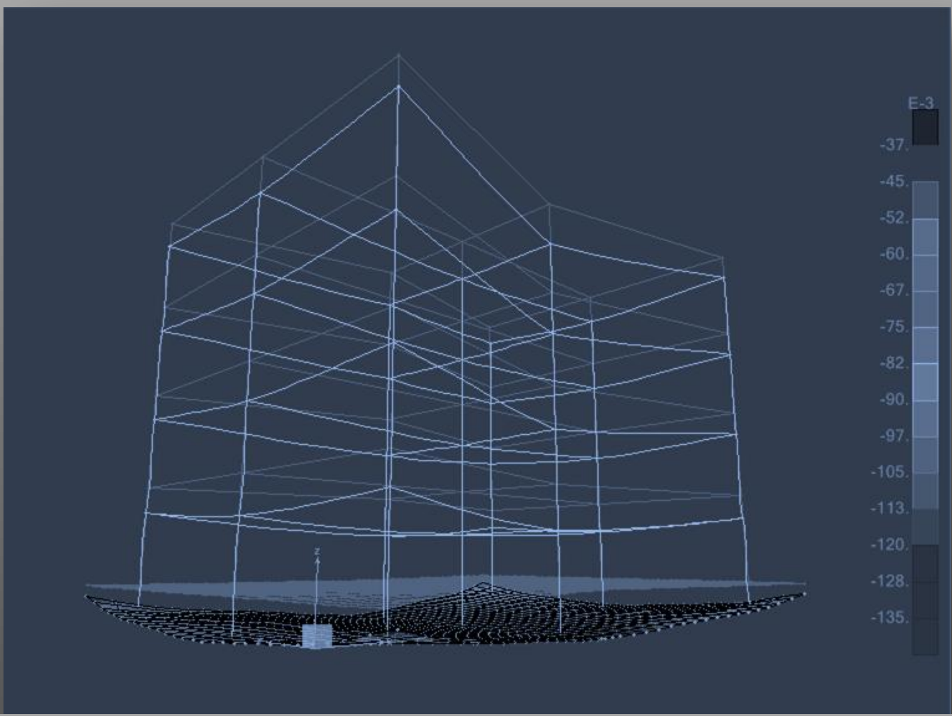
NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL CIVIL OF ENGINEERING

POSTGRADUATE STUDIES ADERS

MSc in Analysis and Design of Earthquake Resistant Structures



ABSTRACT

SSI SOFTWARE DEVELOPMENT

FOR SHALLOW FOUNDATIONS ON ELASTIC LAYERED

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SSI Software Development for shallow foundations on elastic layered soil

Introduction

During the last decades Soil-Structure Interaction has been a subject of extensive research with either analytical or semi-analytical methods. However, for practical problems the Winkler method remains the most popular tool for an engineer despite its well-known disadvantages.

The purpose of this research is a software development regarding the effects of *SSI* for static loading, on the response of a structure with shallow foundation laying on elastic layered soil. The applied procedure, Layered Soil Structure Interaction *LSSI*, has a purely analytical approach [*Stavridis*, 2002] that includes the variability of soil proprieties. Recent release of the Sap2000 OAPI (Open Application Programming Interface) from Csi Inc. has made feasible this effort providing also the benefit of immediate access in most engineering offices.

Before API, a methodology based on a theoretical approach with various consecutive analysis procedures and elaborated numerical calculations couldn't give answer to routine engineering problems guaranteeing discretization precision, elimination of user errors and immediateness of the results. With the API functions in Visual Basic programming language is achieved the development of *LSSI* in a plugin form for Sap2000. The user after importing the structure in Sap2000 specifies the soil's geometric and elastic properties and executes the analysis. Even without any particular knowledge of the theoretical approach can retrieve information for the structure's settlement and sollecitation state. The image below explains the procedure's flowchart.

In the LSSI procedure the interaction of the structure with the soil is carried out using a structural model with fictitious supports inserted at the contact nodes of the foundation elements with the soil surface. The analysis of the discretized structure in Sap2000 is combined to an analytical algorithm that determines the deformational behavior of the soil to determine the system's stiffness matrix and consequently the system's settlements. Imposing the latter to the foundation's contact nodes is achieved fictitiously the presence of the soil in the Sap2000 environment. At this point the system's model is ready for analysis to give the sollecitation state and settlements of the structure for external static loading.

Description of LSSI procedure

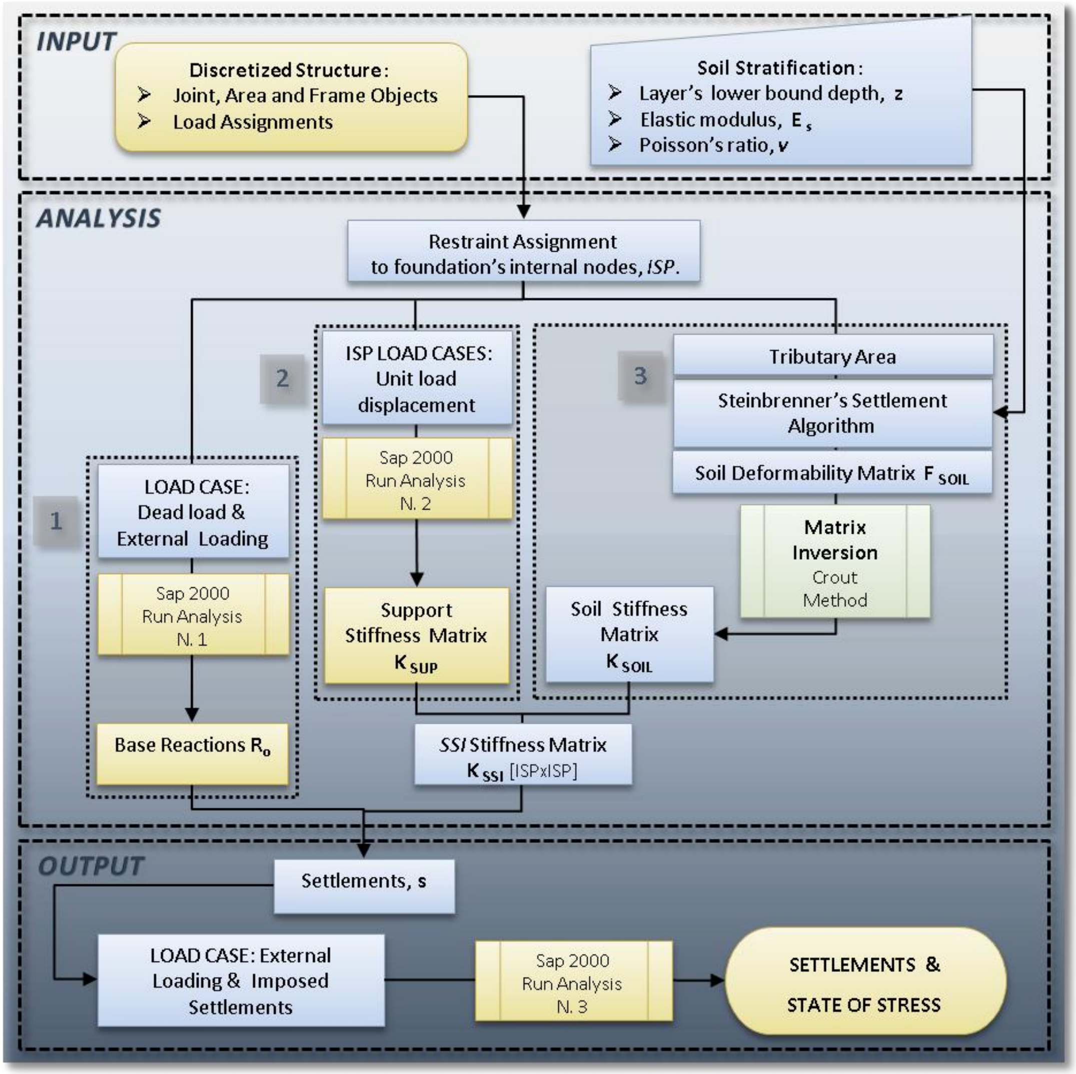

Figure 1 Procedure LSSI (Layered Soil Structure Interaction). Flowchart

The code starts by storing the input data. The layered soil is characterized by three parameters. The geometry is defined by the depth of the lower bound of each layer from surface z while for the elastic properties of the soil are sufficient the elastic modulus E and the Poisson's ratio ν (values from specimens tested in laboratory). The discretized structure is also stored by retrieving labels and coordinates of joints, area and frame elements.

- Once communication between Sap2000 and the code is been established, restraints to each foundation contact node can be assigned. Internal active contact nodes of the foundation soil common interface are grouped into a group named "ISP" (internal supported points) instead peripheral inactive nodes of the foundation are assigned to a group named "ESP" (external supported points). Also their tributary area is determined, an equivalent rectangular area of influence of each contact node that will call later the process to determine soil deformability.

$$\forall \text{ ISP * } \rightarrow \quad U_1 \neq 0; U_2 \neq 0; U_3 = 0; \quad R_{1,\ 2,\ 3} \neq 0$$

$$\forall \text{ EXTSP } \rightarrow \quad U_1 \neq 0; U_2 \neq 0; U_3 \neq 0; \quad R_{1,\ 2,\ 3} \neq 0$$

* assuring that no horizontal movements of the foundation would occur

- The procedure LSSI begins with retrieving the reactions of foundation Ro for a simple analysis in Sap2000 of the simply supported structure for dead load and eventual external loading.

- The second subroutine regards the determination of the foundation's stiffness matrix based on consecutive analyses of the Sap model so many as the number of the foundation contact nodes. To each contact node *i* is imposed a unit load displacement $w_i = 1$ and are retrieved the reactions caused by this settlement in the foundation's contact nodes that will fill column by column the elements of the stiffness matrix.

$$\begin{cases} R_1 = k_{11} \cdot \Delta_1 + k_{12} \cdot \Delta_2 + \cdots + k_{1n} \cdot \Delta_n \\ R_2 = k_{21} \cdot \Delta_1 + k_{22} \cdot \Delta_2 + \cdots + k_{2n} \cdot \Delta_n \\ \vdots \\ R_{n-1} = k_{n-1\,1} \cdot \Delta_1 + k_{n-1\,2} \cdot \Delta_2 + \cdots + k_{n-1\,n} \cdot \Delta_n \\ R_n = k_{n1} \cdot \Delta_1 + k_{n2} \cdot \Delta_2 + \cdots + k_{nn} \cdot \Delta_n \end{cases}$$

By assembling reactions, that are equal to 'k' for a load case of unit load displacement, in a square matrix [**K**] (n x n) the stiffness matrix is derived.

$$\{R_{SUP}\} = [\boldsymbol{K}_{\mathbf{SUP}}] \cdot \{\Delta_{\mathbf{SUP}}\}$$

- The soil stiffness matrix is determined by inversion, calculating the deformability matrix with an analytical algorithm. To each contact node *i* is imposed this time a unit load, $P_i = 1$. Using the Steinbrenner's theory of immediate settlement in a corner of a uniformly loaded area, extended to layered soils, is determined the settlement of all contact nodes due to this load applied. The settlements derived for each contact node will fill a column of the deformability matrix.

$$\begin{cases} \Delta_1 = f_{11} \cdot P_1 + f_{12} \cdot P_2 + \cdots + f_{1n} \cdot P_n \\ \Delta_2 = f_{21} \cdot P_1 + f_{22} \cdot P_2 + \cdots + f_{2n} \cdot P_n \\ \vdots \\ \Delta_{n-1} = f_{n-1\,1} \cdot P_1 + f_{n-1\,2} \cdot P_2 + \cdots + f_{n-1\,n} \cdot P_n \\ \Delta_n = f_{n1} \cdot P_1 + f_{n2} \cdot P_2 + \cdots + f_{nn} \cdot P_n \end{cases}$$

$$\{\Delta_{soil}\} = [\boldsymbol{F}_{soil}] \cdot \{\boldsymbol{P}_{soil}\}$$

By assembling settlements, that are equal to 'f' for a load case of unit load, in a square matrix [**F**] (n x n) the flexibility matrix is derived.

$$\forall\, i \in \text{ISP} \quad \xrightarrow{P_i=1} \quad \begin{pmatrix} \Delta_{soil,\ 1} \\ \Delta_{soil,\ 2} \\ \cdots \\ \Delta_{soil,\ n-1} \\ \Delta_{soil,\ n} \end{pmatrix} = \begin{pmatrix} f_{1i} \\ f_{2i} \\ \cdots \\ f_{n-1\, i} \\ f_{n\, i} \end{pmatrix}$$

- At this point the procedure can solve the linear problem presented by the following equations and determine the foundation's settlements.

$$\{-\Delta_{\text{SOIL}}\} = [F_{SOIL}] \cdot \{-P_{SOIL}\} \qquad (1)$$

$$\{-R_{\text{SUP}}\} = [K_{SUP}] \cdot \{-\Delta_{SUP}\} \qquad (2)$$

$$\overset{(1)}{\Rightarrow} \{-P_{SOIL}\} = [K_{SOIL}] \cdot \{-\Delta_{SOIL}\} \qquad (3)$$

$$\overset{(2)}{\Rightarrow} \{R_O\} - \{R_{SUP}\} = \{R_O\} + [K_{SUP}] \cdot \{-\Delta_{SUP}\} \qquad (4)$$

But: $\{R_o\} - \{R_{SUP}\} = \{-P_{SOIL}\}$ (5)

$$\xrightarrow{(3),(4),(5)} [K_{SOIL}] \cdot \{-\Delta_{SOIL}\} = \{R_o\} + [K_{SUP}] \cdot \{-\Delta_{SUP}\} \qquad (6)$$

Also : $\{\Delta_{SUP}\} = \{\Delta_{SOIL}\} = \{\Delta\}$ (7)

$$\xrightarrow{(6),(7)} [K_{SOIL}] \cdot \{-\Delta\} - [K_{SUP}] \cdot \{-\Delta\} = \{R_o\}$$

$$\Rightarrow [K_{SOIL} - K_{SUP}] \cdot \{-\Delta\} = \{R_o\}$$

$$\Rightarrow [K_{SUP} - K_{SOIL}] \cdot \{\Delta\} = \{R_o\}$$

Numerical Example: Structure on Mat Foundation

A concrete structure consists of an upper slab with rectangular hole located in its central area which transmits the loads to four peripheral walls and four inner columns resting on continuous mat foundation. The ends of the four columns are interconnected through beams of rectangular cross section. The concrete elastic modulus is assumed equal to 30.000 MPa. The foundation soil consists of three horizontal layers resting on hard rock underground ($z_1 = 3\ \mathrm{m}\ E_1 = 26000\mathrm{kPa};\ z_2 = 9\ \mathrm{m}\ E_2 = 8000\mathrm{kPa};\ z_3 = 12\ \mathrm{m}\ E_3 = 35000\mathrm{kPa}$) . The Poisson's ratio is taken for all layers equal to v = 0,3. The upper plate is loaded with a uniform load of 20 kN/m^2 and four concentrated loads each one of 1500 kN are applied at the top of the four columns.

The settlements and state of stress of the foundation retrieved from the LSSI procedure are displayed in the figures below.

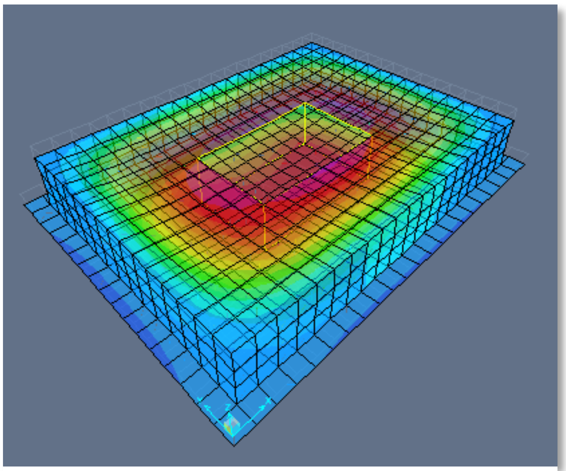
Figure 2 Deformed Shape under static loading

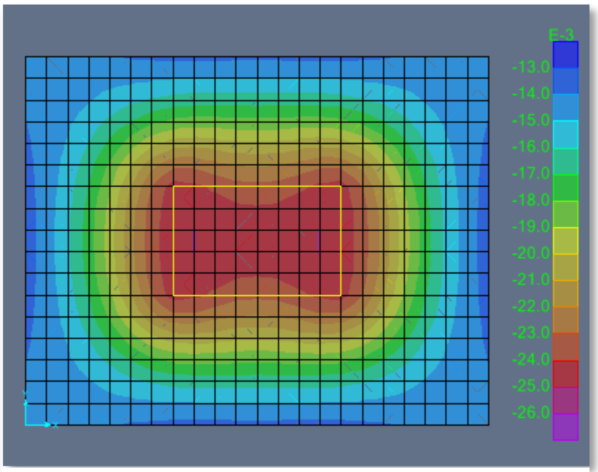

Figure 3 Foundation Settlements, [m]

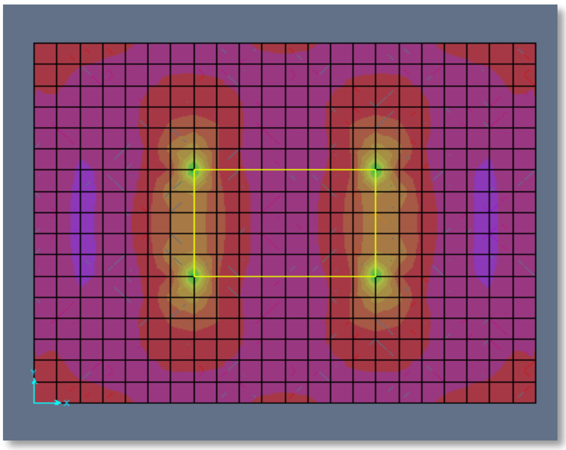
Figure 4 Resultant Forces Moment M11 [kNm/m]

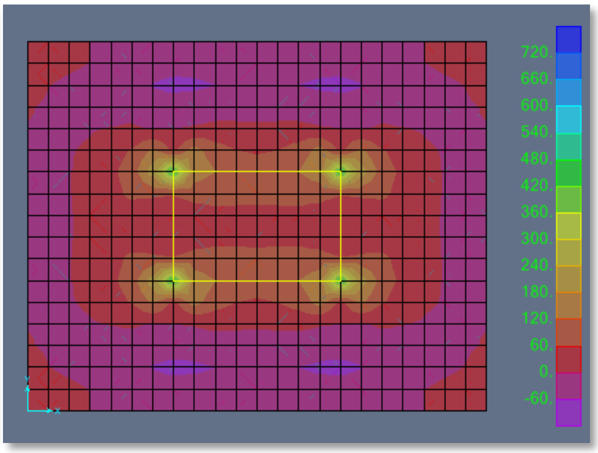

Figure 5 Resultant Forces Moment M22 [kNm/m]

For comparison purposes, the results for a modulus of subgrade reaction $k_s = 21.730\ kN/m^3$ are also presented.

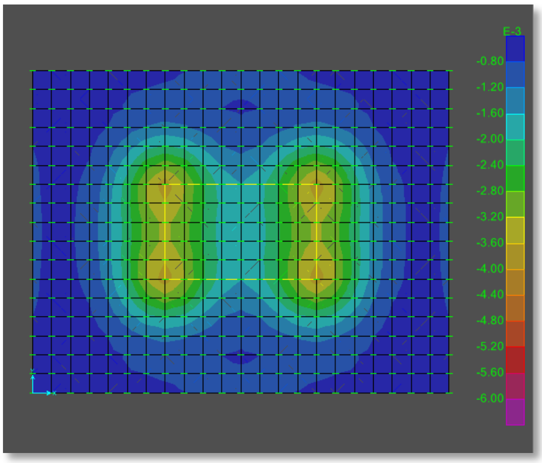

Figure 7 Foundation Settlements, Winkler method [m]

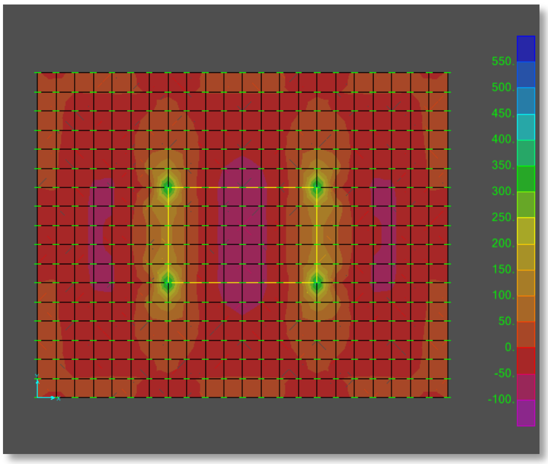

Figure 8 Resultant Forces Moment M11, Winkler method [kNm/m]

Conclusions

The aim herein was to introduce a new, effective approach to develop software for the soil structure interaction, by implementing LSSI procedure. The aforementioned was achieved by making use of some of the latest technology available in software development for engineers, such as the SAP2000 Application Programming Interface. In order to fulfil the targeted scope, a new application has been developed, capable of controlling the SAP2000 workflow through its OAPI, while performs pre- and post-processing of the relative data.

The findings of the effort presented in this dissertation, refer to the contribution of automating the LSSI analysis procedure and to conclusions made after comparison of results with other methods.

- The LSSI treats with a purely analytical approach the well-known problem of SSI and providing knowledge about the predicted immediate settlements and state of stress of the structure. Using this tool engineers are able to deduct decisions for the structure's design, assuring results with discretization precision, immediateness of results and elimination of user errors.

- One of the most important aspects of LSSI is that includes the variability of soil proprieties with depth determined from laboratory tests on soil specimens. LSSI through OAPI has made feasible to represent fictitiously the soil supporting the structure into the Sap2000 environment without using finite elements.
- Comparison of the LSSI analysis to the results obtained considering the Winkler's method, it can be affirmed that this methodology describes better the real response of the system soil - structure under static loading. In fact Winkler not only underestimates the predicted settlements of the foundation but also isn't able to describe the different behavior between foundations of different stiffness laying on soils with small a value of modulus of elasticity. On the contrary for the case of stiffer soils the predicted settlements and state of stress seem to be in agreement to those obtained from Winkler's method.
- This effort also provides the benefit of creating a tool that is of immediate access in most engineering offices due to the vast use of Sap2000 that LSSI involves for analysis